

# **Pairing Water Rights to Land Parcels – Connecting the Prior Appropriations Doctrine and Croplands in the Western US**

Megan W. Schantz

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University

In partial fulfillment of the requirements for the degree of

Master of Science

in

Civil Engineering

Landon T. Marston, Chair

John C. Little

Claire M. White

December 18, 2024

Blacksburg, Virginia

Keywords: Prior Appropriations Doctrine, Water Rights, Agriculture Irrigation

Copyright 2024, Megan W. Schantz

# **Pairing Water Rights to Land Parcels – Connecting the Prior Appropriations Doctrine and Croplands in the Western US**

Megan W. Schantz

## **ABSTRACT**

Agricultural production in the western United States faces uncertainty with climate change leading to reduced crop yields from higher temperatures, lower precipitation rates, and shifting the growing seasons. This impacts farmers and their livelihood but more broadly, the United States's food supply and economic activity. While climatic characteristics are necessary to understand how crop production in the western United States will shift, many studies neglect the role that the water rights priority system plays in determining which croplands receive water under drought conditions. This study introduces a methodology to pair water rights, including priority dates, to land parcels and irrigated croplands. Crops were analyzed within hydrologic and state boundaries to determine which are at risk under the water rights priority system in drought conditions. Lastly, outputs from a global hydrologic model were used to assess water availability under common large-scale water allocation schemes versus the priority system in practice in the western United States, to evaluate schemas impact on water's spatial distribution. The novel pairing of land and water rights in this study increased water right boundaries from 29 to 59 percent across 10 states by implementing spatial overlays, radius, and waterway methods, with the spatial overlays achieving the highest accuracy. Median priority dates of the nine most cultivated crops in the western United States revealed a hierarchical system for water rights seniority, with oats and other hay having the most senior water rights, while junior water rights showed less of a hierarchy, although corn appeared to have the most junior water rights. This study is significant as it establishes a novel framework for linking water rights to croplands, enabling regional-scale analysis and introducing a methodology to integrate this data into a global hydrologic model to achieve insights on a field-level.

# **Pairing Water Rights to Land Parcels – Connecting the Prior Appropriations Doctrine and Crops in the Western US**

Megan W. Schantz

## **GENERAL AUDIENCE ABSTRACT**

Agricultural production in the western United States faces growing uncertainty as climate change leads to higher temperatures, reduced precipitation and shifting growing seasons. Climatic changes affect farmers' livelihoods and, more broadly, the United States' food supply, but the specific ways these changes influence agricultural production remain poorly understood. This is largely because many studies overlook the critical role of the water rights priority system that governs water allocation in the western United States. To address this issue, we developed a methodology to pair water rights with land parcels, linking the priority system to crop boundaries. We analyzed crop trends within hydrologically and politically connected regions to identify which crops are most likely to face water shortages during drought periods. The pairing of land and water rights using the introduced methods expanded water right boundaries by 30 percent. The water rights for the nine most common crops in the western United States revealed a ranking for those with the highest priority, with oats and other hay having the most secure access to water during droughts. In contrast, lower-priority crops showed no distinct pattern, though corn emerged as the least likely to receive water during drought conditions. This study provides a framework for connecting water rights to croplands, allowing for regional analysis and introducing a method to use this information in global water models to better understand water access at the field level.

# Table of Contents

1 Introduction.....	1
2 Methodology .....	3
2.1 Study Boundaries and Data.....	3
2.2 Linking POD-POU and Defining POU Boundaries.....	5
2.2.1 Data Preparation .....	5
2.2.2 Linking PODs to POU's .....	7
2.2.3 Delineating Boundaries .....	8
2.2.4 Boundary Accuracy and Limitations.....	9
2.3 Assigning Crops to POU Boundary .....	10
2.4 PCR-GLOWB 2 Water Availability .....	12
3 Results.....	14
3.1 Can irrigation water rights be paired with land parcels to determine the water allocation priority of irrigated crop fields? .....	14
3.1.1 Water Right Pairing and Boundary Coverage Improvements .....	14
3.1.2 Boundary Accuracy of Methods on State-Defined POU Boundaries .....	17
3.2 Which crops exhibit greater exposure to water shortage due to their water right priority? 23	
3.3 Does the water allocation scheme in hydrological models impact spatial variation in water availability?.....	29
4 Conclusion .....	33
References.....	35
Appendix A – Supporting Tables .....	37

# 1 Introduction

Agriculture in the arid and semiarid western United States heavily depends on irrigation (Marston et al., 2018). In 2015, 42 percent of all freshwater withdrawals were for irrigation, accounting for approximately 118 billion gallons per day (Bgal/d), which represents a 2 percent increase since 2010 (Dieter et al., 2018). Although these withdrawals span the entire country, they are disproportionately concentrated in the 17 western states (Kenny et al., 2009). In these states, irrigation constitutes 85 percent of freshwater withdrawals and supports 74 percent of the irrigated acres with California, Idaho, Colorado, and Montana accounting for 49 percent of the total irrigation withdrawals (Kenny et al., 2009). Because irrigated agriculture accounts for one of the largest sources of water withdrawals in the United States, understanding water supply trends is crucial for farmers and policymakers in the western United States. Agriculture also plays a critical role in the national economy, accounting for 5.4 percent of the United States Gross Domestic Product (GDP) and 10.5 percent of employment (USDA Economic Research Service, 2024). However, increasing competition for water from urbanization, aging infrastructure, industrial uses, and minimum streamflow has intensified in recent years, further stressing water availability for agriculture (Xu et al., 2014). Compounding these pressures is global climate change, which introduces uncertainty regarding future water supplies. Changes in precipitation patterns, temperature increases, and shifts in snowpack melt timing (Wu 2015; Qin et al., 2020) all have the potential to disrupt water availability during critical growing seasons, consequently impacting crop yields and the United States agriculture economy (Backlund et al., 2008).

Climatic water patterns in the western United States are further influenced by distinct political systems that govern water use. Water rights in this region are governed by the Prior Appropriations Doctrine, which has shaped water management in the region since the mid-19<sup>th</sup> century. Originally developed to support large-scale mining and agriculture activities in the region, the doctrine operates on a “first in time, first in right” principle (Gopalakrishnan, 1973). This means that the priority of water use is determined by the date of the original claim, with older (senior) water rights taking precedence over newer (junior) rights during times of water scarcity (Gopalakrishnan, 1973). Unlike in the eastern United States where water rights are attached to land ownership under the riparian rights system (Hutchins, 1977), the Prior Appropriations Doctrine allows water to be withdrawn at a designated point of diversion (POD) and used elsewhere at a separate place of use (POU). Each water right is tied to a specific volume allocation, representing the maximum water permitted for use, which may be forfeited through non-use (Thompson et al., 2018). Water rights must also fulfill a “beneficial use” purpose, such as irrigation, domestic, or industrial uses (Tesoriero, 2024). Because of the political system in place, large amounts of water used for irrigation can be used far from its source, influencing the way water flows and making it difficult to study.

There have been numerous studies that analyze the effects of drought on agriculture through a lens of climatic characteristics, focusing on crop correlations reflected in drought indexes (Kuwayama et al., 2018; Lu et al 2020). These studies neglect water rights in the western United States, assuming water users have equal and uniform water access. A major reason for this assumption is the complexity of water rights data, which falls under state jurisdiction and varies

in its availability and format. Recently, the Western States Water Council and Pennsylvania State University completed the standardization of state water rights data, which paves the way for more comprehensive analyses (Western States Water Council, n.d.; Lisk et al., 2024). This offers a solution to the fragmentation issues that have previously hindered the integration of water rights into large-scale studies, potentially enhancing the accuracy and relevance of future research. Prior to the standardization of state data, there has been limited research explicitly pairing water rights to crop production outcomes in the context of drought. An early attempt to address this gap, conducted by Oregon Water Resources Department (OWRD), developed techniques for assigning water rights to quarter-quarters (Beamer & Bromley, 2022). The method developed by ORWD utilizes Bureau of Land Management (BLM) land ownership, dividing townships (160 acres) to quarter-quarters (40 acres). However, the method developed by OWRD is limited in its accuracy due to the application of field boundaries to a standard grid, which may simplify water right boundaries.

This study addresses two key knowledge gaps: understanding the relationship between PODs and POUs in the western United States and examining the political implications of drought on agriculture by linking the water rights priority system to croplands. The first component establishes a methodology to link water rights to their associated croplands using land parcel information and cropland data. This provides critical insights into the connection between PODs and POUs, which is essential for understanding water distribution in times of scarcity. The second component examines how the Prior Appropriations Doctrine affects water security for specific crops in the western United States. The analysis focuses on the Hydrologic Unit Code 4 subregion and state levels, aligning with the scales at which water management decisions are made, accounting for the complexities of hydrologic and geographic boundaries. Additionally, the research proposes a framework for integrating its findings into a hydrologic model, comparing water availability under a priority-based allocation system to one without prioritization.

To analyze the effect water rights have on crops, three research questions were proposed.

- 1) Can agriculture irrigation water rights be paired with land parcels to determine the water allocation priority of irrigated crop fields?
- 2) Which crops exhibit greater exposure to water shortage due to their water right priority?
- 3) Does the water allocation scheme in hydrological models impact spatial variation in water availability?

The data and methods used to address these questions are first presented, followed by a detailed discussion of the findings. Key results, study limitations, and the broader implications of the research are then highlighted in the concluding section.

## 2 Methodology

### 2.1 Study Boundaries and Data

This analysis utilized water rights data from Water Data Exchange (WaDE), a program created by the Western States Water Council to standardize water rights data across the western United States (Western States Water Council, n.d.). WaDE applies a consistent data standard across state water right records, addressing the challenge of analyzing water rights data across state boundaries since each state independently collects and manages its own water rights data. WaDE updates its dataset biannually as new data becomes available and as the status of water rights change. For this study, the WaDE dataset from December 2023 was used. Although WaDE is one of the most comprehensive sources of water rights for the western United States, it remains incomplete due to several states not having fully digitized or adjudicated all their water rights. Furthermore, some states provide verified linkages between PODs and POUs, while others do not.

WaDE provides POD data for 18 western states, but only 10 states have verified POD-POU linkages. These 10 states were analyzed using the methodology outlined in Section 2.2. The remaining eight states were not assessed in this study due to incomplete data. States with verified POD-POU linkages provide POU information as either point coordinates or polygons delineating the boundary of where the water right is applied. Table 1 categorizes states based on whether they have verified POD-POU linkages and lists the number of water rights for each state from WaDE’s 2023 data for all beneficial use categories.

**Table 1.** States with and without POD-POU linkages and corresponding number of water rights from Water Data Exchange (WaDE).

<b>States with POD-POU Linkages</b>	<b># of Water Rights</b>	<b>States without POD-POU Linkages</b>	<b># of Water Rights</b>
Arizona	267,304	Alaska	17,456
Idaho	176,886	California	807,118
Montana	342,498	Colorado	161,016
Nebraska	197,579	Kansas	31,112
Nevada	39,365	New Mexico	217,110
Oklahoma	12,842	North Dakota	3,569
Oregon	68,035	South Dakota	10,053
Utah	150,745	Texas	147,597
Washington	85,930		
Wyoming	70,430		

In some states, WaDE provides POU boundaries for water rights, but that information is not available consistently amongst all rights. For example, in Idaho, 92 percent of water rights have POU polygon boundaries, 8 percent have point coordinates, and 0.01 percent lack POU location information. To fill these gaps, Regrid land parcel data was used to delineate missing POU boundaries. Regrid compiles land ownership data from municipal and state governments, which

is then standardized into a nationally consistent data format. Regrid data is available as shapefiles that outlines the boundaries of every land parcel in the United States, with nearly 100 percent county coverage in the contiguous United States (Loveland Technologies, n.d.). Approximately 94 percent of this data is updated annually. For this analysis, the January 2024 Regrid dataset was used. The Regrid dataset used in this analysis had full coverage for the states included.

To support the integration of WaDE water rights data with Regrid land parcels, the National Hydrography Dataset (NHD+) was utilized (USGS WaterWatch, n.d.). NHD+ provides a detailed stream network for both natural and man-made waterways across the United States, along with Hydrologic Unit Codes (HUC) and reach codes for major rivers and canals. HUC boundaries define watersheds based on surface hydrologic features and are assigned a 2- to 12-digit code, with the number of digits indicating the spatial scale from large to small (USGS, n.d.). This study used HUC4 subregions, the second-largest scale, to capture broader regional trends while avoiding the aggregation of hydrologically unrelated water rights. Major rivers and canals helped connect water rights to nearby waterways to widen the area analyzed.

Once POU boundaries were established, the POUs were spatially matched with irrigated croplands using two raster datasets: the Cropland Data Layer (CDL) (Cropland Data Layer, n.d.) and the Landsat-based Irrigation Dataset (LANID) (Xie et al., 2021). Both CDL and LANID have a 30-meter resolution and provide yearly data snapshots related to land use and irrigation. CDL data from 2011 to 2020 was used to identify crops and their locations, while LANID data from the same period was utilized to determine irrigated areas, thereby refining rasters to irrigated croplands. The combination of datasets enabled a comprehensive representation of land and water use.

To further assess the impacts of water right allocation schemes on water availability, the global hydrologic model PCR-GLOWB 2 was employed (Sutanudjaja, et al., 2018). The model's 30 arc-second version was used to provide the highest possible resolution, corresponding to a 1-kilometer by 1-kilometer grid at the Earth's equator. The model provided monthly total runoff data, which was summed to align with the yearly temporal resolution of the other datasets used in this study. The datasets used in this study are detailed and referenced in Table 2.

**Table 2.** Summary of datasets used in analysis.

<b>Dataset</b>	<b>Source</b>	<b>Relevant Variables</b>
Water Data Exchange (WaDE)	(Water Rights Data, n.d.)	Point of Use/Point of Diversion Linkages, Water Right Locations, Beneficial Use, Owner Name, Priority Date, Water Source, and Allocation Flow Rate
Regrid Property Parcel Data	(Loveland Technologies, n.d.)	Land Parcel Areas and Owner Name
National Hydrography Dataset (NHD+)	(USGS WaterWatch, n.d.)	HUC Boundary Areas and Major River Locations
Cropland Data Layer (CDL)	(Cropland Data Layer, n.d.)	Crop Location
Landsat-based Irrigation Dataset (LANID)	Xie et al. (2021)	Irrigated Land Locations
PCR-GLOWB 2	Sutanudjaja, et al. (2018)	Monthly Total Runoff

## 2.2 Linking POD-POU and Defining POU Boundaries

### 2.2.1 Data Preparation

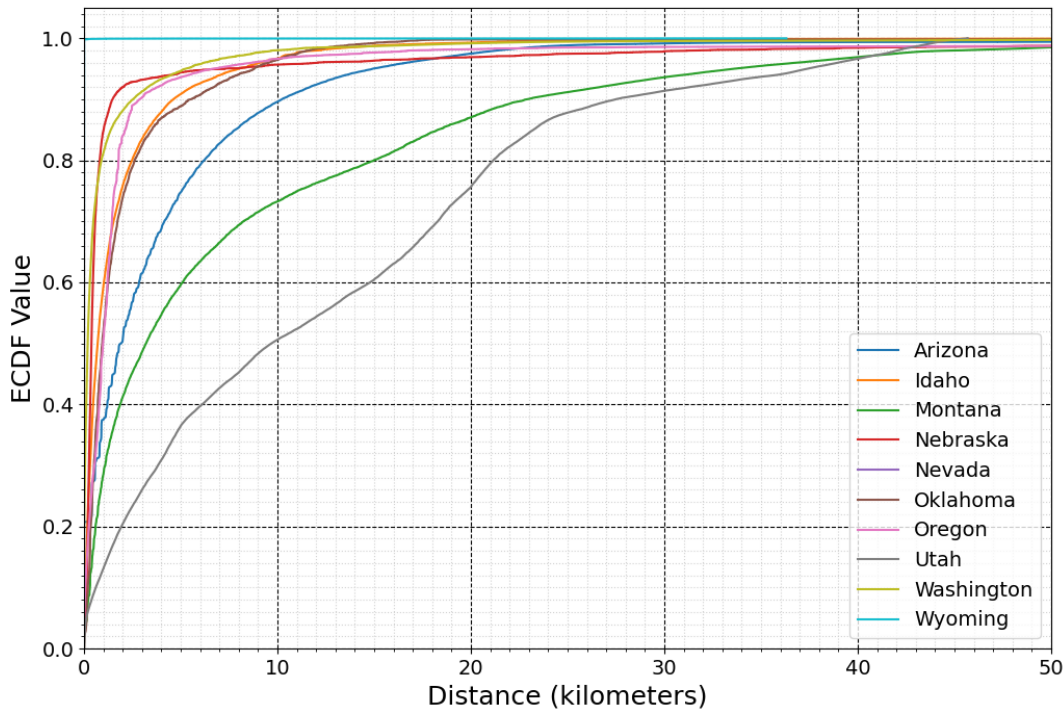
Before linking PODs to POU and defining POU boundaries, water rights were filtered to only include agriculture irrigation as the beneficial use. The irrigation water rights were then categorized into three types based on the locational and boundary details provided for the water right's POU. The three types include water rights with a state-defined POU boundary (Type 1), water rights with state-defined POU coordinates but no corresponding property boundary (Type 2), and water rights without any POU information (Type 3), for which only POD coordinates were provided. The focus of this study was on states with some defined POU (i.e., the 10 states listed in the first column of Table 1), either coordinates or boundaries, as these states generally have more complete records and serve as a foundation for pairing water rights to POU boundaries. However, these states still have water rights without POU information, necessitating a novel methodology to identify and connect unlinked PODs to possible POU. This methodology relied on existing POD-POU linkages within each state to determine a search radius for pairing unlinked PODs. The breakdown of POU data by state is presented in Table 3.

**Table 3.** The count of POU data provided by state governments categorized by the level of POU information: Type 1 includes water rights with state-defined POU boundaries, Type 2 includes water rights with POU coordinates, and Type 3 lacks POU information.

<b>State</b>	<b>Boundary (Type 1)</b>	<b>Coordinates (Type 2)</b>	<b>Undefined (Type 3)</b>
Arizona	0	7,673	28,235
Idaho	86,114	7,718	141
Montana	21,162	134,340	26,232
Nebraska	5,119	438	21,736
Nevada	216	8,437	672
Oklahoma	5,287	1,129	5,742
Oregon	18,317	89,554	112
Utah	347,445	138,029	47,077
Washington	24,641	30,766	29
Wyoming	0	28,611	978
<b>Total</b>	<b>508,301</b>	<b>446,705</b>	<b>130,954</b>

To address different spatial resolutions of POU types, tailored processes for data preparation were applied. Type 1, which were complete, required no additional processing. Type 3, containing only POD data, were linked directly to POU boundaries using a two-step methodology described in Section 2.2.2. In contrast, Type 2, which included both POD and POU data, required a more complex approach to account for their multidimensional relationships. For these, water rights were expanded into unique POD-POU pairings. For example, a water right associated with 2 PODs and 3 POUs would result in 6 distinct POD-POU combinations. Spatial overlays were then applied to pair these POUs to their associated locations described in Section 2.2.3.

Once each POD-POU pair was determined, the distances between linked PODs and POUs were calculated for Type 1 and Type 2 data using the great circle distance, or the distance between two points based on Earth’s sphere. This calculation was performed to analyze the distribution of distances between coordinates. The results, shown as an empirical cumulative distribution function (ECDF) in Figure 1, reveal a clear trend in 6 states: 90 percent of POD-POU linkages are located within 10 kilometers of each other. The results of Figure 1 were used to determine the search radius to link PODs to POUs in Type 3 data, as discussed in the following section.



**Figure 1.** Empirical cumulative distribution function graph of POD to POU distances in Type 1 and Type 2 data.

### 2.2.2 Linking PODs to POUs

As shown in Table 3, 12 percent of water rights lack POU information (Type 3). To address this, we used a two-step process first using radial searches and then waterways to link PODs to POU boundaries. First, POU boundaries were identified by drawing a radius from POD coordinates to locate nearby Regrid land parcels, a process named the radius method. This method assumes that water is typically used near the point where it is diverted and that the water right and land parcel(s) are registered under a similar owner name. Therefore, the radius method searches for Regrid land parcels with similar owner name to the water right holder’s name within 10 kilometers of POD coordinates. A 10-kilometer search radius was chosen because the results in the preliminary analysis (Figure 1) indicate most POUs were within 10 kilometers of its POD.

If no match was found by the radius method, a secondary method, the waterway method, was applied. The waterway method assumes that water may be used farther from the diversion point than the radius search perimeter but there must be a nearby natural or man-made waterway to transport the water from the POD to the distant POU. The waterway method identified any manmade and natural waterways within one kilometer of the POD that stretched beyond the 10-kilometer radial search perimeter. Next, the waterway method identified Regrid land parcels with similar owner names located along the waterway beyond the 10-kilometer search radius. The waterway method was introduced since not all POD-POU linkages are within 10 kilometers (Figure 1). Due to high computational costs and the increased likelihood of false matches,

increasing the search radius beyond 10-kilometers would not be effective. The waterway method allows for a narrower search of potential POD-POU pairings by only searching along waterways. POD-POU linkages with large distances between coordinates are likely due to the presence of large irrigation projects or interbasin water transfers (IBTs), which move water from one hydrologic basin to another.

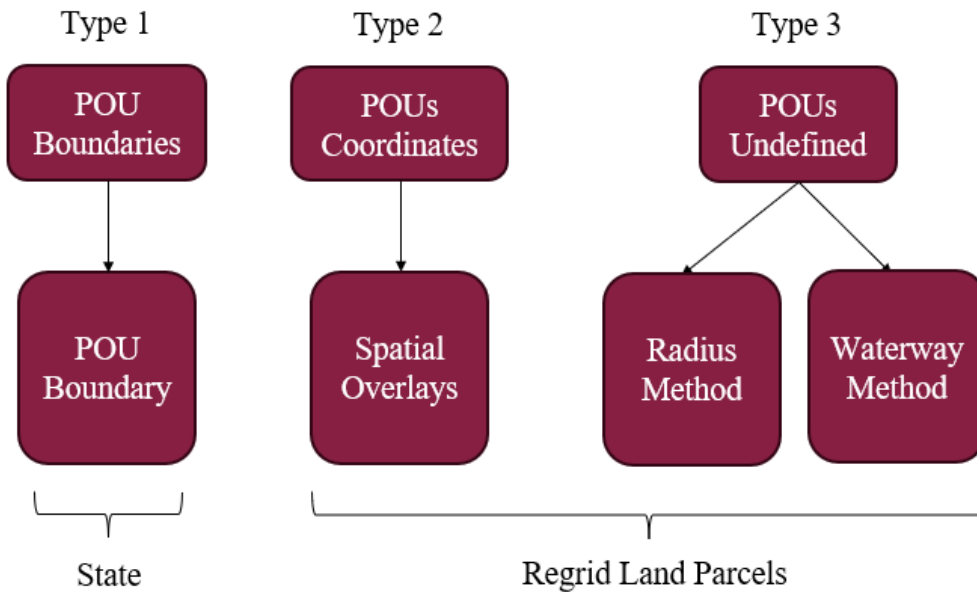
The radius and waterway methods relied on matching POD coordinates to land parcels using the Regrid dataset, which provides land parcels as polygon boundaries. We used the Token Set Ratio (TSR) to pair POD coordinates to Regrid land parcel(s) using similar ownership names between the land and water right records. The TSR was calculated using the fuzzywuzzy Python package (Cohen, T. n.d.). The TSR calculates similarity between two strings while disregarding word order, making it effective in handling naming variations like 'last, first' and 'first, last.' The TSR score ranges from 0 (completely dissimilar) to 100 (identical strings). A large search distance from PODs increased the risk of false matches, therefore a high TSR threshold (a lower bound of string similarity) of 70 was applied to reduce these errors. If a land parcel owner name exceeded a TSR of 70, it was paired to the water right. For instances where there were multiple Regrid land parcels scored above 70, all Regrid land parcels were matched. If no land parcels exceeded 70, the water right went to the waterway method for further analysis. While the 10-kilometer search radius worked for most states, two states, Arizona and Utah, required significant amounts of computational storage because of the high number of Type 3 data, seen in Table 3. As a result, the radius had to be reduced to 7 kilometers and 3 kilometers, respectively.

The waterway method utilized data from the National Hydrography Dataset (NHD+) (USGS WaterWatch, n.d.) to identify major rivers and canals in the western United States. To determine which water rights could be transferred beyond the 10-kilometer radius, a 'doughnut buffer' was created, searching for the same reach code prefix within a 1-kilometer range of the known POD coordinates, and between 10 and 10.1 kilometers. A reach code is a unique 14-digit identifier for continuous sections of surface water with similar hydrologic characteristics (U.S. Environmental Protection Agency, n.d.), with the first 8 digits (the prefix) defining a broader waterway region. If the same reach code prefix was found in both the inner and outer buffer, the water right was considered transferable along the waterway. For PODs deemed transferable along a nearby waterway, a 3-kilometer buffer was created along the waterway, extending from 10 to 20 kilometers from the POD coordinate. The Regrid land parcels identified within the additional area using the waterway method were evaluated for owner name similarity, keeping only those with a TSR above the threshold of 70.

### *2.2.3 Delineating Boundaries*

As shown in Table 3, 41 percent of water rights have POU coordinates but do not have POU boundaries (Type 2). Therefore, we used spatial overlays to assign POU boundaries. POU boundaries were defined by overlaying POU coordinates on surrounding Regrid land parcels and owner names were compared using the TSR. This method assumes that location and owner name similarities are required for POU boundary delineation. The POU coordinates were first spatially joined to the Regrid parcel they overlapped, and then to adjacent land parcels. This was done to capture multiple land parcels that could belong to the same owner and thus the same water right

and to consider slight inaccuracies in coordinate location. Owner names from water rights and Regrid parcels were compared using the TSR, and all parcels with a TSR above 50 were considered a good match. While higher TSRs increased the accuracy of name matching, a threshold of 50 was chosen for POU coordinates because searching within a smaller area near the known place of use provided reasonable matches, even with a lower threshold. Figure 2 outlines the methodology used for linking PODs to POUs (Section 2.2.2) and delineating POU boundaries (Section 2.2.3).



**Figure 2.** Visual describing the methods undergone in Type 1, Type 2 and Type 3 data.

#### 2.2.4 Boundary Accuracy and Limitations

To evaluate the accuracy of linking PODs to POUs and delineating POU boundaries, we conducted a validation process using state-defined POU boundaries (Type 1). While exact accuracy cannot be assessed for Type 2 and Type 3 data due to the absence of state-defined POU boundaries, examining accuracy in Type 1 data provides a basis for estimating the overall accuracy of each method. Spatial overlays were applied to Type 1 POU coordinates, and the radius and waterway methods were applied to Type 1 POD coordinates, using identical parameters as employed for Type 2 and Type 3 records, as detailed in Sections 2.2.2 and 2.2.3. The number of land parcel pairings generated was recorded, and the percentage of pairings was calculated. Regrid land parcels paired in this process were examined against their state-defined boundaries to calculate the intersection area. The intersection area quantifies the overlap between Regrid land parcels and state-defined POU boundaries, serving as a measure of linkage and delineation accuracy. The intersection area was calculated using the intersection tool in geopandas (Jordahl et al., 2023). After calculating the intersection areas, the intersection percentage was determined by dividing each intersection area by its corresponding state-defined POU boundary area, both individually and in aggregate. This approach enabled an assessment of

how accurately Regrid land parcels aligned with state-defined boundaries on both an individual and collective basis.

Several limitations and assumptions influenced the methodology. First, the accuracy of the Regrid land parcel data presented minor challenges. In certain cases, multiple Regrid parcels overlapped but had differing owner names, potentially due to the creation of new records instead of updates to existing ones. For example, of the 1,102,735 parcels in Idaho, 0.4% (4,454 parcels) were found to have the same geometry but different owner names. In this study, all Regrid land parcels were used since it was unclear which property record was correct. Additionally, the methodology assumes that a TSR score above a threshold (50 or 70) constitutes a "good match" when comparing water rights owner names to land parcel owner names. This threshold was set to capture potential generational or familial discrepancies, where one family member owns the land while another owns the water right. However, this assumption may lead to incorrect matches between unrelated individuals who share a common name. Additionally, spatial overlays with adjacent parcels used for Type 2 data restricted POU boundary delineation to a few parcels. This constraint could reduce accuracy by not accounting for potential location inaccuracies or large POU boundaries. Another limitation lies in the computational constraints and the potential for inaccurate pairings caused by large search radii in Type 3 data. The preliminary analysis showed that most POD-POUs are within 10 kilometers of each other, a considerable distance that poses challenges for accurate mapping. To address POD-POUs pairs farther away, the waterway method was introduced, though it may still have limitations due to its constrained scope.

To address potential limitations in the waterway method, a sensitivity analysis was conducted to test the assumptions underlying its application. This analysis assessed how varying buffer sizes and TSR thresholds affected matching accuracy. The initial assumptions used a buffer of 10 to 20 kilometers and a TSR threshold of 70. To test the robustness of these assumptions, the buffer was expanded incrementally to 50 kilometers, and the TSR threshold was adjusted to 50. This analysis evaluated how changes in these parameters impacted the ability to accurately pair water rights to land parcels.

### **2.3 Assigning Crops to POU Boundary**

The POU boundaries from Type 1 data and the POU boundaries created for Types 2 and 3 data were combined into a single dataset that was then used throughout the remainder of the analysis. These boundaries were spatially overlaid with CDL and LANID data to calculate the irrigated area per crop in square meters per year within each POU. To accomplish this goal two raster datasets, CDL and LANID, were multiplied to identify irrigated croplands. Once irrigated croplands were assigned to POUs, the total area for each crop per year was summed using the zonal statistics geoprocessing tool in ArcGIS. Although data from 2019 was chosen for this analysis because it represents the year with the least water availability, all crop-years were calculated.

The POU boundaries were then assigned to their respective HUC4 subregion and state by the location of their POD coordinate, forming a new combined delineation, which we call HUC4-State Zones. Assigning PODs, POUs, and their associated water rights to HUC4-State Zones

enables the connection between irrigated croplands and water allocation system boundaries. Because water rights are managed within hydrologically connected watersheds and along state lines, this method highlights regions where water rights directly interact and influence one another. HUC4-State Zones are large enough to capture regional trends, while remaining detailed enough to avoid associating unrelated water rights. To critically analyze high crop-producing regions, HUC4-State Zones were ranked by irrigated area, and the top 20 were examined to understand crop sensitivity under drought conditions.

Within HUC4-State Zones, 30 crops, representing 95 percent of the United States’ irrigated cropland (Gambhir et al., 2024), were examined independently. The remaining crops were categorized into five groups: Grains and Oilseeds, Vegetables, Fruit and Tree Crops, Double Cropping, and Forage, with the breakdown of crops in each group detailed in Table 13 in Appendix A. Within the 20 zones, the median priority dates of the nine most common crops, which consist of 95 percent of the irrigated area in the zones, were analyzed in greater detail to determine which crops are more likely to face curtailments during water shortages. Table 4 lists the 30 individual crops and 5 overarching crop groups examined in this study, with the nine most common crops in bold. We analyzed median priority dates instead of mean priority dates, as medians are less affected by the presence of outliers. Median priority dates were examined by crop and HUC4-State Zones to determine if specific crops or zones exhibited greater exposure to water shortage due to their priority date.

**Table 4.** List of the 30 most common crops in the United States and remaining crops grouped into Grains and Oilseeds, Vegetables, Fruit and Tree Crops, Double Cropping, and Forage. The nine bolded crops are the nine major crops in the 20 highest producing HUC4-State Zones.

<b>Crops and Crop Groups</b>		
<b>Alfalfa</b>	Grains and Oilseeds	Sorghum
Almonds	Grapes	Soybeans
Apples	Lentils	<b>Spring Wheat</b>
<b>Barley</b>	Millet	Sugarbeets
Beans	<b>Oats</b>	Sugarcane
Canola	Oranges	Sunflower
<b>Corn</b>	<b>Other hay</b>	Sweet corn
Cotton	Peanuts	Tomatoes
Double Cropping	Peas	Vegetables
Durum Wheat	Pecans	Walnuts
<b>Forage</b>	<b>Potatoes</b>	<b>Winter Wheat</b>
Fruit and Tree Crops	Rice	

In the examination of median priority dates, we used the Mann-Whitney U test to identify statistically significant differences between the priority dates of crops within each HUC4-State Zone. This method was chosen to address the non-parametric nature of the data and its unequal variances. The null hypothesis posited that no statistically significant differences existed among the median priority dates of crops, and the test aimed to either reject or fail to reject this

hypothesis. Rejection of the null hypothesis indicated that the crops' median priority dates were statistically significantly different from one another. Given that eight or nine crops were present in each zone, a Bonferroni correction was used, and the p-values were adjusted to 0.007 and 0.006, respectively, to account for multiple comparisons within the zone. The null hypothesis was rejected only if the p-values were below these thresholds. First, crops with the most senior or most junior priority dates were identified and analyzed. These crops were classified as 'secure' or 'at-risk' if their median priority date was statistically significantly older or more recent, respectively, compared to at least one other crop. When multiple crops shared the same median priority date and were significantly higher or lower than others, but not from each other, they were all categorized as 'secure' or 'at-risk'. In four instances, the most extreme median priority date was not statistically significant, so the next most extreme statistically significant median priority date was used instead. In three instances, no statistical significance could be determined, therefore leaving those blank.

## **2.4 PCR-GLOWB 2 Water Availability**

PCR-GLOWB 2 is a global hydrologic and water resources model (Sutanudjaja, et al., 2018). For smaller areas, such as the Snake River Basin in the Northwest United States, the model can produce results at the 30 arc-second resolution or approximately a 1-kilometer grid. For each grid, water availability is calculated from the soil-water exchange, atmospheric conditions, and the underlying groundwater reservoir, with water routed through cells from upstream to downstream. All sectoral water demands are met as long as they are less than available water supplies. When demands exceed available surface water supplies, available surface water is allocated proportionately among irrigation, public use, livestock, and industrial water uses relative to their initial allocation (Sutanudjaja et al., 2018). Remaining water demands are met through groundwater as long as groundwater demands do not exceed pumping capacity. Water availability and water demands are calculated in one arc-degree by one arc-degree allocation zones, truncating at country borders (Sutanudjaja et al., 2018).

Though the water allocation scheme used in PCR-GLOWB 2 is common among large-scale hydrological models, water is not allocated in this manner in the western United States. Instead, under the Prior Appropriation Doctrine, water users are assigned a priority based on when their water rights were established, with senior water rights being fully fulfilled before junior water rights under water shortage. To address whether water allocation schemes in hydrological models impact spatial variation in water availability, two different methods of distributing water were applied. The first follows the PCR-GLOWB 2 model of proportionally reducing water allocations based on a one arc-degree grid, while the second incorporates the priority system of water rights, ensuring senior rights are fulfilled before junior rights.

While this study does assess the effects of spatial variability of differing water allocation schema, it is an exploratory analysis. This study does not implement water rights into PCR-GLOWB 2 which will more accurately reflect water allocations impact on water availability, but it creates a method for the scaling of POU boundaries to 1-kilometer grids to input to PCR-GLOWB 2. The analysis in this study utilized the model output variable monthly runoff total to

calculate water availability. This provides a snapshot of water availability in local areas but does not capture the entire water network, limiting the results to local trends and not specific use cases. Monthly runoff total is the sum of direct runoff, interflow, and baseflow in meters per grid cell area. The monthly runoff variable was converted to cubic meters per second and summed to obtain the yearly runoff. The year with the least amount of runoff was used to demonstrate, as closely as possible, how water allocation schemes would work in drought conditions.

Before performing the exploratory analysis, POU boundaries within the Snake River Basin were transformed to align with the PCR-GLOWB 2 model structure. POU boundaries associated with both surface water and groundwater withdrawals were included in the analysis. We chose the Snake River Basin for analysis due to its comprehensive state-verified water rights data, substantial reliance on irrigation, and its high levels of agricultural production. Since the model operates on a 1-kilometer grid, POU boundaries had to be simplified and scaled to match the model resolution. POU boundaries were resolved to 1-kilometer grid cells by calculating the centroid of each field, overlaying the POU to its respective grid cell, and summing the water allocations for each priority year within the cell. Water allocations were calculated annually according to priority dates, creating a corresponding allocation for each 1-kilometer grid cell per priority year in the Snake River Basin.

The first method in the exploratory analysis follows the PCR-GLOWB 2 model structure and proportionally reduces water allocations based on availability at the one-degree grid resolution. This means that if water availability meets 80 percent of water demand within a grid, then each water allocation in that grid gets 80 percent of their total allocation. Water availability and demand were calculated on a one-degree grid basis within the Snake River Basin and the percent difference between water availability and demand was found. The percent difference was multiplied by the water availability to find the amount of water available after allocation on a one-degree grid basis.

The second method incorporates the priority system of water rights, ensuring senior water rights are fulfilled before junior water rights. For this method, water allocations for 1-kilometer grid cells were separated based on priority date year. Starting with the earliest priority date, the water allocations for each year were subtracted from the available water. This process decreases water availability by priority date, allowing senior water right holders to access their full claim before junior water right holders which identifies the grid cells most likely to experience water stress due to the priority system.

There are limitations to this analysis due to transforming POU boundaries to 1-kilometer grids and analyzing based on one model parameter, runoff. Transforming POU boundaries to 1-kilometer grids increases the area of the water right, assigning an arbitrary 1 square kilometer to the POU. This can inaccurately reflect the details of water rights in comparison to the land parcel scale. Additionally, analyzing water availability as the total runoff does not accurately reflect the entire water network, as total runoff does not account for river discharge or the larger movement of water in the region, inaccurately reflecting water availability near rivers and water bodies.

## 3 Results

### 3.1 Can irrigation water rights be paired with land parcels to determine the water allocation priority of irrigated crop fields?

#### 3.1.1 *Water Right Pairing and Boundary Coverage Improvements*

Before assessing the likely accuracy of the methods, we evaluated improvements in POU boundary coverage by analyzing the number of POU boundaries created through linking PODs to POU and delineating boundaries. Pairing water rights to land parcels was conducted on a state-by-state basis to evaluate how many water right boundaries were created in this methodology compared to how many boundaries were provided by state governments. As previously seen in Table 3, Type 1 data availability varied significantly between states, reflecting differences in state reporting guidelines and the accuracy of available data. Some states, like Idaho and Oklahoma, presented limited opportunities for the proposed methodology to add value, as the number of water rights closely matched the number of state-defined boundaries. Conversely, states like Utah, Montana, and Oregon showed greater potential for improvement.

The results of delineating POU boundaries from POU coordinates using spatial overlays and adjacent parcels, as shown in Table 5, show a range of pairing percentages, though the overall percentage was low at 24 percent. Montana, Nebraska, Nevada, and Oklahoma achieved pairing rates above 40 percent, while other states fell significantly short, with Oregon and Utah having percentages in the single digits. Analyzing beyond percentages, the number of remaining unpaired water rights per state provides important insight. Montana, Oregon, and Utah have a total of 277,252 remaining unpaired water rights, accounting for 82 percent of the total unpaired water rights. This concentration of unpaired rights may reflect challenges unique to these states, such as inaccurate POU coordinates or more complex ownership naming techniques. However, the overall low percentage paired indicates the need for a more comprehensive method.

**Table 5.** Results from spatial overlays in Type 2 POU boundary delineation detail the initial number of water rights, the number paired, the unpaired remainder, and the percentage of paired water rights.

State	POU Coord (Type 2)	Type 2 – Spatial Overlay	Unpaired	% Paired
Arizona	7,673	2,514	5,159	33
Idaho	7,718	1,349	6,369	17
Montana	134,340	71,796	62,544	53
Nebraska	438	257	181	59
Nevada	8,437	4,051	4,386	48
Oklahoma	1,129	697	432	62
Oregon	89,554	7,539	82,015	8
Utah	138,029	5,336	132,693	4
Washington	30,776	7,375	23,401	24
Wyoming	28,611	7,472	21,139	26
<b>Total</b>	<b>446,705</b>	<b>108,386</b>	<b>338,319</b>	<b>24</b>

The results of linking PODs to POUs using the radius and waterway methods, as shown in Table 6, again reveal a wide range of pairing percentages across states but are notably higher than spatial overlays in Type 2 data. States such as Wyoming, Oregon, and Nebraska have percentages below 50 whereas all other states are above 60. However, percentages don't provide the full picture, and the concern is the number of unpaired water rights, particularly high in Arizona, Utah, and Nebraska. The lower pairing rates in Utah and Arizona were expected due to the reduced search radius required for computational feasibility, which likely limited the method's effectiveness. Nebraska's results, however, were unexpected and require further investigation. The radius method was considerably more effective, pairing 85,875 water rights, while the waterway method paired 573. The high number of pairs created by the radius method highlights the method's ability to pair water rights and supports its underlying assumption that water is generally used near its source. Despite the success of these methods, 34 percent of water rights remained unpaired, underscoring some limitations of the methodology.

**Table 6.** Results from radius and waterway methods in Type 3 POD-POU linkages detail the initial number of water rights, the number paired, the unpaired remainder, and the percentage of paired water rights.

State	POU Undefined (Type 3)	Type 3 – Radius	Type 3 – Waterway	Unpaired	% Paired
Arizona	28,235	17,958	79	10,198	64
Idaho	141	91	0	50	65
Montana	26,232	25,102	32	1,098	96
Nebraska	21,736	9,474	76	12,186	44
Nevada	672	445	4	223	67
Oklahoma	5,742	4,422	7	1,313	77
Oregon	112	44	0	68	39
Utah	47,077	28,121	351	18,605	60
Washington	29	25	0	4	86
Wyoming	978	193	24	761	22
<b>Total</b>	<b>130,954</b>	<b>85,875</b>	<b>573</b>	<b>44,506</b>	<b>66</b>

These results, combined with state-defined boundaries (Type 1), resulted in an average POU boundary coverage of 59 percent of all water rights within the study states, with eight states achieving coverage above 50 percent. This approach provided a 30 percent increase compared to state-defined boundaries alone. As shown in Table 7, some states saw substantial gains, with increases of up to 57 percent. However, in states like Idaho, where most water rights already had state-defined boundaries, the increase was minimal at only 1 percent. Individual states may have seen a more dramatic increase in coverage with a smaller number of water rights paired. One example being Nevada with a 49 percent increase of POU boundary coverage with 4,716 water rights paired. These results demonstrate that, while refinements to the methodology are needed to further increase the number of POU boundaries created, the boundaries established in this analysis already represent a substantial improvement.

**Table 7.** The increase in state water right boundaries from merging state-defined POU boundaries (Type 1) with boundary delineation (Type 2) and POD-POU linkages (Type 3).

<b>State</b>	<b>Coverage % from State Boundaries</b>	<b>Coverage % including New Methodology</b>	<b>% Change</b>
<b>Arizona</b>	0	57	57
<b>Idaho</b>	92	93	1
<b>Montana</b>	12	65	53
<b>Nebraska</b>	19	55	36
<b>Nevada</b>	2	51	49
<b>Oklahoma</b>	43	86	43
<b>Oregon</b>	17	24	7
<b>Utah</b>	65	72	7
<b>Washington</b>	44	58	14
<b>Wyoming</b>	0	26	26
<b>Average</b>	<b>29</b>	<b>59</b>	<b>30</b>

### *3.1.2 Boundary Accuracy of Methods on State-Defined POU Boundaries*

To determine the likely accuracy of spatial overlays, the radius method, and the waterway method, we applied these methodologies to state-defined POU boundaries (Type 1) and compared them with the Regrid land parcel POU boundaries generated by each approach. To evaluate delineation trends and overall boundary accuracy, we examined the number of pairs, pairing percentages, and intersection area percentages created in each method. The intersection area between the Regrid POU boundary and the state-defined POU boundary was calculated to highlight areas where the methodology proved accurate and where further refinement is needed. Arizona and Wyoming were not included in this analysis as they lack state-defined POU boundaries.

Results of the spatial overlay analysis in Type 1 data varied significantly from state to state, indicating that the pairing percentage and accuracy is highly influenced by state-specific factors, as seen in Table 8. On average, POU coordinates of state-defined boundaries were paired with Regrid land parcels 41 percent of the time and had an average intersection area, or accuracy, of 54 percent. Spatial overlays achieved the highest accuracy in Montana, Oregon, Oklahoma, and Nebraska, exceeding 65 percent. However, the pairing percentage varied notably among these states. In contrast, states like Idaho and Washington showed much lower intersection area, with 28 and 35 percent, respectively, suggesting challenges in accurately defining POU boundaries. These variations indicate that, even in states where spatial overlays accurately defined POU boundaries, adjusted techniques are necessary to pair the remaining water rights. Furthermore, because only overlaying and adjacent Regrid land parcels were considered, some Regrid boundaries may not fully align with actual POU boundaries, limiting the method's accuracy. Because the pairing percentage and the intersection area percentage greatly vary amongst states,

it is difficult to identify consistent trends data and highlights the complexities of assigning POU coordinates to boundaries across states.

**Table 8.** Results from spatial overlays in Type 1 POU boundary delineation detail the initial number of water rights, the number paired, the percentage of paired water rights, and the intersection area percentage between state-defined and spatial overlay boundaries.

State	Boundary (Type 1)	Count of Pairs	Pairing %	Intersection Area %
Arizona	0	-	-	-
Idaho	86,114	49,360	57	28
Montana	21,162	4,443	21	73
Nebraska	5,119	3,475	69	66
Nevada	216	118	55	51
Oklahoma	5,287	2,856	54	67
Oregon	18,317	5,170	28	68
Utah	347,445	56,135	16	46
Washington	24,641	7,494	30	35
Wyoming	0	-	-	-
<b>Total/Average</b>	<b>508,301</b>	<b>129,051</b>	<b>41</b>	<b>54</b>

The radius method showed clearer trends, with a more consistent and higher matching rate, averaging 65 percent, but a lower average intersection area of 35 percent. This suggests that while the radius method effectively paired POD coordinates to POU boundaries by linking to the overlapping Regrid land parcel(s), the pairings are either incorrect or the POU boundary area may be underrepresented. This outcome could be due to the large search area and higher TSR threshold applied in the radius method. The radius of 10 kilometers likely introduces incorrect pairings of PODs to POUs, increasing the pairing percentage but resulting in a low intersection area percentage. The TSR threshold in the radius method was 70, unlike the threshold for spatial overlays which was 50, which could limit the number of Regrid land parcel(s) paired to the POD. Although some state-level differences remained, the overall results indicate that the radius method is reliable for linking PODs to POUs across states, but the accuracy needs to be improved. Table 9 provides detailed results for the radius method.

**Table 9.** Results from the radius method in Type 1 POD-POU linkages detail the initial number of water rights, the number paired, the percentage of paired water rights, and the intersection area percentage between state-defined and spatial overlay boundaries.

<b>State</b>	<b>Boundary (Type 1)</b>	<b>Count of Pairs</b>	<b>Pairing %</b>	<b>Intersection Area %</b>
Arizona	0	-	-	-
Idaho	86,114	69,829	81	25
Montana	21,162	14,708	70	18
Nebraska	5,119	4,691	92	23
Nevada	216	165	76	80
Oklahoma	5,287	4,187	79	35
Oregon	18,317	7,403	40	35
Utah	347,445	68,032	20	34
Washington	24,641	15,092	61	21
Wyoming	0	-	-	-
<b>Total/Average</b>	<b>508,301</b>	<b>184,107</b>	<b>65</b>	<b>35</b>

The accuracy of the waterway method was consistently low across all states, indicating limitations in its application. The overall pairing rate in the waterway method was near zero with only Idaho, Utah, and Washington pairing water rights to land parcels. Due to how the methodology was executed, water rights that were not matched in the radius method went to the waterway method. Because the radius method achieved high pairing rates across most states, fewer water rights were evaluated in the waterway method potentially leading to these results. From the findings in the preliminary analysis, Montana and Utah were expected to have the highest pairing percentages in the waterway method because many of their POD-POU links expanded beyond the 10-kilometer radius. Utah has the highest pairing percentage in the waterway method, but the intersection area was low suggesting POU boundaries are inaccurate. Montana did not pair any water rights to land parcels. These findings underscore the need for either refinement of the waterway method or exploration of alternative approaches to improve accuracy. The results for the waterway method are shown in Table 10.

**Table 10.** Results from the waterway method in Type 1 POD-POU linkages detail the initial number of water rights, the number paired, the percentage of paired water rights, and the intersection area percentage between state-defined and spatial overlay boundaries.

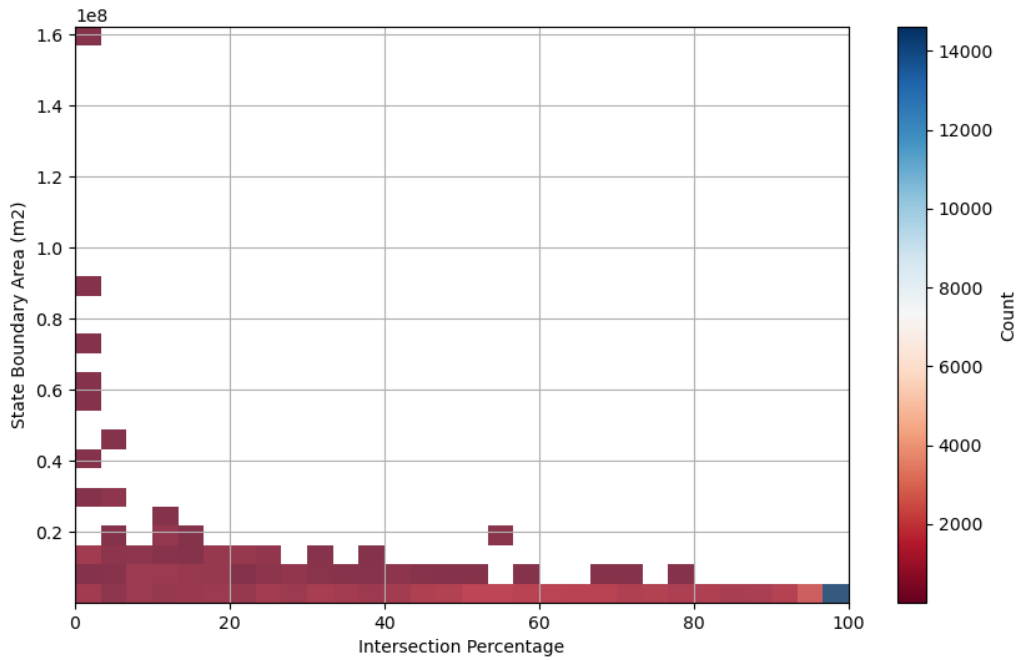
State	Remaining Boundary (Type 1)	Count of Pairs	Pairing %	Intersection Area %
Arizona	-	-	-	-
Idaho	16,285	24	0.2	0
Montana	6,454	0	0	0
Nebraska	428	0	0	0
Nevada	51	0	0	0
Oklahoma	1,100	0	0	0
Oregon	10,914	0	0	0
Utah	279,413	15,515	5.6	1.5
Washington	9,549	38	0.4	0.03
Wyoming	-	-	-	-
<b>Total/Average</b>	<b>324,194</b>	<b>15,577</b>	<b>0.76</b>	<b>0.19</b>

The waterway method assumed a POD-POU connection along a nearby natural or man-made water channel between 10 and 20 kilometers, and it was originally thought that the inaccuracy stemmed from this assumption being too restrictive. A sensitivity analysis was conducted to explore this further. Expanding the buffer from 20 to 50 kilometers had no impact or decreased intersection area, with only a few additional matches identified, except in Utah. Lowering the TSR threshold to 50 provided similar results. Idaho, Oklahoma, Oregon, and Washington saw slight increases in pairing percentages, though these remained below 2 percent with almost zero intersection area. In Utah, 13,874 additional pairs were created, but the intersection area declined by 0.2 percent. These results indicate that expanding the search radius to 50 kilometers along a nearby waterway and lowering the TSR threshold to 50 was ineffective across all states. The results for the sensitivity analysis are presented in Table 11.

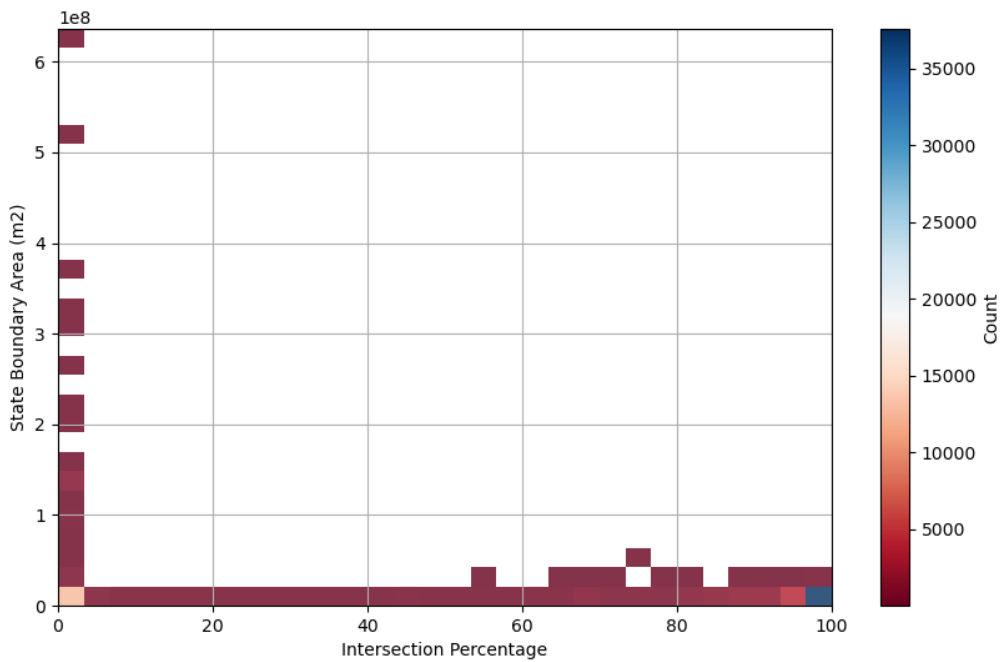
**Table 11.** Results from the sensitivity analysis in Type 1 POD-POU linkages detail the initial number of water rights, the number paired, the percentage of paired water rights, and the intersection area percentage between state-defined and spatial overlay boundaries. The sensitivity analysis increased the search radius to 50 kilometers and decreased the TSR threshold to 50.

State	Remaining Boundary (Type 1)	Count of Pairs	Pairing %	Intersection %
Arizona	-	-	-	-
Idaho	16,285	152	0.9	0
Montana	6,454	0	0	0
Nebraska	428	0	0	0
Nevada	51	0	0	0
Oklahoma	1,100	21	1.9	0
Oregon	10,914	28	0.3	0
Utah	279,413	29,389	10.5	1.3
Washington	9,549	166	1.7	0.01
Wyoming	-	-	-	-
<b>Total/Average</b>	<b>324,194</b>	<b>29,756</b>	<b>1.9</b>	<b>0.16</b>

To examine trends in intersection areas captured by spatial overlays and the radius method, we conducted a detailed analysis of the relationship between state boundary area and intersection percentage in Idaho. A detailed analysis was not done on the waterway method because of the low accuracy in the initial and sensitivity analyses. Figure 3 is a heat map visualizing the relationship between state-defined boundary area and intersection percentage for spatial overlays. Figure 4 visualizes the same relationship for the radius method. The figures reveal that the highest number of pairs is concentrated in the far-right corner, indicating a strong correlation between small POU boundaries and a high intersection percentage. However, Figure 4 shows that the radius method had a significant number of small POU boundaries that had little to no overlapping area, likely because of the large search radius. Additionally, the figures have a vertical line that hugs the y-axis, showing that larger POU boundaries tend to have near zero intersection percentages. This suggests that these methods struggle to pair larger areas accurately. Although less pronounced, similar patterns were observed in heat maps for other states, which indicates that this limitation is not unique to Idaho. These findings highlight the challenging trade-off between expanding the search area and preserving accuracy, particularly when beginning with a POD coordinate.



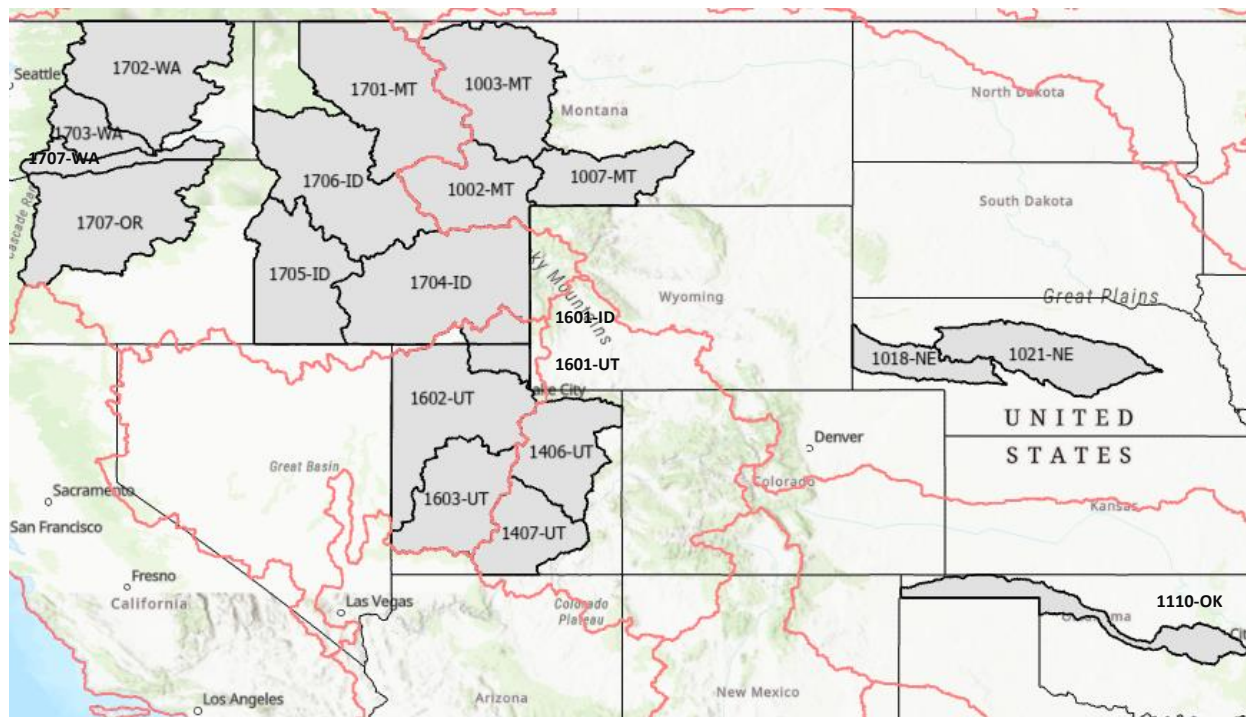
**Figure 3.** Relationship between intersection percentage and state-defined POU boundary area in spatial overlays for Type 1 in Idaho.



**Figure 4.** Relationship between intersection percentage and state-defined POU boundary area in the radius method for Type 1 in Idaho.

### 3.2 Which crops exhibit greater exposure to water shortage due to their water right priority?

The analysis of crop trends across the western United States focuses on the 20 HUC4-State Zones with the highest irrigated areas in 2019, as shown in Figure 5. These zones are grouped within broader hydrologic regions, or HUC2 boundaries, which represent large-scale watersheds. Most of the zones are part of the HUC2 Pacific Northwest Region, located in the northwestern United States, with nine falling within this region. The remainder are distributed across the Missouri Region, Great Basin Region, Upper Colorado Region, and the Arkansas-White-Red Region. Although most of the zones share geographical borders and grow similar crops, primarily those used for animal feed such as alfalfa, forage, and barley, their priority dates vary significantly. This variation highlights the influence of water governance across regions, affecting how water rights are prioritized. Despite governance differences, crops grown across the regions are consistent, reflecting common agricultural practices of the broader area.



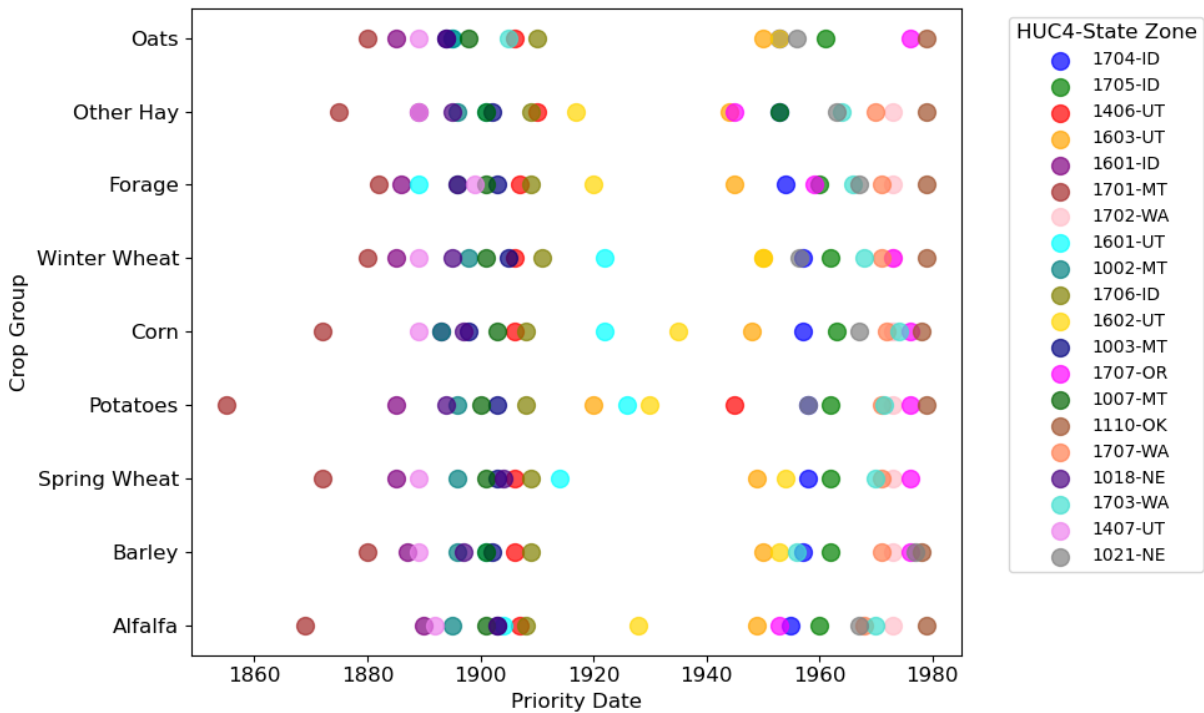
**Figure 5.** The 20 HUC4-State Zones with the most irrigated area in the western United States. HUC2 boundaries are outlined in pink.

The nine major crops account for 95 percent of the irrigated area across all 20 HUC4-State Zones, with only five basins falling below 85 percent. Among these, 1703-WA has the lowest coverage of the nine crop groups, at 52 percent, because apples and Fruit and Tree Crops consist of 38 percent of the irrigated agriculture in the zone. Table 12 provides detailed numbers for the total irrigated area, the irrigated area covered by the selected crop groups, and the percent covered for each HUC4-State Zone.

**Table 12.** The total irrigated area, along with the irrigated area and percentage for nine major crops across 20 HUC4-State Zones in 2019.

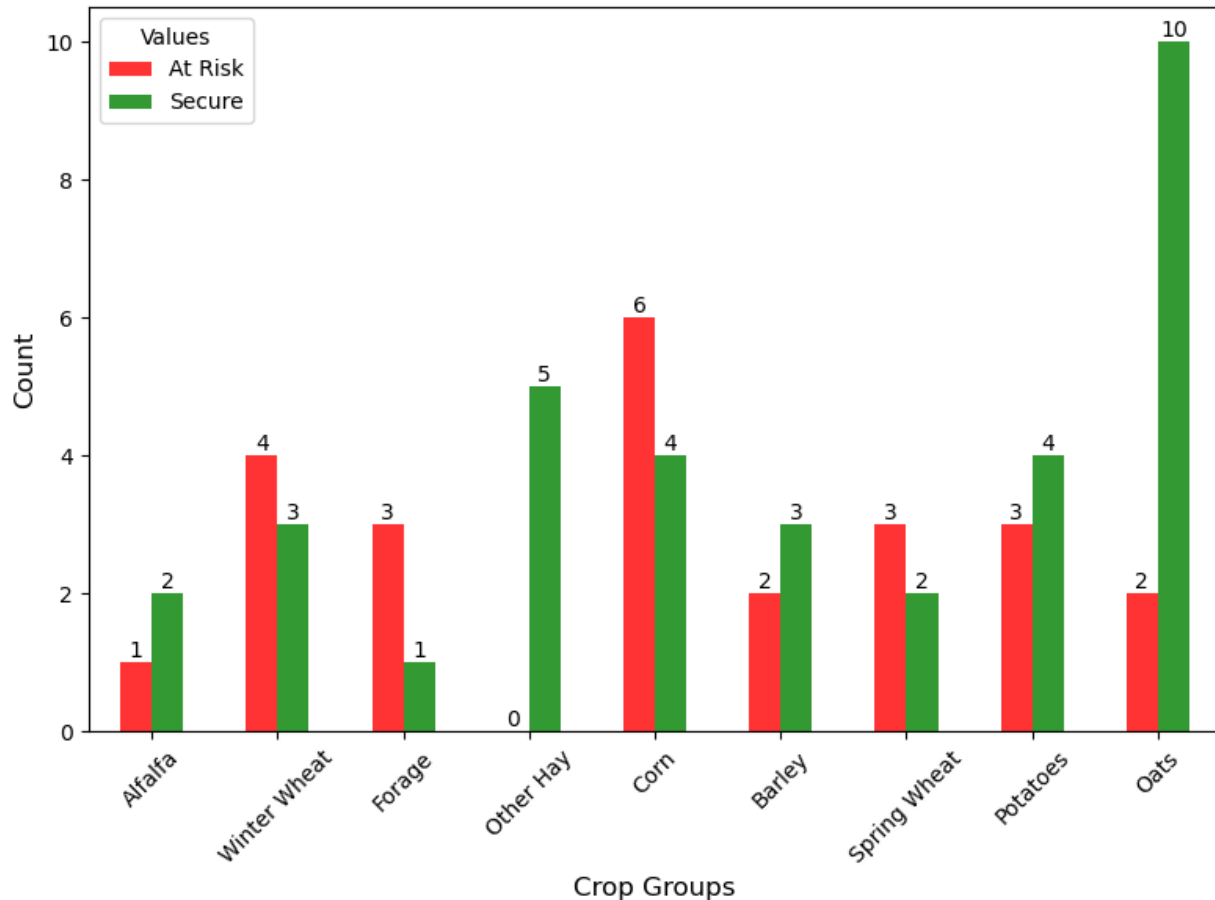
HUC4-State Zone	Irrigated Area (km <sup>2</sup> )	Irrigated Area of Selected Crops (km <sup>2</sup> )	% Covered	HUC4-State Zone	Irrigated Area (km <sup>2</sup> )	Irrigated Area of Selected Crops (km <sup>2</sup> )	% Covered
1704-ID	283,674	271,248	96%	1602-UT	1,771	1,650	93%
1705-ID	22,155	19,738	89%	1003-MT	1,435	1,363	95%
1406-ID	8,975	8,887	99%	1007-MT	1,351	1,294	96%
1603-UT	8,682	8,643	100%	1707-OR	1,344	1,194	89%
1601-ID	7,457	7,146	96%	1110-OK	1,256	998	80%
1701-MT	4,193	4,121	98%	1707-WA	1,090	838	77%
1601-UT	3,773	3,634	96%	1018-NE	1,026	882	86%
1702-WA	3,712	2,737	74%	1703-WA	978	506	52%
1002-MT	2,982	2,901	97%	1407-UT	871	866	99%
1706-ID	2,010	1,989	99%	1021-NE	594	453	76%

Of the nine major crop groups, corn, forage, other hay, barley, winter wheat, and alfalfa are grown in all zones. The remaining three crop groups, oats, potatoes, and spring wheat are grown in 18 or 19 of the zones. Median priority dates for crop groups across zones are generally consistent, as seen in the relatively even horizontal lines in Figure 6. However, the overall trend reveals two distinct halves: crops with earlier median priority dates and those with later ones. Other hay and alfalfa have the earliest dates, primarily in the 1910s, followed by forage and oats in the 1920s. Barley, winter wheat, and corn are concentrated in the 1940s, while spring wheat and potatoes exhibit the latest median dates in the 1950s. Overall trends do not account for HUC4-State Zone distinctions, which can be initially inferred in Figure 6 to have significant differences in median values. This is evident in the near-vertical color-coded lines, spaced widely along the x-axis, highlighting the variation across zones.



**Figure 6.** Dot plot displaying the median priority date for the nine major crops in the 20 HUC4-State Zones with the largest irrigated areas, categorized by crop.

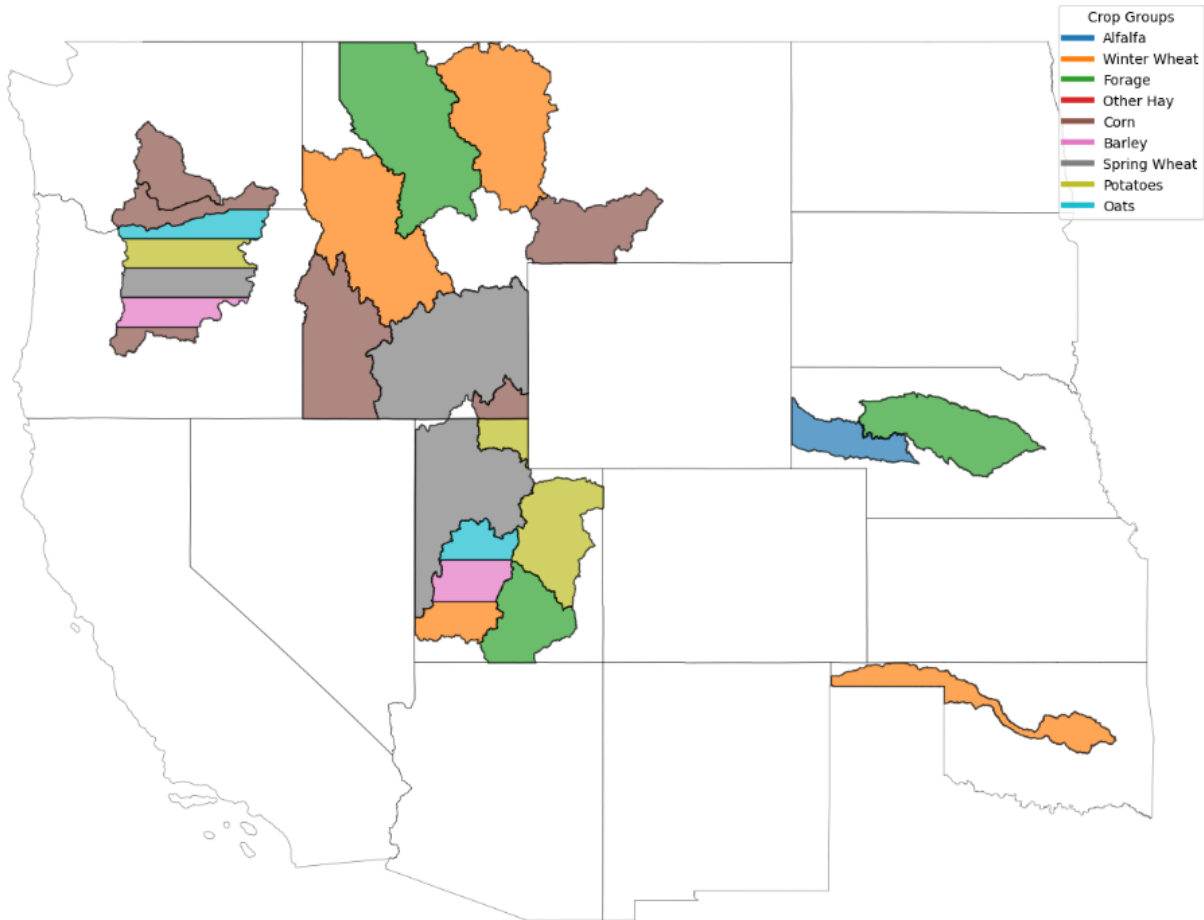
A closer analysis of crop priority date distribution revealed different results than those suggested by the overall trends. Instead of relying on an overall median across HUC4-State Zones to determine crops' seniority, the Mann-Whitney U test was applied within each HUC4-State Zone to assess the distribution of priority dates for each crop. This approach identified crops categorized as 'most secure' or 'most at-risk' within each basin, highlighting whether water right seniority consistently favored specific crops. If a crop was not statistically significantly different from other crops, it was not considered 'most secure' or 'most at-risk'. The results revealed that oats had statistically significantly more senior priority dates in 10 HUC4-State Zones, a trend that was not as evident in Figure 6 but becomes apparent in Figure 7. The remaining eight crops displayed a more dispersed pattern of water right seniority, with other hay emerging as the second most secure crop, achieving most senior status in five zones. Corn was the crop most frequently categorized as at-risk in six HUC4-State Zones; however, the trends were less pronounced for at-risk crops, with most other crops being categorized as at-risk in two to four zones, suggesting a more balanced distribution of vulnerability.



**Figure 7.** Most secure and most at-risk crops based on statistical significance in the Mann-Whitney U test within HUC4-State Zones.

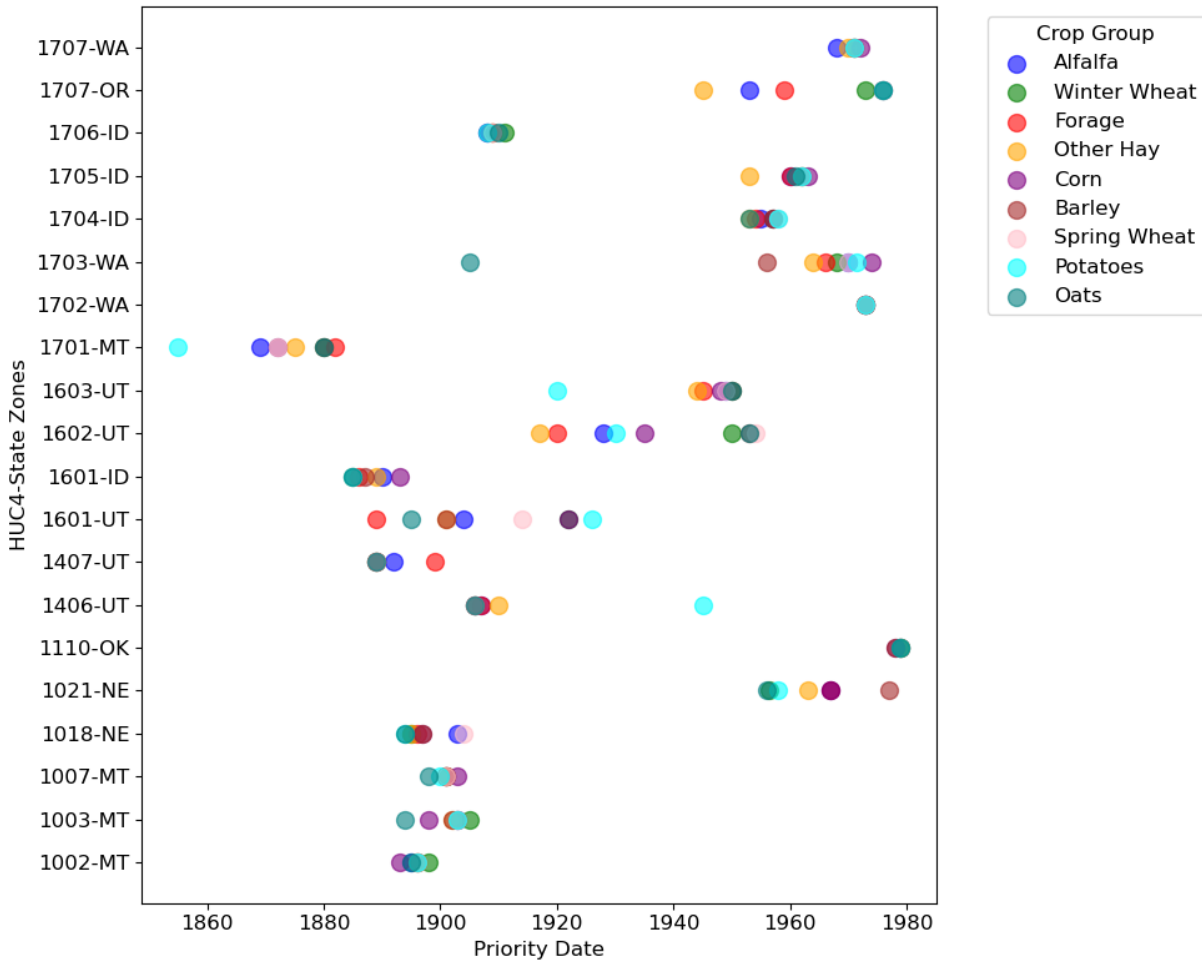
HUC4-State Zones can have multiple statistically significantly secure or at-risk crops, making it important to consider whether the crops hold their status individually or share it with others. Additionally, spatial distribution of secure or at-risk crops can provide insights if similarities persist amongst basins. Figure 8 illustrates which crops are the most secure across each HUC4-State Zone. For instance, oats, which have the highest number of secure water rights in 10 basins, show varying degrees of dominance. In seven of these basins, oats are either the only secure crop or tied with just one other crop. However, in three zones, oats are tied with three or four other crops, reducing their overall seniority dominance. Notably, three basins, including those in Utah and southeastern Idaho, exhibit significant overlap in crop security, with multiple crops sharing senior status. While the underlying cause is uncertain, it may relate to governance practices at the state or basin level, complicating efforts to definitively identify the most senior crops. No clear regional patterns emerged regarding which crop held the most senior status.





**Figure 9.** Distribution of the most at-risk crops across the top 20 HUC4-State Zones. Zones with multiple most at-risk crops are proportionally divided, while zones without any are left blank.

However, grouping all crops together and analyzing from one zone to another, median priority dates vary significantly. As seen in Figure 10, most priority dates are clustered within HUC4-State Zones but the clusters range approximately a century. HUC4-State Zone 1701-MT holds the oldest water rights, with median priority dates in the 1880s. In contrast, 1702-WA and 1110-OK have the most junior water rights, with median priority dates in the 1970s and 1980s. Furthermore, 1702-WA has an overlapping cluster, which may be the result of state reporting practices. Although differences between other zones are less pronounced, the figure reveals that priority dates are more strongly influenced by HUC4 subregions than by state boundaries, varying significantly across HUC4 subregions in the same state but remaining consistent across states in the same HUC4 subregion. Further, besides the presence of a few outliers, there is a general trend of priority dates following HUC2 regions. That is, the first two numbers of the HUC4-State Zone have similarities amongst their median priority dates. Statistical significance was not calculated to support this claim, but the general trend is that water rights in the Missouri Region are older than the water rights in the Pacific Northwest Region. This indicates that water right priority system differences are driven by hydrologic boundaries.

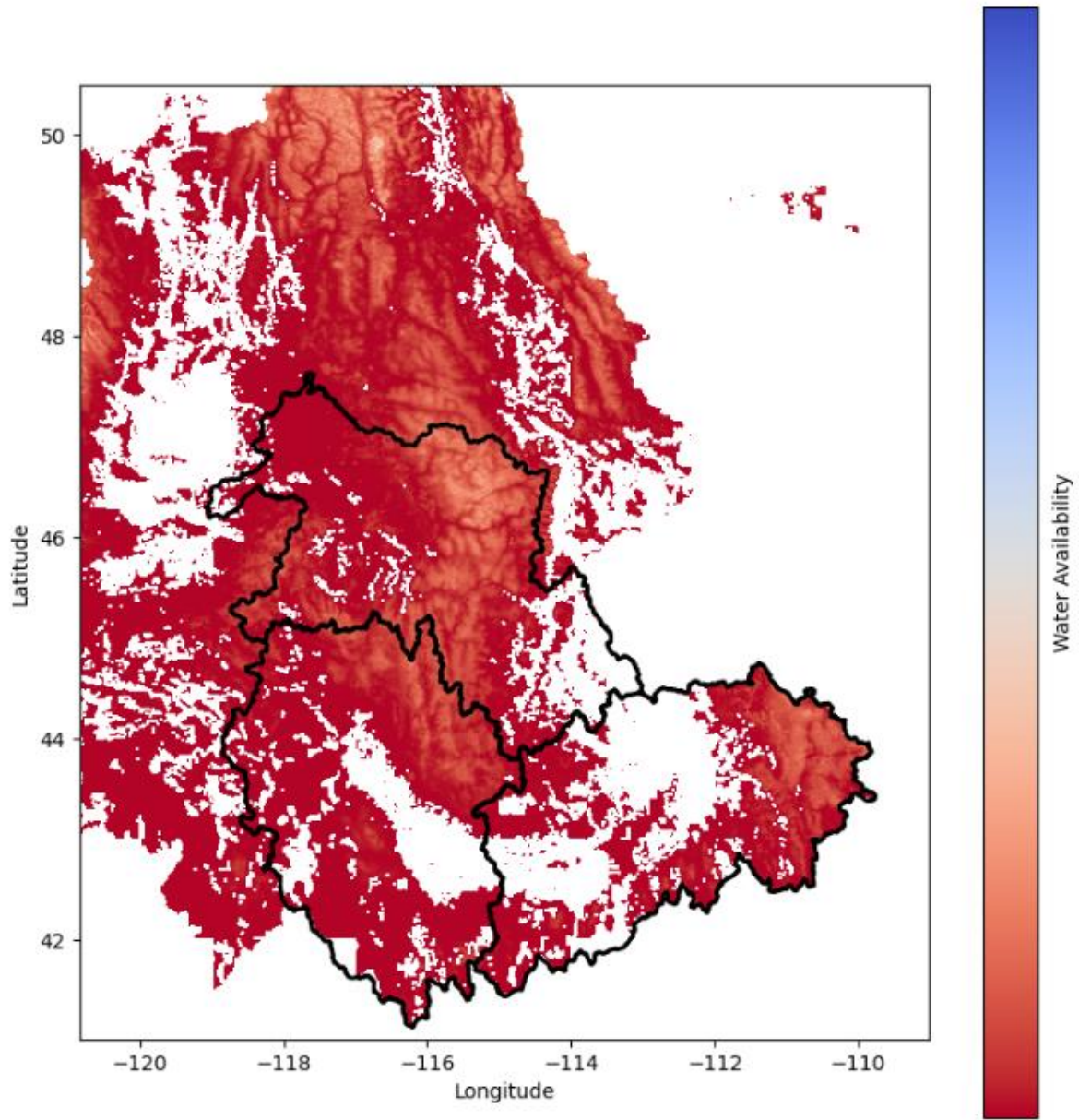


**Figure 10.** Dot plot displaying the median priority date for the nine major crops in the 20 HUC4-State Zones with the largest irrigated areas, categorized by HUC4-State Zone.

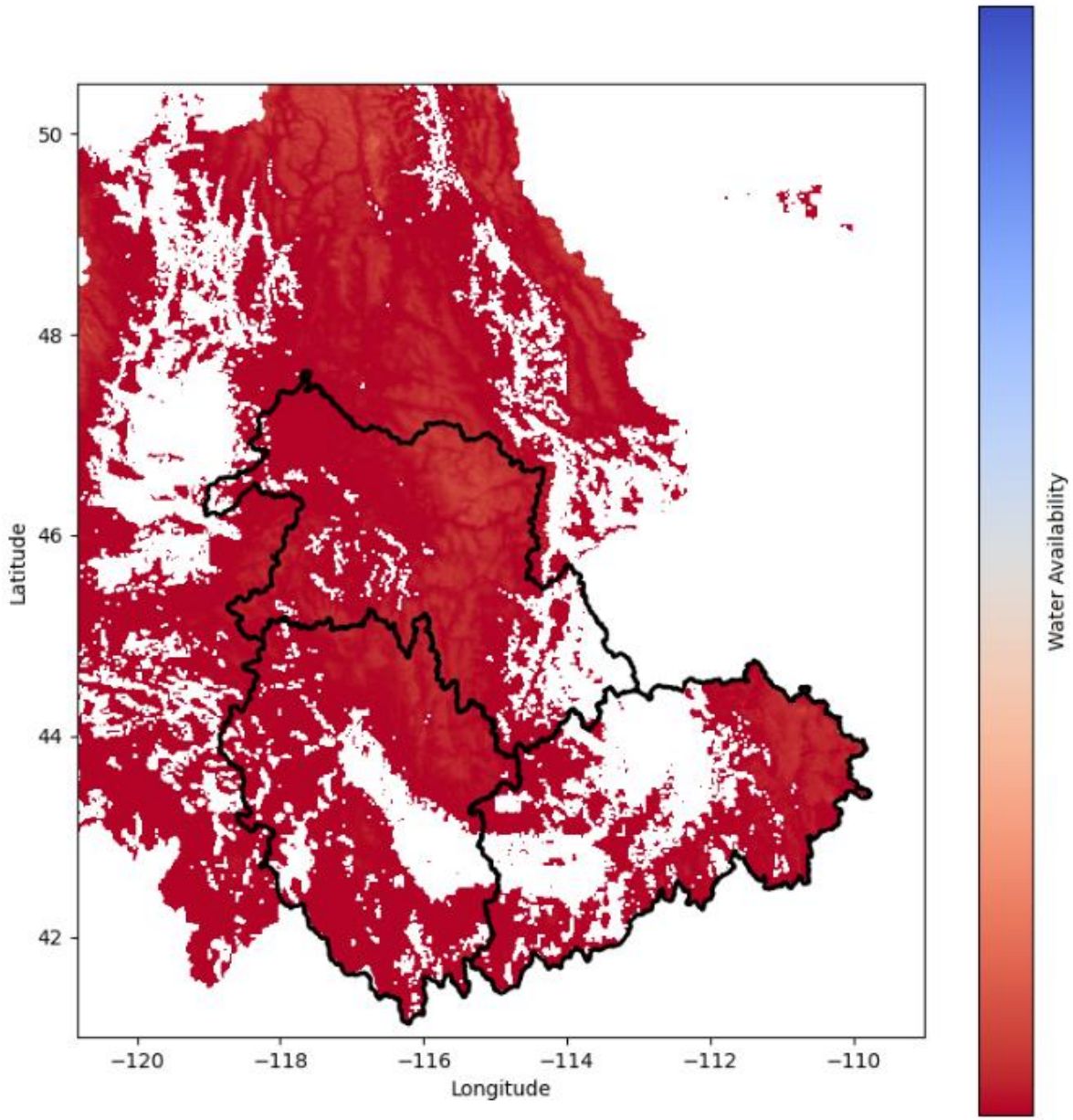
### 3.3 Does the water allocation scheme in hydrological models impact spatial variation in water availability?

The exploratory analysis of incorporating the water priority system into hydrologic model results offers a snapshot of local water availability using the runoff variable from PCR-GLOWB 2. To evaluate how water allocation schemes influence spatial variations in water availability, figures were generated to visually compare the two outlined methods. While these figures highlight differences in magnitude, they do not provide comprehensive numerical calculations, as factors such as sectoral demands, river discharge, and groundwater were excluded from this analysis. Instead, the figures focus on illustrating how the allocation methods impact outcomes, with the key insights derived from the observed differences. Cells that appear blank in the figures indicate the absence of runoff, either because the area is hydrologically disconnected (e.g., outside the HUC2 Pacific Northwest Region) or because it lies in low-lying areas where runoff is most likely considered river discharge. This pattern is particularly evident along the Snake River.

Figure 11 illustrates water availability under the PCR-GLOWB 2 allocation scheme, which proportionally distributes water based on availability, while Figure 12 represents water availability under the western United States water rights priority system. The most notable differences between these figures are in the magnitude and spatial distribution of water availability, with similar trends observed within and outside the Snake River Basin, outlined in black. Under the PCR-GLOWB 2 allocation scheme, water availability is significantly higher and more broadly distributed. A possible explanation lies in the treatment of negative values under the water rights allocation scheme, which are effectively treated as zero. In the water rights system, when a water right holder cannot meet their allocation, they are cut off entirely, resulting in no water availability. This leads to an overrepresentation of zero values, as shortages are not shared like the PCR-GLOWB 2 allocation scheme. However, this would require a clear distinction between regions or holders with water and those without, a pattern not observed in Figure 12.



**Figure 11.** Water availability calculated from the PCR-GLOWB 2 allocation schema that proportionally reduces water allocations based on availability at the one-degree grid resolution. The three HUC4s consisting of the Snake River Basin are outlined in black.



**Figure 12.** Water availability calculated from the Prior Appropriations Doctrine allocation schema that uses the water right priority system to fully allocate water to senior rights before junior rights. The three HUC4s consisting of the Snake River Basin are outlined in black.

## 4 Conclusion

In the western United States, accurately determining where and how much water is used is challenging due to the Prior Appropriations Doctrine, which permits water to be withdrawn in one location and used in another, managed in fragmented, state-level systems. This study developed a methodology to pair water rights with their corresponding place of use from standardized water right data created by WestDAAT. POU boundaries were established and aligned with croplands to assess which crops were secure or at-risk during droughts under the water right priority system. Water availability within POU boundaries was evaluated using both the priority system and a common hydrologic model's system, highlighting discrepancies between modeled results and real-world conditions. This study underscores the importance of creating a dataset that incorporates the water right priority system for a more accurate reflection of reality. Understanding water-limited crops can better inform farmers' crop decisions and the nation-wide agriculture market, helping adapt to climatic changes and local water availability.

This study quantified the increase in water right boundaries created using the proposed methods and assessed their likely accuracy. State-defined POU boundaries accounted for 29 percent of water rights records across the 10 states analyzed. By applying spatial overlays, along with the radius and waterway methods to pair water rights to Regrid land parcels, the percentage of defined POU boundaries rose to 59 percent, representing a 30 percent increase. Among the methods, the spatial overlays demonstrated the highest accuracy, achieving a 54 percent intersection area between state-defined POU boundaries and Regrid land parcel boundaries. The radius method showed moderate accuracy with an average intersection area of 35 percent. In contrast, the waterway method showed minimal accuracy in both the initial approach and subsequent sensitivity analysis, suggesting that its underlying assumptions may require reevaluation or that a new methodology should be developed to address water rights along IBTs.

After assessing water right boundaries, the median priority dates of the nine most cultivated crops in the western United States were visualized to identify broad trends and evaluated to find statistical significance within HUC4-State Zones using the Mann-Whitney U test. A hierarchical system for the most secure water rights was identified, with oats emerging as the most secure crop across the zones, being statistically significantly more senior than other crops in ten zones, followed by other hay, which held this status in six zones. In contrast, a hierarchy was less apparent among at-risk crops, as most were at-risk in only two to four zones, although corn stood out as the most at-risk, appearing in six zones. The crop priority date medians plotted by HUC4-State Zone revealed clusters aligning with HUC2 boundaries rather than state lines, suggesting that water rights are shaped more by hydrological factors than political boundaries.

The key issue addressed in this study is the lack of data availability of western United States. Although the proposed methodology aimed to bridge this knowledge gap and demonstrated some improvements, data availability challenges persist. To address these limitations, future work could explore replacing spatial overlays with a radius-based method for POU coordinates. This approach could increase the number of water rights paired with Regrid land parcels, potentially improving the pairing percentage and increasing accuracy by analyzing more parcels.

Additionally, future research for linking PODs to POU's should investigate how adjusting the radius distance and TSR thresholds optimizes intersection area. Achieving a balance between pairings and accuracy is crucial; for example, lowering the TSR threshold might reduce intersection area but increase pairings, a trade-off that could be mitigated by fine-tuning the search radius. The waterway method encountered significant challenges, indicating the need to reassess the underlying assumptions or refine the methodology. A starting point could be increasing the buffer around the waterway to greater than 3-kilometers, which may help increase the low pairing percentage.

Another key issue persists when analyzing water rights using HUC4-State overlap regions, as HUC4 subregions often extend beyond state boundaries, causing their fragmentation when only in-state rights are considered. This restriction can narrow the scope of analysis and limit comparisons, overlooking water allocations in neighboring states within the same HUC4, which may influence overall water availability and regional trends. Furthermore, when senior water right holders make a "call" on their rights, requesting their full allocation during times of scarcity, only upstream users are affected by these calls. This can create disparities in how water shortages are managed, as downstream users may not face the same restrictions or impacts as upstream users. To address these limitations, a framework was developed to integrate POU boundaries into hydrologic models. Incorporating water rights into hydrologic models is essential for understanding water rights dynamic interactions and the combined hydrologic and political boundaries of the Prior Appropriations Doctrine. Analyzing a HUC4-State Zone, or any region, in isolation reveals general trends, but it lacks field-level precision. Integrating water rights into a hydrologic model like PCR-GLOWB 2 removes the constraints created by hydrologic and political zones. Additionally, incorporating water rights into a model eliminates relying on a single model parameter, embedding the water rights data within the model's intricate water network, improving water availability accuracy.

This study underscores the need to address gaps in data availability and integrate water rights into hydrologic models, bridging the divide between legal frameworks and practical water management. Delineating POU boundaries and linking PODs to POU's is essential for accurately identifying where water is used and understanding its allocation under the Prior Appropriations Doctrine, which is critical for evaluating agricultural water security and availability. By advancing methodologies that link water rights to croplands, this research provides a foundation for assessing future agricultural production in the context of climate change. As climate variability continues, understanding the interaction between hydrology and policy will be essential for adapting to drought conditions. Refining these approaches will help farmers make informed decisions to sustain their agricultural production and livelihoods, while also supporting the United States economy in understanding shifts in agricultural trends. This work represents an important step toward understanding the changes in agriculture due to climate change through policy, offering a path forward for more adaptive and accurate water management strategies.

## References

- Backlund, P., Janetos, A., & Schimel, D. (2008). The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. U.S. Environmental
- Beamer, J., & Bromley, M. (2022). (tech.). Developing Irrigation Water Use Estimates for the State of Oregon Final Technical Completion Report. Desert Research Institute. Protection Agency, Climate Change Science Program.
- Cohen, T. (n.d.). FuzzyWuzzy. PyPI. Retrieved September 24, 2024, from <https://pypi.org/project/fuzzywuzzy/>
- Cropland Data Layer. USDA. (n.d.). Retrieved September 24, 2023, from [https://www.nass.usda.gov/Research\\_and\\_Science/Cropland/Release/](https://www.nass.usda.gov/Research_and_Science/Cropland/Release/)
- Dieter, C. A., Maupin, M. A., Caldwell, R. R., Harris, M. A., Ivahnenko, T. I., Lovelace, J. K., Barber, N. L., & Linsey, K. S. (2018). *Estimated use of water in the United States in 2015* (Circular 1441). U.S. Geological Survey. <https://pubs.usgs.gov/circ/1441/circ1441.pdf>
- Gambhir Lamsal, Landon T Marston. Monthly crop water requirements of irrigated crops in the United States from 1981-2019. ESS Open Archive . July 11, 2024.
- Gopalakrishnan, C. The Doctrine of Prior Appropriation and Its Impact on Water Development.: A Critical Survey. *Am. J. Econ. Sociol.* 32, 61–72 (1973). [The Doctrine of Prior Appropriation and Its Impact on Water Development](#)
- Hutchins, W. A. (1977), *Water Rights Laws in the Nineteen Western States*, vol. III, Nat. Resour. Econ. Div., Econ. Res. Ser., U.S. Dep. of Agric., Washington, D. C. [Water Rights Laws in the Nineteen Western States - Wells Aleck Hutchins - Google Books](#)
- Jordahl, K., den Bossche, J. V., Fleischmann, M., Wasserman, J., McBride, J., Gerard, J., Tratner, J., et al. (2023). *GeoPandas: Python tools for geographic data*. Retrieved from <https://geopandas.org>
- Kenny, J. F., Barber, N. L., Hutson, S. S., Linsey, K. S., Lovelace, J. K., & Maupin, M. A. (2009). Estimated use of water in the United States in 2005 (No. 1344). US Geological Survey. [USGS Circular 1344: Estimated Use of Water in the United States in 2005](#)
- Kuwayama, Y., Thompson, A., Bernknopf, R., Zaitchik, B., & Vail, P. (2019). Estimating the value of earth observations in hydrological modeling. *American Journal of Agricultural Economics*, 101(5), 1349–1366. <https://doi.org/10.1093/ajae/aay037>
- Lisk, M.D., Grogan, D.S., Zuidema, S. et al. Harmonized Database of Western U.S. Water Rights (HarDWR) v.1. *Sci Data* 11, 598 (2024). <https://doi.org/10.1038/s41597-024-03434-6>
- Loveland Technologies. (n.d.). Landgrid. Retrieved September 24, 2024, from <https://landgrid.com/parcels.USPS>
- Lu, J., Carbone, G. J., Huang, X., Lackstrom, K., & Gao, P. (2020). Mapping the sensitivity of agriculture to drought and estimating the effect of irrigation in the United States, 1950–2016. *Agricultural and Forest Meteorology*, 292, 108124.
- Marston, L., Ao, Y., Konar, M., Mekonnen, M. M., & Hoekstra, A. Y. (2018). High-resolution water footprints of production of the United States. *Water Resources Research*, 54(3), 2288-2316. <https://doi.org/10.1002/2017WR021923>

- National Hydrography Dataset. National Hydrography Dataset | U.S. Geological Survey. (n.d.). Retrieved September 24, 2024, from <https://www.usgs.gov/national-hydrography/national-hydrography-dataset>
- Qin, Y., Abatzoglou, J.T., Siebert, S. et al. Agricultural risks from changing snowmelt. *Nat. Clim. Chang.* 10, 459–465 (2020). <https://doi.org/10.1038/s41558-020-0746-8>
- Sutanudjaja, E. H., Van Beek, R., Wanders, N., Wada, Y., Bosmans, J. H., Drost, N., ... & Bierkens, M. F. (2018). PCR-GLOBWB 2: a 5 arcmin global hydrological and water resources model. *Geoscientific Model Development*, 11(6), 2429-2453.
- Tesoriero, A.J., Erickson, M.L., Conaway, C.H., Tomaszewski, E.J., and Green, C.T., eds., 2024, Knowledge gaps and opportunities for understanding water-quality processes affecting water availability for beneficial uses: U.S. Geological Survey Open-File Report 2023–1086, 81 p., <https://doi.org/10.3133/ofr20231086>.
- Thompson, B. H., Leshy, J. D., & Abrams, R. H. (2018). *Legal control of water resources: Cases and materials* (6th ed.). Foundation Press. <https://search.worldcat.org/title/Legal-control-of-water-resources--cases-and-materials/oclc/1039322017>
- USDA Economic Research Service. (2024, February). Selected Charts from Ag and Food Statistics Charting the Essentials. Retrieved from <https://www.ers.usda.gov/webdocs/publications/108461/ap-121.pdf?v=1164.2>
- U.S. Environmental Protection Agency. (n.d.). *Reach code definition*. Retrieved October 21, 2024, from [https://enviro.epa.gov/enviro/ef\\_metadata\\_html\\_tri\\_page?p\\_column\\_name=reach\\_code#:~:text=Description%3A%20A%20reach%20code%20is,National%20Hydrography%20Dataset%20\(NHD\)..](https://enviro.epa.gov/enviro/ef_metadata_html_tri_page?p_column_name=reach_code#:~:text=Description%3A%20A%20reach%20code%20is,National%20Hydrography%20Dataset%20(NHD)..)
- USGS (n.d.). *Hydrologic unit codes (HUCs)*. U.S. Department of the Interior. Retrieved November 6, 2024, from <https://nas.er.usgs.gov/hucs.aspx>
- Western States Water Council. (n.d.). *Water data exchange (WADE)*. Retrieved January 2023, from <https://westernstateswater.org/wade/>
- Williams, A. P., Seager, R., Abatzoglou, J. T., Cook, B. I., Smerdon, J. E., & Cook, E. R. (2015). *Contribution of anthropogenic warming to California drought during 2012–2014. Science Advances*, 1(1), e1400082. <https://doi.org/10.1126/sciadv.1400082>
- Wu, SY. Changing characteristics of precipitation for the contiguous United States. *Climatic Change* 132, 677–692 (2015). <https://doi.org/10.1007/s10584-015-1453-8>
- Xie, Y., Gibbs, H. K., & Lark, T. J. (2021). Landsat-based Irrigation Dataset (LANID): 30 m resolution maps of irrigation distribution, frequency, and change for the US, 1997–2017. *Earth System Science Data*, 13(12), 5689–5710. <https://doi.org/10.5194/essd-13-5689-2021>
- Xu, W., Lowe, S. E., & Adams, R. M. (2014). Climate change, water rights, and water supply: The case of irrigated agriculture in Idaho. *Water Resources Research*, 50(12), 9675–9695. <https://doi.org/10.1002/2013wr014696>

## Appendix A – Supporting Tables

**Table 13.** Crop crosswalk for remaining 5 percent of crops.

Crop Group	Crop Name		
Grains and Oilseeds	Tobacco Other Small Grains Speltz Safflower Mustard	Pop or Orn Corn Rye Flaxseed Rape Seed	Triticale Other Crops Buckwheat Camelina
Vegetables	Eggplants Turnips Mint Misc Veggies & Fruits Onions Chickpeas Carrots Garlic	Gourds Cauliflower Sweet Potatoes Watermelons Cucumbers Herbs Asparagus Broccoli	Radishes Celery Pumpkins Cabbage Lettuce Squash Peppers Greens
Fruit and Tree Crops	Caneberries Peaches Pears Prunes Avocados Plums Blueberries	Hops Other Tree Crops Pistachios Olives Pomegranates Strawberries Cranberries	Cherries Citrus Cantaloupes Honeydew Melons Nectarines Apricots
Double Cropping	WinWht/Soybeans Triticale/Corn Lettuce/Cotton Barley/Sorghum WintWht/Cotton Corn/Soybeans	WinWht/Corn Lettuce/Durum Wht Lettuce/Barley WinWht/Sorghum Soybeans/Cotton Barley/Soybeans	Oats/Corn Lettuce/Cantaloupe Durum Wht/Sorghum Barley/Corn Soybeans/Oats
Grassland Crops	Clover/Wildflowers Fallow/Idle Croplands Grassland/Pasture	Sod/Grass Seed Pasture/Grass Vetch	Switchgrass Shrubland