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The Complexities of Irrigation Efficiency: Groundwater Data, Agro-Hydrology, and Water Decision-Making in Central Oregon

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Abstract

Irrigation efficiency projects aim to conserve water for in-stream flow and agricultural use by reducing water losses throughout the system. Piping irrigation canals is a common irrigation efficiency method that results in trade-offs: while it increases efficiency of irrigation water conveyance, it reduces incidental groundwater recharge. This paper focuses on the data and decision-making of canal piping, focusing primarily on understanding the potential impacts of reduced canal leakage on shallow wells. By conducting a spatial analysis of shallow wells in the basin at risk of being impacted by canal piping, and combining this with interviews with water managers in central Oregon's Upper Deschutes Basin, we demonstrate the complex socio-natural dynamics and politics of water conservation decision-making. The research finds that irrigation canal piping is fully supported by water managers in the study area as a means of physically shifting flows of water towards particular valued uses, yet at the same time there is not enough data to understand the potential impacts of canal piping on water users reliant on canal seepage. Given the lack of localized shallow groundwater monitoring data, water managers are reliant upon basin-scale model predictions when defining the trade-offs in canal piping. Broadly, the research demonstrates that well-intended water management decisions can have trade-offs and impacts that are not well understood, pointing to the need for more groundwater monitoring and critical attention to the multiple scales of irrigation efficiency to inform the co-management of surface water and groundwater for the many water users within a basin.

Keywords: Irrigation efficiency; trade-offs; decision-making; groundwater; data

Highlights:

- Irrigation efficiency can impact basins in ways that are not understood.
- Water managers rely on incomplete evidence when making efficiency decisions.
- Irrigation efficiency efforts may negatively impact shallow domestic wells.
- The politics of data gaps must be taken seriously in water management.
- Critical lenses help to understand the complexity of irrigation efficiency.

Introduction

Balancing demand for freshwater with finite supply presents a major water management challenge. Agricultural irrigation is the world's largest user of freshwater, accounting for approximately 70% of global extractions (Grafton et al., 2017). Irrigation efficiency efforts strive to improve the "crop per drop" ratio of water for agriculture (Grafton et al., 2018). With the goal of 'saving' water for purposes such as increased agricultural use, environmental flows, or urban water supply, irrigation efficiency includes methods such as field level modernization (e.g., sprinkler and drip technology) and updated water delivery systems (e.g., piping or lining irrigation canals).

While increasing efficiency sounds straightforward and desirable, the politics and trade-offs involved in decreasing water 'waste' are far from simple (Perry and Steduto, 2017; Lankford, 2012a; Lankford et al., 2020). Scholars have noted a lack of attention to the debated history and motivations for implementing irrigation efficiency (Lankford, 2012b; van Halsema and Vincent, 2012); the numerous hydrologic scales, affected actors, and the distribution of gains and losses which result when changes are made to an irrigation system (Molden et al., 2010); and the variations in specific political, economic, and socio-technical context (Kuper et al., 2017; Lankford et al., 2020). These debates and the complexity of actors and elements involved in irrigation efficiency have likely "hampered fuller research and monitoring" of the subject (Lankford et al., 2020). Given the complexity involved— from geology to law and politics— there is a need for more place-based studies of the localized impacts of irrigation efficiency.

This paper takes a critical perspective on irrigation efficiency, examining a particular example of irrigation efficiency decision-making to explore gains and losses in a local hydrologic system. We ask whether localized impacts can actually be identified given existing groundwater monitoring data. Focusing on those with the power to make water management decisions, we critically examine the values and knowledge systems used by water managers when deciding to implement water efficiency projects that produce trade-offs.

In the Upper Deschutes Basin in central Oregon, the focus of this paper, water managers have been implementing irrigation canal piping projects for over 30 years. The water saved from piping is reallocated mainly to the Deschutes River to restore flows for critical habitat to support endangered species. Yet, the reduction in canal seepage by piping plays a role (albeit small in comparison to other factors like climate variations) in observed and modeled groundwater level declines in the Upper Deschutes Basin (Gannett and Lite, 2013). Local news articles, lawsuits, community websites, and public comments highlight the concerns held by some community members about the unintended consequences of canal piping on water supply wells and ecosystems reliant on the water leaked from canals, which has artificially elevated the shallow groundwater system over the last 100 years.

The case of water conservation through canal piping in the Upper Deschutes Basin demonstrates the complexity of irrigation efficiency. First, we show that irrigation efficiency is not just a technical question, but is also socio-political in nature, with different potential positive and negative impacts on different sets of actors, although the direct impacts are not fully understood. Second, the case highlights the gaps in knowledge around irrigation efficiency decision-making: our analysis shows that decisions are being made by water managers without sufficient data for understanding trade-offs and impacts. This paper contributes to a deeper understanding of the ways in which data and knowledge translate into decision-making by those who hold power. We highlight the gaps in data available to understand the trade-offs, which unevenly impact various human and non-human water users, and note the lack of critical examination of assumptions in efficiency discourse. We make the case that, moving forward into a drier climate, more equitable water management requires acknowledgment of the complexity of making water management decisions when agro-hydrological flows are not fully understood, along with more transparent consideration of trade-offs and those who may be impacted.

Review of Literature on Irrigation Efficiency

Irrigation efficiency has been examined and problematized through several different lenses. We first discuss the history of the idea of irrigation efficiency and how its understanding has developed over time in the fields of hydrological science and engineering. We then discuss critical and political ecological perspectives.

History of irrigation efficiency: from classical definitions onward

Hydrological sciences and the actual practice of irrigation have developed along different trajectories, at different scales, and with different objectives for water accounting, resulting in no set of common definitions in irrigation efficiency (Perry, 2007). The classical definition of efficiency, which is the ratio of the irrigation water consumed by the crop to the total water diverted, was, and still is, used by the engineering field for over 40 years after Israelson (1950) first defined it in the literature. Any water that is not used by the crop is considered to be water loss or waste in the classical definition of irrigation efficiency.

In the 1990s, multiple studies promoted moving away from the classical definition of irrigation efficiency towards better understanding the impacts of return flows and beneficially used 'lost' water in the system (Willardson et al., 1994; Allen et al., 1996, 1997; Willardson and Allen, 1998). To acknowledge the water 'losses' in classical efficiency as only losses on paper, neoclassical irrigation efficiency definitions work to bring attention to the outflows that are beneficially recycled within the basin (Seckler et al., 2003). Researchers have worked to break 'water use' into multiple categories. For example, Perry (2011) defined irrigation efficiency using three categories: changes in storage, consumed fraction, and non-consumed fraction. The multiple definitions address two problems: first, 'efficiency' is value-laden, meaning from the farmer's perspective, water use efficiency is desirable but at the basin scale, the answer is not clear. Second, a simplified view of irrigation efficiency assumes that increased efficiency results in 'saved' water, yet this claim cannot be made without tracing where that water was previously going (Perry, 2011).

Natural and physical scientists have taken up this more-complex picture of irrigation efficiency, demonstrating that while it can be successful at conserving water for an intended goal, the changes to the hydrologic system can ultimately result in the increased consumption of water at the basin scale (Grafton et al., 2018; Pfeiffer and Lin, 2014; Wheeler et al., 2020; Batchelor et al., 2014; Ward and Pulido-Velazquez, 2008). Irrigation efficiency can also result in declines in groundwater levels which were previously recharged by the inefficient use of water (Meredith & Blais, 2019; Arumí et al., 2009). Disagreements surrounding the definitions of 'beneficial use' and 'water loss' at different scales has led to confusion about the intended goals of irrigation efficiency and has even led to some calling for the elimination of "the 'E' word from the literature on irrigation altogether" (Perry, 2007; Seckler et al., 2003, p. 38).

Critical perspectives: Political ecology and hydrosocial theory

Meanwhile, political ecologists and hydrosocial theorists have studied irrigation efficiency through a critical lens to uncover the power relations, knowledge production, and social and physical scales involved in irrigation efficiency decision making (Trottier, 2008; Boelens and Vos, 2012; Lankford et al., 2020; Molden et al., 2010; Birkenholtz, 2008). In some cases, irrigation efficiency can reproduce inequitable water allocations through the discursive act of labeling some water as 'waste' and other water as 'beneficial use' (Cantor, 2017). Critical scholars have noted that 'efficient' and 'beneficial' are subjective terms with power relations and knowledge production embedded in their definitions and use, creating winners and losers within a basin (Trottier, 2008; Boelens and Vos, 2012; Lankford et al., 2020; Molden et al., 2010; Birkenholtz, 2008).

Critical scholarship emphasizes that terminology and definitions used in irrigation efficiency can vary depending on which actors and at what scale within the system are being asked (Perry, 2007; Seckler et al., 2003). Efficiency measures are frequently employed in response to 'scarcity' or 'crisis' narratives. For example, in a political ecology analysis of the term 'water crisis', Trottier (2008) argues that power relations are disguised as "scientific rationality" (p. 212). Social actors decide when there is a water shortage, and the different definitions of 'water crisis' produce "conceptual building blocks that legitimizes some actors, de-legitimizes others, and makes others simply invisible" (Trottier 2008, p. 198). This power structure influences scientists' capacity to ask questions and the ways in which they formulate them, leading to policy recommendations for 'solutions' that might be a setback to others (Trottier, 2008). According to Trottier (2008), "the insistence on efficiency within the dominant discourse on water management prevents us from understanding how water uses and water technologies are embedded within social processes that keep evolving" (p. 206).

Building upon growing critical perspectives and recognition of the need for a more holistic approach, Lankford et al. (2020) introduced a scale-based framework to better understand the paradoxes and trade-offs of irrigation efficiency. This work seeks to address the complexity and subjectivity of the many "motives, measures, effects, and technologies" which impact different groups and locations differently (Lankford et al., 2020, p. 1). Lankford et al. (2020) encourage irrigation efficiency researchers to conduct transdisciplinary work, with critical attention to scales, motives, and values to inform equitable and sustainable water resource decisions. They argue that irrigation efficiency policy should be critically examined because the lack of multi- and cross-scale accountability can imply "significant justice and equity effects" (p. 17). This critical work points to the importance of local, case-study based research to understand specific dynamics, given that irrigation efficiency projects involve a complex mix of physical, technological, and socio-political factors at multiple scales.

Case study: Groundwater in the Upper Deschutes Basin

Groundwater hydrology and water use

The Deschutes basin is located within central Oregon's semi-arid landscape just east of the Cascade mountain range and is home to the Deschutes River, a major tributary of the Columbia (Figure 1). The Deschutes River provides water for a diverse range of needs, including irrigation, drinking water, critical fish and wildlife habitat, cultural and traditional sustenance for Indigenous Peoples including the Confederated Tribes of Warm Springs, generating hydroelectricity, and recreation (DRC, 2008, p. 3). Land use in the Deschutes Basin is predominantly agricultural, forestry, and wildland recreation (Deschutes Basin Board of Controls, 2019). The study area's geology is dominated by volcanic, volcaniclastic, and volcanically derived sedimentary deposits (Gannett et al., 2017).

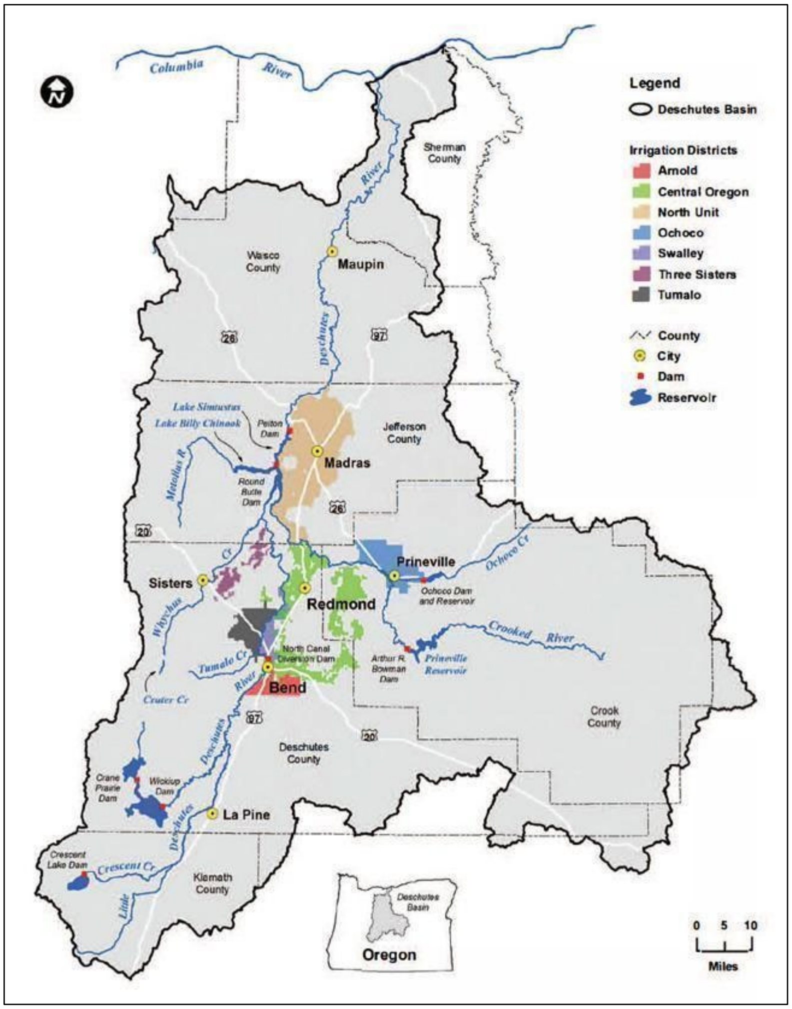


Figure 1: Map of the Deschutes Basin with major rivers, reservoirs, dams, cities, and irrigation districts (from Deschutes Basin Board of Control, 2019).

In the past 30 years, the city of Bend, population 100,421 in 2019, has grown by approximately 490 percent from its population of 20,469 residents in 1990 (U.S. Department of Commerce, 1992). Bend's water supply comes from a combination of surface and groundwater from the Deschutes regional aquifer (City of Bend, 2007). The rest of the population in the study area is more rural, where residents rely on wells for domestic water supply (Gannett and Lite, 2013). Groundwater development is most intense in the Upper Deschutes Basin's population centers, including Bend, Redmond, Sisters, Madras, Prineville, and La Pine (Gannett et al., 2001). Agricultural irrigation is by far the largest consumer of water in the basin, diverting approximately 863.4 million cubic meters (700,000 acre-feet) from the Deschutes River and its tributaries annually (GSI, 2017). Eight irrigation districts distribute the Deschutes River's water for use in agriculture. Approximately 68,392 hectares (169,000 acres) are irrigated in the study area, with most of the water coming from the Deschutes River (Gannett et al., 2017).

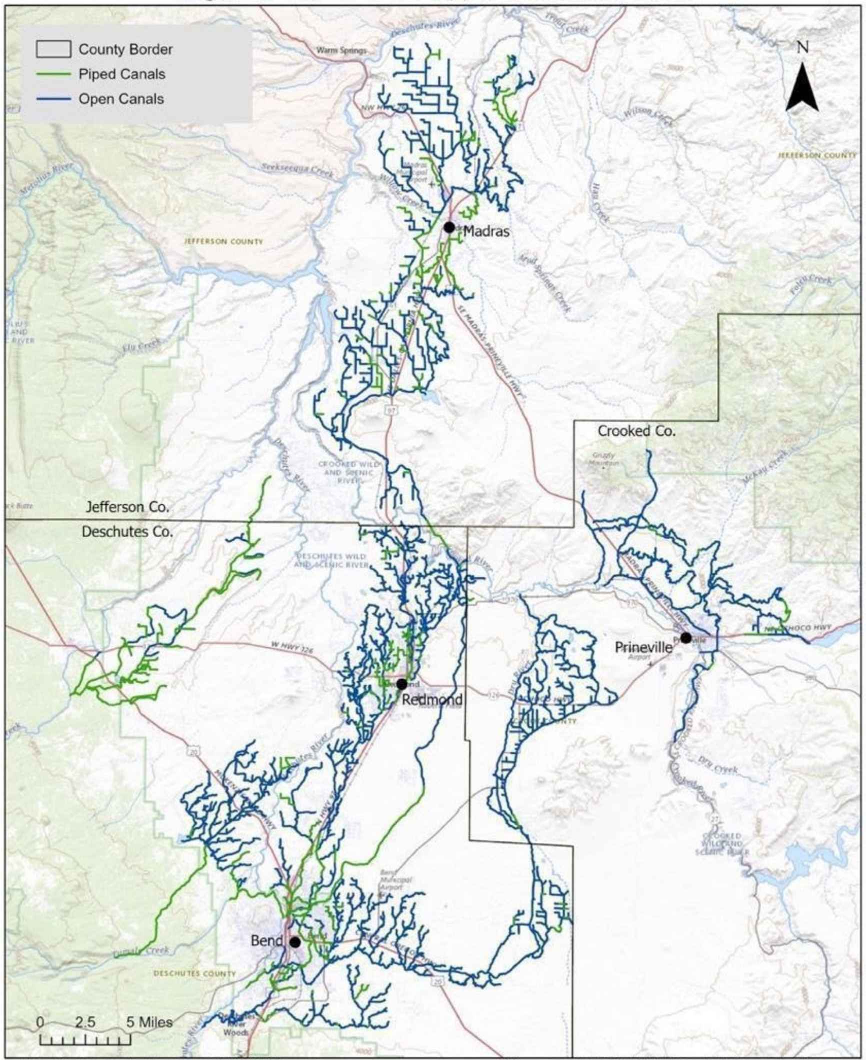
Landowners in the basin have been prohibited by the State of Oregon from appropriating any additional surface water for many years due to over-appropriation of the resource (Gannett et al., 2001), resulting in reliance upon groundwater to meet the needs of the basin's quickly growing population. Groundwater and surface water are tightly interconnected due to the Upper

Deschutes Basin's young, highly permeable volcanic geology. Groundwater recharge to the Deschutes River is the reason for its historical steady flows (O'Connor et al., 2003), which supports a range of summer-time recreational activities on the river. The increase in groundwater demand has led to concerns about the impacts of groundwater withdrawal on surface water.

Today, the combination of less precipitation, increased extraction of groundwater resources, and significant volumes of water diverted from the river for irrigation has put a strain on the interconnected hydrological system (Deschutes Basin Board of Controls, 2019; Gannett and Lite, 2013). The overall altered flow regime in the Upper and Middle Deschutes River has impacted both geomorphology and biological integrity, placing three species (steelhead trout, bull trout, and Oregon spotted frog) on the Endangered Species List under the Endangered Species Act. The diversion of water for irrigation not only disrupts habitats, but also social systems in the basin because the Deschutes River and its tributaries form the basis for most economic and recreational activities in the area (Deschutes Basin Board of Controls, 2019; Vineyard and Cantor, 2024), putting the Basin's hydrological system in the political, economic, and social spotlight in recent years.

Irrigation efficiency efforts

To conserve water for the Deschutes River, old, unlined irrigation canals are piped and buried to more efficiently convey water. Piping began in the mid-1980s and is an on-going project in the central Upper Deschutes Basin (Figure 2). This conservation effort is driven by the incidental take permits issued by the US Fish and Wildlife Service and the National Marine Fisheries Service under section 10(a)(1)(B) of the Endangered Species Act (Deschutes Basin Board of Controls, 2019). The irrigation districts in the basin, as well as the city of Prineville, were issued incidental take permits to allow the continued use of the surface water from the Deschutes River and its tributaries without the threat of prosecution for harming the endangered species. The Deschutes Basin Habitat Conservation Plan outlines conservation options available to the districts, including reducing water deliveries, creating incentives for landowners to reduce demand for water, and lining/piping of irrigation canals (Deschutes Basin Board of Controls, 2019).



Map By: Becky Anderson on 1/21/2022

Sources: OWRD, USGS, Marshall Gannett, Oregon Spatial Data Library

Figure 2: Irrigation canals (piped and open) in the Upper Deschutes Basin (as of 2018).

Irrigation canal piping has been chosen as a means of reducing water usage because it is estimated that nearly half the irrigation water never reaches its destination: approximately 46 percent of water moving through the 1,159 kilometers (720 miles) of open-earth main canals is lost to leakage. In 2013, seepage was estimated to be reduced by 19 percent due to canal piping conservation efforts (Gannett and Lite, 2017). Theoretically, piping canals provides a way for irrigation districts to return water to the Deschutes River without reducing rates of water consumption, although quantifying the impacts is challenging. As of 2018, 337 kilometers (209.43 miles) of the irrigation canals in the study area had been converted to pipe, leaving 1,388 kilometers (862.60) miles of canals as open earth (note: these values include main canals, laterals, and private ditches). The Upper Deschutes River Basin (2019) study found that the total opportunity for water conservation by piping district owned canals within the study area could be 246 million cubic meters/year (200,000 acre-feet/year), which would cost an estimated $2.4 billion.

Yet, canal seepage is thought to be a “significant component of the groundwater budget” in the study area (Sceva, 1968; Gannet et al., 2001; Gannett and Lite, 2013, p. 4). Canal seepage provided an estimated 467 million cubic feet/year (379,000 acre-ft/year) of recharge to the study area in the mid-1990s (Gannett and Lite, 2017; Gannett et al., 2004). The canal leakage is believed to support shallow local, and possibly perched, aquifers as well as discharge to spring-fed streams in the lower elevation areas, providing cool water to the Deschutes, Crooked, and Metolius Rivers (Gannett et al., 2004; Gannett et al., 2017). A USGS study attributed 10 percent of groundwater decline between 1997 and 2008 to irrigation canal piping efforts in the basin. This has sparked public concerns about potential negative impacts of piping canals on humans and ecosystems reliant on shallow groundwater. Many wells throughout the region in close proximity to canals likely experience fluctuations due to irrigation canal leakage, with an average of 0.3 to 3 meters (1 to 10 feet) of change in the water table seasonally (Gannett et al., 2001). In an extreme case, annual fluctuations likely caused by irrigation canal leakage of nearly 30 meters (100 feet) have been documented in the study area (Gannett et al., 2001).

Irrigation canal piping has not always received cooperation and agreement of the local community. Cantor and Ross (2021) studied the "pipeline politics" of irrigation canal efficiency updates in central Oregon and found that Bend residents have made canal piping a challenge for irrigation districts. Controversy over canal piping has generated multiple lawsuits in the recent past, with residents going so far as to lie down in front of excavation equipment (Ramsayer, 2011) and drill holes in the pipes (Harvel, 2021) to stop or alter irrigation efficiency projects. Concerns expressed by the public include worries about private wells going dry, negative impacts to wildlife and vegetation, negative consequences of decreased cold-water recharge to streams, aesthetics, and costs of piping over other alternatives (FCA, 2018).

Complexity of an agro-social-hydrologic system

There are many changing stocks and water flows in the Upper Deschutes Basin, creating a complex interconnected system influenced by hydrologic, climatic, geologic, agricultural, and social elements. As mentioned above, there are multiple water users in the basin. Changes in the way water is being used and conveyed in the system results in shifts in the "recoverable" and "non-recoverable" flows. The seepage from open irrigation represents a recoverable flow, yet when canal piping occurs, the resulting water savings from the efficiency gain are not isolated. Figure 3 depicts some of the hydrological interactions in the basin. When an irrigation canal is piped, the groundwater seepage is reduced, as well as the evapotranspiration, impacting all elements in the system. It is important to note that the shifts in the hydrologic system are difficult to measure and quantify. Moreover, additional shifts (for example, climate change, shifts in domestic use, or changes in field-level agricultural irrigation practices) are likely occurring simultaneously, making it even harder to measure the exact impact of a single change like canal piping.

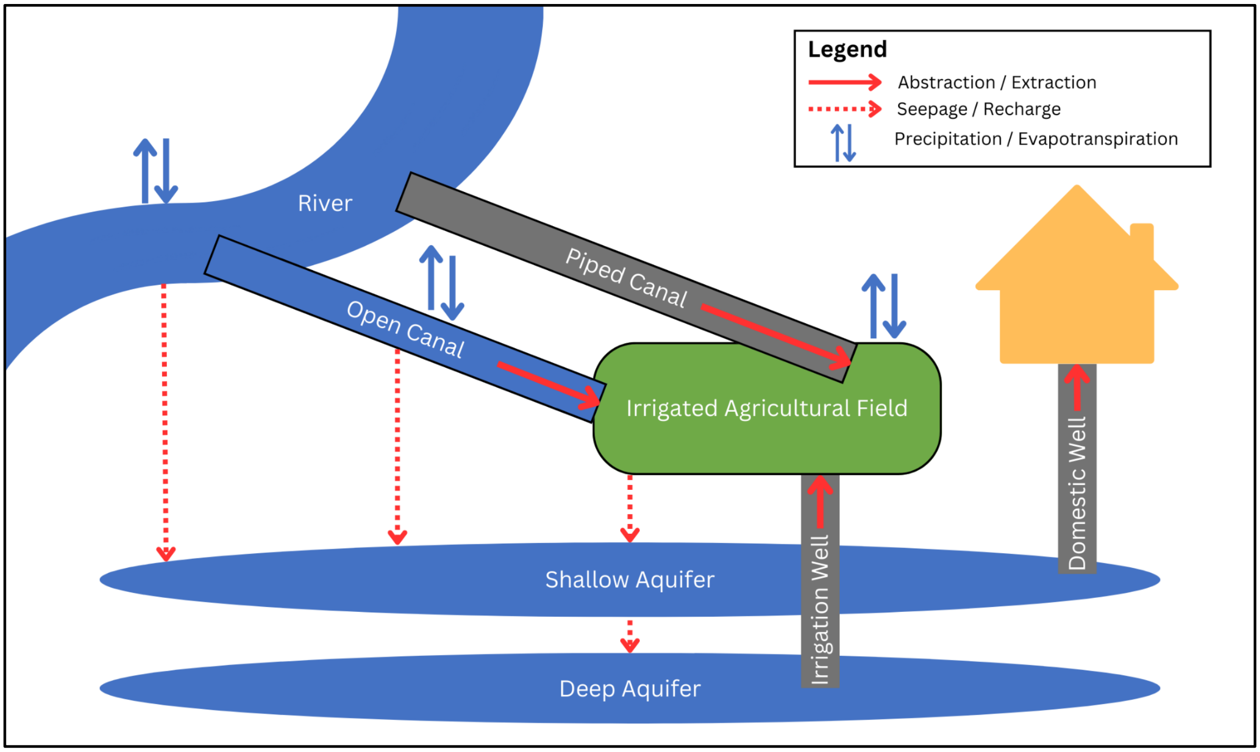


Figure 3: Simplified agro-hydrology water budget schematic (not to scale).

Methods

Given the local controversies over whether and how canal piping impacts shallow groundwater, this research uses a mix of spatial and qualitative methods to examine whether these impacts can be understood within the complex system given the current level of publicly available groundwater data in the Upper Deschutes Basin, and how water managers make decisions with the level of information available.

Spatial Analysis Methods

An analysis of shallow groundwater wells in the study area was conducted to understand potential trade-offs and consequences of irrigation canal piping. Shallow wells in the study are defined as wells with a completed depth of 91.4 meters (300 feet) deep or less following Gannett et al.'s (2001) separation of shallow wells in the area as 30.5 to 91.4 meters (100 to 300 feet) deep. To determine the vulnerability of wells, we analyzed the spatial distribution of shallow groundwater wells in the Upper Deschutes Basin near irrigation canals. We also analyzed the years of monitoring data available from shallow wells in the study area to explore whether existing data is adequate to understand well vulnerability.

For the spatial analysis of shallow wells, we used well data from the Oregon Water Resources Department (OWRD) to map shallow wells in the basin within each section (square mile). The well data was obtained from Marshall Gannett (downloaded from OWRD's Groundwater Information System) in August of 2021 (Gannett, personal communication, August 8, 2021) along with a township range section shapefile, which became the unit of analysis. Shallow wells were considered wells that were 91.4 meters (300 feet) or less and greater than 0 meters to exclude wells with no data. To examine shallow well monitoring data availability, water level data from OWRD's Groundwater Information System was used to map shallow wells with ‘adequate’ monitoring data in the Upper Deschutes Basin, following methodology from Albano et al. (2020) to help define criteria. Shallow wells with a minimum of three water level measurements from the same month each year (preferably March), and the data spanning a minimum of 5 years within the range of 1985 to present (2022) were included in the analysis. Five years of monitoring data was set as the minimum for the purpose of finding more than short-term trends in shallow groundwater. The wells were sorted to a minimum of 5 years, 10 years and 20 years of water level measurement data to display the spatial distribution of the temporal range of shallow water level data availability in the study area. The data range was set to 1985 to 2022 to include water level measurements from just before the 1990s impacts to groundwater by canal piping were beginning to be noticed (Gannett and Lite, 2013) to the current conditions in the basin after significant piping has occurred. For a full description of spatial analysis methods, see Appendix A.

Qualitative Methods

To better understand the politics and values involved in irrigation efficiency efforts and knowledge production, the first author conducted 16 semi-structured interviews with a total of 18 water managers in the Upper Deschutes Basin area. Participants were identified through an initial search of policy documentation, supplemented by snowball sampling. Participants reflected a range of perspectives and institutions in the basin, including representatives from irrigation districts, state government agencies, conservation groups, water supply utilities, and research institutions (Table 1). The names of participants are not used in this paper to protect privacy.

Table 1: Interview Participants by Water Manager Type

Water Manager Type	Number of Interview Participants
Irrigation District & Water Supply Representatives	3
Government Officials (Federal & State)	7
Nonprofit/NGO Representatives	7
University Researchers	1

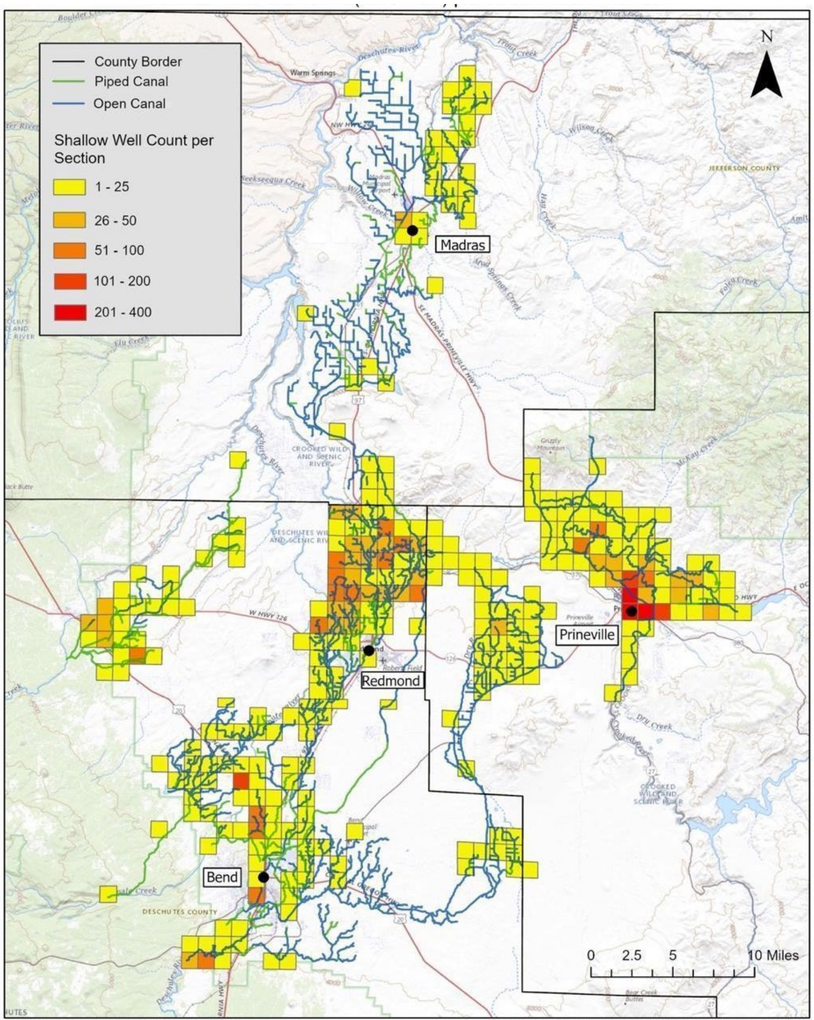
Interviews took place on Zoom between August and November 2021, lasting between 30 minutes and two hours, and were transcribed for analysis. Interviews consisted of open-ended questions about the participants’ experience and work related to water in the basin, what they saw as the most important water issues, their definition of efficient water use, and their perspectives on irrigation canal piping. Transcripts were coded using a grounded, inductive approach (Charmaz, 2006) in combination with ‘flexible’ qualitative data analysis methods (Deterding et al. 2018). Through the coding process, themes were identified to understand water managers’ definitions, decision-making processes, and values around efficiency in relation to irrigation canal piping.

Results

Spatial analysis of groundwater and impacts on shallow wells

Given that irrigation canal piping has the potential to impact local groundwater recharge, we conducted a spatial analysis of shallow groundwater wells and monitoring locations in the study area. Overall, this analysis showed that: 1. there are many shallow wells near irrigation canals; 2. many of these shallow wells could be vulnerable to groundwater declines; 3. groundwater monitoring is uneven and most of the monitoring wells with long-term data availability are *not* located in the areas with the highest concentrations of vulnerable shallow wells; and 4. the data and models that do exist show declining groundwater levels associated with canal piping. Overall, the lack of monitoring makes it difficult to know the extent to which canal piping is impacting or will impact shallow wells. This represents an important knowledge gap and reflects the inherent complexity of comprehensively understanding an agro-hydrologic system like the Upper Deschutes Basin.

First, we examined the relationship between shallow wells and irrigation canals. Within the three counties examined, there are 1,351 sections (2.6 square kilometers; 1 square mile) with at least one shallow well that is ≤ 91.4 meters (300 feet) deep. Specifically, 350 sections intersecting the irrigation canals contain at least one shallow well, with 149 sections intersecting piped irrigation canals and 315 sections intersecting open irrigation canals. Figure 4 shows the number of shallow wells per section intersecting the irrigation canals in the study area, but only includes shallow wells with static water level data to be compared with vulnerability maps. Sections intersecting irrigation canals around Prineville, north of Redmond, and to a lesser extent around Bend, have the highest count of shallow wells.

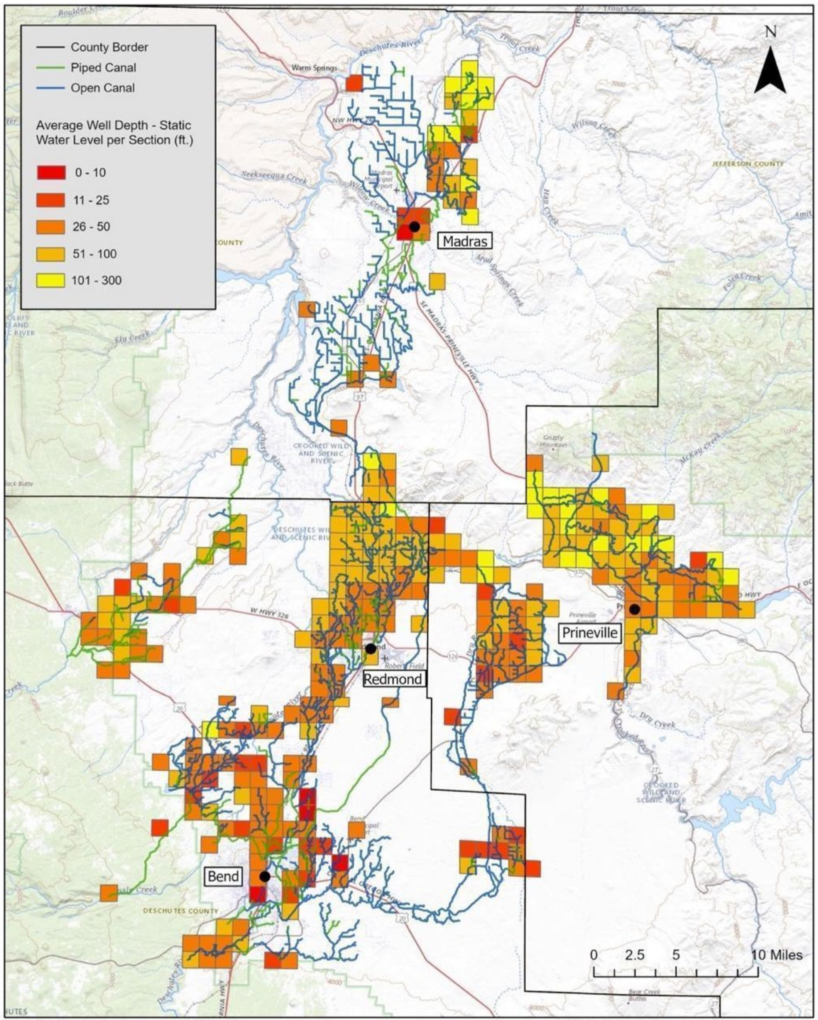


Map By: Becky Anderson on 1/7/2022

Sources: OWRD, USGS, Marshall Gannett, Oregon Spatial Data Library

Figure 4: count of shallow wells per section intersecting irrigation canals.

Second, we examined the vulnerability of these shallow wells. Many sections in the study area contain shallow wells that are vulnerable to groundwater level declines, potentially putting humans at risk of losing access to drinking water. The vulnerability of the shallow wells in the study area, defined here as the difference between the completed well depth and the static water level (also known as water table), is presented in Figure 5. Multiple sections to the east and north of Bend appear to have the highest average vulnerability between 0-3.1 meters (0-10 feet) or 3.6-7.6 meters (11-25 feet).

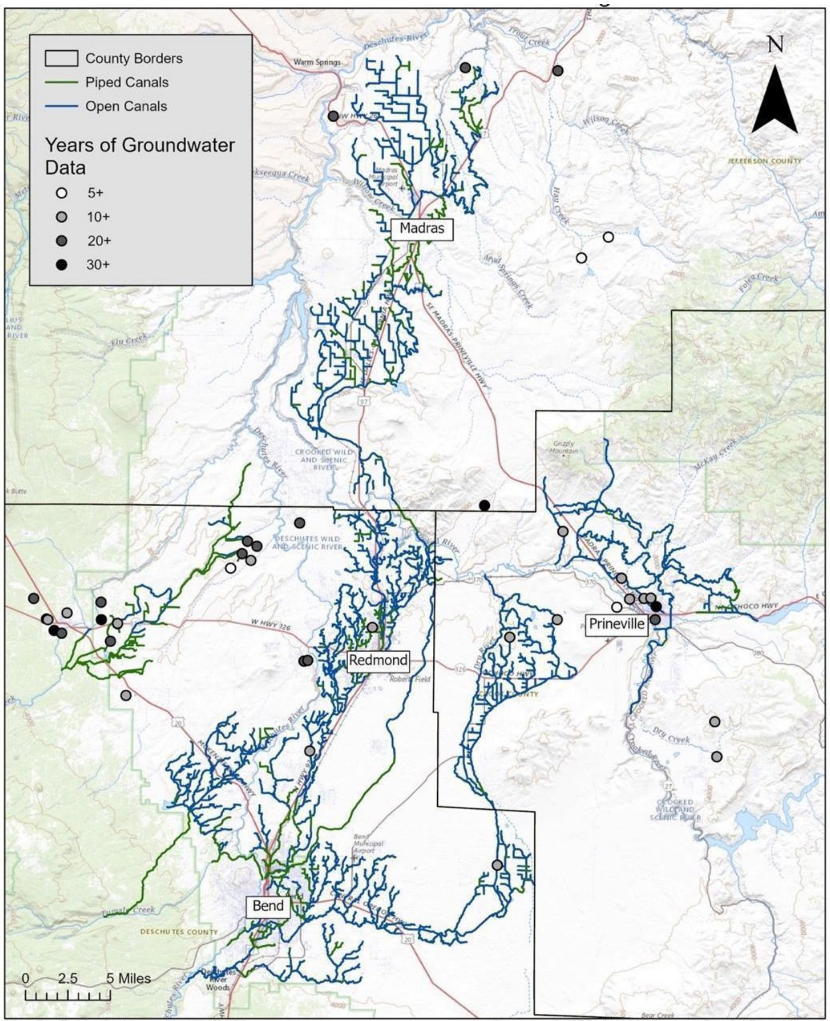


Map By: Becky Anderson on 1/7/2022

Sources: OWRD, USGS, Marshall Gannett, Oregon Spatial Data Library

Figure 5: Average shallow well vulnerability per section intersecting irrigation canals.

Third, we studied the availability of groundwater monitoring data. To better understand the level of shallow groundwater data from OWRD's database, Figure 6 presents the locations of shallow wells based on the extent of adequate data available, cropped to the study area in proximity to irrigation canals. There are a total of 76 shallow wells in Deschutes, Jefferson, and Crooked counties which meet the data requirements. Within 1.61 kilometers (1 mile) of the irrigation canals, there are 22 shallow wells which meet the data requirements. Table 2 presents the number of wells with groundwater monitoring data in the broader study area and within 1.61 kilometers (1 mile) of irrigation canals. The spatial distribution of shallow wells which meet the minimum requirement of data is not even throughout the study area, which means it is difficult to know local shallow groundwater patterns related to canal piping.



Map By: Becky Anderson on 1/14/2022

Sources: OWRD, USGS, Oregon Spatial Data Library

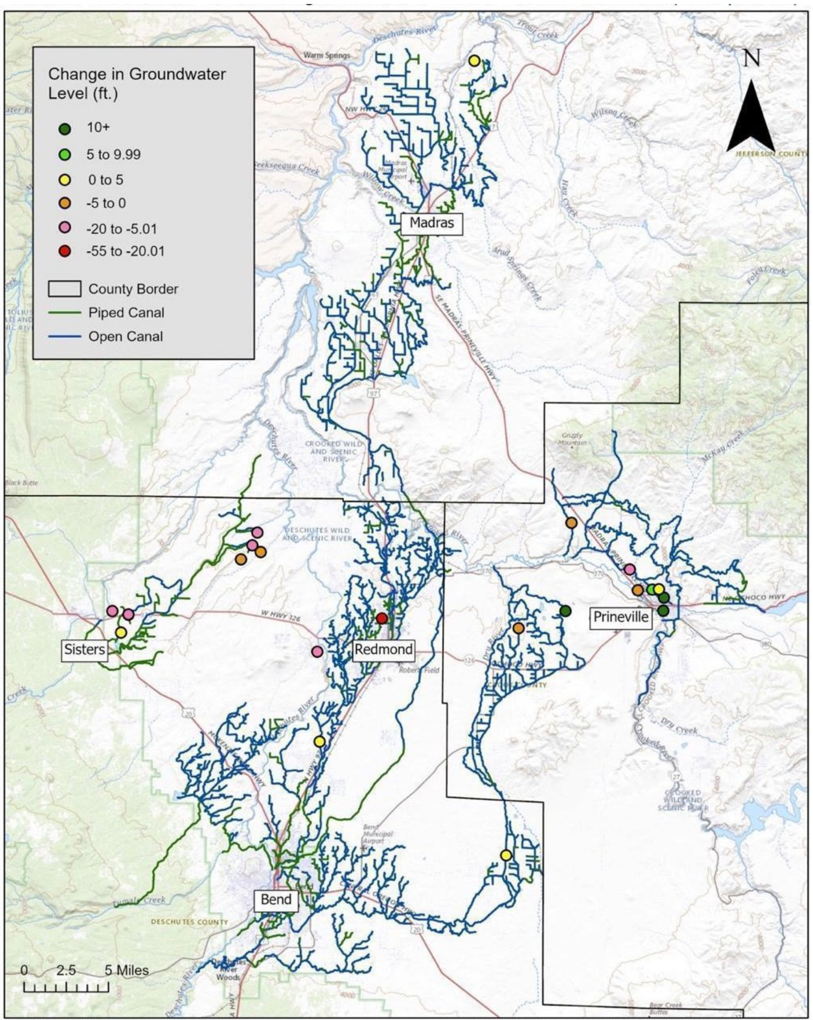
Figure 6: Location of shallow wells with monitoring data.

Table 2: Number of shallow wells (≤91.4 meters [300 feet]) with at least 5 years of monitoring data

Area	**Total**	**Wells with 5+ Years of Data**	**Wells with 10+ Years of Data**	**Wells with 20+ Years of Data**
Three Counties*	76	22	27	27
Within 1.61 km (1 mile) of Irrigation Canals	22	1	12	9

*Deschutes, Jefferson, and Crooked

Finally, we examined documented changes in groundwater levels. Nearby irrigation canals, it seems that the overall trend in groundwater is declining, yet it is difficult to make conclusions with limited data. Figure 7 presents changes in groundwater levels from the first to last measurement at each of the 22 well locations which met the data requirements within 1.61 kilometers (1 mile) of the irrigation canals in the study area. Wells represented as dark green, green, and yellow experienced an increase in groundwater levels over varying years within the range of 1985 to 2022. Shallow wells represented as orange, pink, and red experienced a decline in groundwater levels.



Map By: Becky Anderson on 3/21/2022

Sources: OWRD, USGS, Oregon Spatial Data Library

Figure 7: Shallow groundwater level changes between first and last measurements (between 1985 to 2022).

Previously-run groundwater models in the study area predict declines in shallow groundwater levels due to canal piping, although quantified changes in the groundwater and surface water system are not well known. In a USGS analysis of groundwater level changes in the Upper Deschutes Basin from 1997-2008, a model was used to simulate groundwater declines resulting from decreased groundwater recharge due to canal piping (referred to in the study as "lining") (Gannett and Lite, 2013). This study only included canal piping up to 2008, which is a limitation considering the irrigation canal dataset used in the figures above was updated in 2018 after significantly more canals had been piped. Two models were run in the study, examining shallower and deeper aquifers, and both simulated declines in groundwater levels, with greater declines closer to canal segments near Bend, concluding that 10 percent of the groundwater levels declines in the basin can be attributed to canal piping. Modeling is helpful to understand predicted changes in a hydrologic system, yet again, the changes in groundwater levels due to canal piping is complex and not an isolated system, making it difficult to understand the tangible, real impacts of irrigation piping.

To summarize, based on our spatial analysis and the previously run groundwater models, we note a lack of data around shallow groundwater wells in the study area, especially near the irrigation canals and in the areas predicted to experience the most intense effects of irrigation efficiency. This aligns with Lankford et al. 's (2020) claim that irrigation systems are often empirically data-short. Small-scale changes in the shallow aquifer system likely go unnoticed by the current monitoring system in place, especially around Bend and Madras where significant piping has occurred, groundwater declines are predicted to be greatest, and few monitoring wells exist.

Water manager perspectives on data gaps and irrigation efficiency

The physical effects of the small-scale, localized shallow groundwater changes in the basin have already been felt by residents in the Upper Deschutes Basin (Collins, 2018) and have the potential of impacting a significant number of shallow wells, as described above. Yet it is not currently possible to fully understand the impacts and trade-offs caused by canal piping. Here we discuss perspectives of water managers, who generally support canal piping despite the lack of data for understanding impacts.

Throughout the interviews, many water managers referred to the results of the two models in the USGS study by Gannett and Lite (2013) when describing their support for irrigation canal piping. Some water managers used the USGS models when describing their support for canal piping because the impact on the aquifer will not be of a "sizable amount." The potential limitations of the groundwater model were not discussed in depth by water managers, despite the reality that models will never fully represent an environmental system (Budds, 2009; Beck et al., 1993). The reliance on basin-scale hydrologic models to inform water management decisions deserves critical attention because relying on this type of modeled scientific data can overlook local-scale material realities, as well as political and economic factors (Budds, 2009; Lave, Biermann, and Lane, 2018).

Water managers in the Deschutes Basin often expressed the difficulty associated with understanding the complexity of groundwater behavior in the study area. The unique nature of the Deschutes Basin's highly permeable and fractured volcanic geology, and the resulting interconnection between surface water and groundwater, came up often in the interviews. Water managers noted the daunting task of trying to prove trade-offs caused by elimination of recharge from canals. This finding echoes previous critical scholarship on groundwater: for example, Simons et al. (2015) describe the difficulty in discerning the pathway of recoverable and non-recoverable flows when water moves from a canal to an aquifer, and Budds (2009) describes the challenge of measuring, managing, and assessing invisible groundwater. In the Upper Deschutes Basin, the uncertainty and difficulty of proving where the 'wasted' water goes shapes how water managers view canal piping, echoing Lankford et al.'s (2020) observation that the complexity of understanding groundwater can influence views of efficiency losses, wastes, and savings.

This challenge played a role in how respondents perceived the potential trade-offs of efficient water management. The visual cues and ease of measurement of surface water are not the case with groundwater, which influences water managers' support for canal piping in the Deschutes Basin. For example, an irrigation district representative discussed the loss of leaked water from canals:

> We don't know what percentage actually makes it to the river. So, if 50% of your canal water leaks, what percentage actually gets to the river? We have no idea. But you do

> know [that] if you take all that water from down there and you move it way back up into the system, you know that water is going to be in the natural system.

Due to the lack of assurance that leaked water from the canals will return to the Deschutes River, which they referred to above as the "natural system," the irrigation district representative was wary of considering the leaked water inherently beneficial to the hydrologic system. Later in the interview, they went on to debate at what point leaked water from a canal transforms from water "owned" by the district to water in an aquifer. They suggested that a shallow well intercepting water from leaky canals could even be considered "stealing" from the district, highlighting the complexity associated with groundwater.

Water managers also expressed views on how public concerns about reduced groundwater recharge should be managed. When asked about these concerns, a second irrigation district representative responded,

> I think [public concern about irrigation canal piping] is an overblown concern by the uneducated […] I think if the State stepped up on [groundwater monitoring], and was able to start educating people, some of those concerns will go away.

This irrigation district representative highlighted a lack of public investment in groundwater monitoring, a concern frequently raised by water managers in the basin. They also expressed that monitoring would aid in proving their assumption that irrigation canal piping is not a serious threat to shallow groundwater wells. Monitoring is a necessary piece of the puzzle to most water managers in this study, yet there is not a single clear-cut view on how much is enough. In another interview, a groundwater scientist viewed the current monitoring in place as adequate for the "scale at which we do basin management," while others expressed the necessity of more monitoring for understanding the smaller-scale, localized effects of canal piping on groundwater levels. For example, a hydrologist from a conservation group viewed the concerns about domestic shallow wells as a question that necessitated more study:

> We need to know how big of a problem it is, we need to know where [domestic wells] are, what their distribution is, and how dependent upon canal leakage the domestic wells are. And in cases where we find out that there are clusters of wells or even individual wells that are dependent upon that canal leakage […] there has to be a solution incorporated, in my opinion, into the permitting procedure because that is an impact.

This perspective emphasized that measures to address these trade-offs should be included within the piping projects themselves. A research hydrologist echoed the need for mitigating efforts because "there are winners and losers in the water management game," illuminating the potential burden placed on property owners who could face the reality of deepening their wells due to canal piping—a process that, in their words, "makes buying a car look easy."

Despite different views on how to prepare, or not prepare, for the prospect of dry wells, most water managers in the basin included in this study agreed that canal piping should continue as a conservation effort to restore the heavily dewatered Deschutes River despite the uncertainties.

Discussion

The use of incomplete groundwater monitoring at specific scales of interest to validate an existing belief about the hydrological system can be power-laden and political (Foucault, 1980; Boelens and Vos, 2012), and highlights the "political-strategic nature of truth production" described by Foucault (1980). Boelens and Vos (2012) describe conflict over truth in the field of water control, noting that truth claims are "used politically, but also work unconsciously" (p. 18). In the Upper Deschutes Basin, the lack of shallow groundwater monitoring and reliance on basin-scale models does not appear to be an entirely neutral act, yet it is also not something water managers are actively or consciously doing, either. The varying levels of attention and monitoring of irrigation water use at different physical scales highlights and elevates specific policy questions while hiding others (Lopez-Gunn et al., 2012; Lankford et al., 2020). Given the scarcity of data, hydrologic modeling of groundwater can be used by government entities to make water management decisions in accordance with their own interests, resulting in uneven use patterns and impacts (Budds, 2009).

It is important to also acknowledge how the physical characteristics of groundwater as invisible and thus 'mysterious' plays a critical role in determining how water managers approach and analyze, or fail to analyze, the potential trade-offs of irrigation efficiency. This highlights how biophysical factors (e.g., the interconnectedness of surface and groundwater in the volcanic landscape; the invisibility of underground flows and seepage) shape water manager's understanding and response to water efficiency challenges. The Upper Deschutes Basin thus provides a telling example of critical physical geography, as the hydrologic landscape and the knowledge politics of groundwater monitoring and modeling co-constitute each other (Lave, Biermann, and Lane, 2018), resulting in a complex socio-environmental landscape at risk of overlooking localized impact on shallow wells.

In addition to the issues of data and knowledge discussed in this paper, discourses and definitions of 'efficiency' shape water managers' decisions and deserve further explanation through additional research. Different definitions and understandings of efficiency, including ideas of what constitutes 'waste,' 'artificial' and 'natural' water flows, can shape water managers' priorities and decisions. For example, some water managers view canal leakage at the basin scale as a waste of water that represents an artificial form of recharge. Water managers' implicit understandings of water as wasted or artificial can shape their decision making in ways that are not always made explicit or recognized and can ultimately result in making water conservation decisions that impact water users in potentially inequitable ways. A useful lens to study the complexity of saving and reallocating water by changing irrigation efficiency is the paracommons framework, which looks at the liminality of water in a shifting hydrologic system and the false expectations that occur when one attempts to definitively trace the before and after conditions (Lankford and Scott, 2023; Lankford, 2013). The debates around the impacts of 'saving' water through irrigation efficiency are exacerbated by the difficulty in quantifying hydrologic changes. This is a theme that requires further consideration through detailed case-study research.

It is essential to recognize the complexity of co-managing surface water and groundwater in a basin and the need for interdisciplinary approaches to address these challenges. This study contributes to existing literature on irrigation efficiency by answering Lankford et al.'s (2020) call for more localized and detailed study of irrigation systems and efficiency efforts, particularly canal piping, which "enable a deeper and more respectful understanding and scrutiny" of the meanings of irrigation efficiency. As mentioned in this paper, conserving water through irrigation canal piping has many positive benefits, including increasing in-stream flow, yet a lack of data and misconceptions around the agro-hydrologic system hinders water managers' ability to understand the potential trade-offs that result irrigation efficiency efforts.

Conclusion

In the Upper Deschutes Basin, water managers do not have enough information at a localized scale to know how shallow wells are impacted by canal piping, due to the difficulty in conceptualizing, quantifying, and mapping agro-hydrologic flows. This lack of data and understanding represents a potential "pitfall", or hidden risk, according to Lankford et al. (2020), because water managers are making decisions without fully understanding the impacts they might have on humans and ecosystems in the basin. The case study of the Upper Deschutes Basin echoes other critical irrigation studies (van der Kooij et al., 2017) in demonstrating the challenges of implementing and documenting efficiency measures in a complex and uncertain hydrologic system.

We conclude with a call for (a) more groundwater monitoring in combination with recognition that measuring hydrologic flows is inherently challenging, (b) increased public engagement and education, and (c) more critical examination of the implicit assumptions around efficiency discourse, including the ways in which data and models are used in water resource decision making.

First, more monitoring and data collection of shallow groundwater could help in understanding the impacts of irrigation efficiency on wells, especially those in localized alluvial aquifers that are the least understood by water managers. Data collection efforts should respond to social context by paying attention to areas that are most vulnerable to canal piping efforts. The spatial results of this study can serve as a guide to these efforts. Current and future canal piping efforts should be paired with increased groundwater monitoring to record the impacts of canal piping efforts on localized groundwater levels. Additional research is needed to fully assess how increased groundwater monitoring would prove to be beneficial (i.e., cost-benefit analysis of various data collection schemes), and it is important to acknowledge both the cost of installing monitoring wells and the delay in the ability to address public concerns in a timely manner. For these reasons, increased groundwater monitoring alone will not resolve the water management challenges in the Upper Deschutes Basin. In addition, efforts to increase groundwater monitoring must be paired with the acknowledgement that precisely quantifying changes in a hydrologic system is not always possible, meaning irrigation efficiency decision making must operate in a space of uncertainty.

Second, along with additional groundwater monitoring, we recommend increased education and engagement with the public to hear and respond to concerns and to offer transparency about water management decision-making. Extending this research by interviewing the broader community about their perspectives would complement this study. We agree with Lite et al. (2022) that federal and state officials should prioritize helping residents with shallow domestic wells. This could look like state or federal programs to financially compensate impacted residents who need to deepen their drinking water wells due to reduced groundwater levels, from a suite of causes including but not limited to, piping irrigation canals. Engaging with the public in a meaningful way through community meetings, focus groups, surveys, and other forms of public outreach will inform water managers on potential actions to address the unintended consequences. This could help facilitate collaboration between those with the power to make decisions in water management and those that are most impacted. As a part of this engagement, sharing the positive impacts of irrigation canal piping on the Upper Deschutes River and endangered species with the public could help demystify some of the concerns.

Finally, we encourage critical reflection from both water managers and scholars. It is important to keep in mind the complexity and multiple scales of irrigation efficiency. The goal of fully understanding such a complex system may be impossible, yet the politics of data gaps must be taken seriously. Water, especially the interconnection of surface water and groundwater, is bound up in overlapping systems and scales with different users and needs. Conserving water through efficiency updates has many benefits, especially in the face of climate change and drought, but the socio-environmental trade-offs must be sufficiently understood to make informed and equitable decisions. We encourage critical consideration of how ideas of 'efficiency' are conceptualized and leveraged, and who is impacted in what ways by these ideas—a point which has broad relevance beyond the water management sector.

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