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Efficiency in the Upper Deschutes Basin: Understanding the Hydrosocial Implications of Irrigation Canal Piping

Rebecca Anderson
Portland State University

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by

Rebecca Anderson

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Thesis Committee:
Alida Cantor, Chair
Martin Lafrenz
Geoffrey Duh

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Abstract

In response to water scarcity, irrigation efficiency projects aim to conserve water for in-stream flow and agricultural use. Piping irrigation canals is a common irrigation efficiency method which reduces the loss of incidental recharge, resulting in trade-offs within a hydrosocial system. Few studies have focused on the consequences of canal piping and none have integrated a critical analysis of the social factors involved in deciding what constitutes 'efficient' water use. This study seeks to fill this gap by combining natural and social science to give attention to the scales and perspectives involved in irrigation efficiency canal piping and the material impacts of 'efficient' water use in central Oregon's Upper Deschutes Basin. From a political ecology lens, I analyze interviews with water managers to uncover the knowledge, values, and motives embedded in the implementation of irrigation efficiency to determine what factors characterize the use of 'efficiency' in water management. I integrate these factors with a spatial analysis of common public concerns surrounding irrigation efficiency in the basin, including shallow well failure caused by the elimination of 'wasteful' leakage. I combine GIS techniques with U.S. Geological Survey groundwater models to determine the extent of vulnerable shallow wells in proximity to irrigation canal piping. Irrigation canal piping is fully supported by water managers in the Upper Deschutes Basin as a means of physically shifting the flow of water towards uses that are most valued, including in-stream flow and providing water to commercial agriculture. The discourses and social construction of water as 'natural' and 'artificial' encourage the support of canal piping, yet at the same time they overlook the water users reliant on canal seepage. Water managers rely on basin-scale model predictions when defining the potential trade-offs in canal piping despite there being a serious lack of shallow groundwater monitoring data. Where data exists near piped canals, it appears that shallow groundwater is declining but it is difficult to know the extent of vulnerable water users at this time. By integrating the technical and social results of this study, I demonstrate that critical physical geography and a hydrosocial lens can contribute to a deeper, more nuanced understanding of the benefits and trade-offs of co-managing surface water and groundwater to achieve resiliency in a quickly growing, socially heterogeneous basin.

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Introduction

Finding management strategies to balance a growing demand for freshwater with finite supply is one of the greatest policy dilemmas. Irrigation is the largest user of freshwater, accounting for approximately 70% of global extractions (Grafton et al., 2017). A common method to decrease water scarcity is to use water more efficiently. With the goal of 'saving' water for continued agricultural use or for other sectors (e.g. environmental flows and urban water supply) irrigation efficiency is a promoted method to improve the "crop per drop" ratio (Grafton et al., 2018). Irrigation efficiency methods include 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 like a straight forward solution, the politics involved in decreasing water 'waste' are far from simple (Perry and Steduto, 2017; Lankford, 2012a; Lankford et al., 2020). Irrigation increasingly overlaps with diverse issues and interests which brings in actors with differing views and strong beliefs around irrigation efficiency, despite a lack of attention to 1) the debated history of the subject (Lankford, 2012b; van Halsema and Vincent, 2012), 2) the numerous hydrologic scales, perspectives, and the gains and losses which result when efficiency changes are made to an irrigation system (Molden et al., 2010), and 3) the importance of specific political, economic, and socio-technical context (Kuper et al., 2017; Lankford et al., 2020).

Natural scientists have studied the material impacts of irrigation efficiency to show 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) and declines in groundwater levels which were previously recharged by the inefficient use of water (Meredith & Blais, 2018; Arumí et al., 2009). Terminology and definitions used in irrigation efficiency can vary depending on which actors and at what scale within the system are being asked, resulting in confusion about the intended goals of the water conservation projects (Perry, 2007; Seckler et al., 2003).

Political ecologists and hydrosocial theorists have studied irrigation efficiency through a critical lens to uncover the power relations, knowledge production, and multiple scales, both social and physical, 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). Lankford et al. (2020) introduced a scale-based framework to better understand the paradoxes and trade-offs of irrigation efficiency and address the complexity and subjectivity of the multitude "motives, measures, effects, and technologies" which impact different groups and locations differently (Lankford et al., 2020, p. 1).

In the Upper Deschutes Basin in central Oregon, irrigation canal piping has been a water conservation project for over 30 years. The water saved from piping is reallocated mainly to the Deschutes River to restore flows for critical habitat, which includes three endangered species. A small portion of the conserved water goes to the irrigation districts for more flexibility and water security to support the agricultural sector in the basin. The reduction in canal seepage by piping plays a role, albeit small in comparison to other factors like climate variations, in the groundwater level declines in the Upper Deschutes Basin, as modeled by the U.S. Geological Survey (USGS) (Gannett and Lite, 2013). Local news articles, lawsuits, public created websites, and public comment sections on canal piping project reports highlight the concerns held by some of the public about the unintended consequences of canal piping on water supply wells and ecosystems reliant on the water leaked from canals, which have artificially elevated the shallow groundwater system over the last 100 years.

The case of water conservation by canal piping in the Upper Deschutes Basin exemplifies how irrigation efficiency is not just a technical question but it also introduces socio-political issues. Yet, there are a lack of studies which holistically bring together the material impacts of irrigation efficiency with the social dynamics and the knowledge politics involved (Lave, Biermann, and Lane, 2018). In Lankford et al.'s (2020) irrigation efficiency framework, the authors encouraged a new methodology which will "move from single methods to multiple, mixed methods that provide relevant information to understand the heterogeneous and often empirical data-short evolving stories of irrigation systems and river basins" (p. 14). Building on previous irrigation efficiency frameworks in combination with applying a hydrosocial and critical physical geography (CPG) lens, this study addresses the potential trade-offs in irrigation canal piping in a novel way to fill the existing data gaps and exemplify the importance of integrating natural and social sciences in critical water studies to inform equitable and just water management and policy moving forward in a drier climate.

The goal of this research is to better understand the ways in which water managers in the Upper Deschutes Basin define efficient water use in terms of irrigation canal piping, and how the motives, discourses, values, and knowledge impact the vulnerability of shallow wells potentially reliant on the water leaked from canals. This thesis begins with a review of previous irrigation efficiency literature, from both the social sciences and natural sciences to emphasize the interdisciplinary data gap that exists. A review of how a hydrosocial lens has been applied to irrigation research will be briefly discussed, as well as how CPG has been used to address socio-political and biophysical issues related to water. Then, I describe the research questions which guide this study and the methods I used to answer them, which include qualitative interview data collection and GIS spatial analyses. The results of the social and physical analyses are presented separately, then are integrated and brought into conversation with one another in the discussion. Finally, I offer recommendations on how the Upper Deschutes Basin, and other basins like it, can move forward with irrigation efficiency projects and at the same time be aware of the unintended consequences and questioning of the existing power relations to promote holistic and equitable hydro-social networks.

Literature Review

To provide a review of the literature on irrigation efficiency and set the state for my critical, mixed-methods research in the Upper Deschutes Basin, I first look at the ways in which social scientists have analyzed the subjectivity of the term 'efficiency' in water management. Then, I discuss examples of irrigation efficiency studies from a physical science perspective. I then zoom out to look at two critical lenses to water resources which I use in my own research: hydrosocial and CPG. Finally, I synthesize these areas to identify the data gaps, which my study addresses.

Irrigation Efficiency Contestation

Efficiency Discourse: The Social Nature of IE

Political ecologists and hydrosocial theorists have grappled with how 'efficient' and 'beneficial' are subjective terms with power relations and knowledge production embedded in their definitions and use in irrigation efficiency, creating winners and losers within a basin (Trottier, 2008; Boelens and Vos, 2012; Lankford et al., 2020; Molden et al., 2010; Birkenholtz, 2008). For example, Boelens and Vos (2012) argue that the effect of efficiency discourse on related policy is rarely examined but can be dangerous when universalized definitions and objectives are used by engineers, and other larger scale actors, in irrigation because of the threat to local notions of efficiency. The study highlights how the concepts in irrigation efficiency (e.g. efficiency and productivity) are not neutral terms, yet when they are naturalized and masked in an objective appearance, it can become a powerful discursive tool (Boelens and Vos, 2012). This discursive tool can contradict the multitude of interests and values of stakeholders, resulting in groups winning access to re-allocated water, while other groups, in particular more vulnerable users, losing access to water. Poverty, gender, Indigenous populations, and other social divisions are geographically distributed within a basin, making it important to assess who gains water by recycling or reusing the 'lost' water to irrigation efficiency projects (Boelens & Vos, 2012).

In a critical political ecology analysis of the term 'water crisis', Trottier (2008) argued that the knowledge created by hegemonic discourse on water disguises power relations as "scientific rationality" (p. 212). Social actors decide when there is a water shortage based on multiple factors, usually tied to irrigation water demands. The author went on to explain that the different definitions of 'water crisis' produce "conceptual building blocks that legitimizes some actors, de-legitimizes others, and makes others simply invisible" (p. 198). This power structure influences scientists' capacity to ask questions and the way in which they formulate them, leading to policy recommendations for 'solutions' that might appear to be a setback to others (Trottier, 2008). In relation to irrigation efficiency, a specific epistemic community decided what constituted 'beneficial' and 'nonbeneficial', resulting in a number of policies based on diagrams depicting the 'correct' flow of water, equations, models, etc. to define and explain 'efficient' irrigation. 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). Rather, efficiency depicts water management as a field that "can be best determined using rational choice theory through the use of models" (p. 206).

The Complexity of Scale: from terminology to equitable water management

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). Hydrology and the practice of irrigation have developed historically at different scales 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 dominate field of engineering 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).

In an attempt 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 with three categories: changes in storage, consumed fraction, and non-consumed fraction. The author defended the need for the definitions based on 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).

Scott et al. (2014) created a conceptual framework that takes into account not only loss and depletion but also recovery, following definitions from Perry (2011). The framework includes four categories of water pathways in irrigation efficiency: consumed fraction, non-consumed fraction, recoverable fraction, and non-recoverable fraction. Using this framework, the authors studied three regions where irrigation efficiency is implemented and found three categories of paradoxes in irrigation efficiency, including one based on geographic scale. The importance of scale is especially pertinent to the piping or lining of irrigation canals, which can have a high presumed efficiency at the local scale, yet at the basin scale, approximately 80-90% of the water to be saved is already consumed somewhere else, resulting in minimal true 'savings' (Perry, 1999). The scale paradox is evident in the Imperial Valley where reduction in seepage from lining the All-American Canal has resulted in Mexico losing approximately 190,000 acre-feet of water per year (Kishel, 1993), causing severe impacts on the economy, the environment and quality of life (Maganda, 2005). Foster and Perry (2010) argue that the 'simple panacea' of traditional irrigation efficiency is a false paradigm that is accepted by groundwater practitioners in the face of the 'water for food production' global dialogue, but in reality is a major policy issue for groundwater when viewed from the basin scale.

Lankford (2012a) assessed the movement towards reconsidering the classical irrigation efficiency 'losses' through new frameworks and noticed that there are multiple risks to water managers, including errors in terminology, poor engagement with local water users, and inappropriate methods to compute efficiency. Noting how scientists seem unable to agree on how to define and assess the performance of irrigation efficiency, Lankford (2012a) addressed the debate on classical efficiency by arguing that classical irrigation efficiency has merit in the management of irrigations systems and should not be eliminated from the vocabulary. Rather than choose one camp in the irrigation efficiency terminology/definition debate, Lankford (2012a) encourages a pluralistic approach to irrigation efficiency to avoid 'mismatches' between demand and supply within one system and between multiple systems at various scales.

Building upon growing irrigation efficiency perspectives and the need for a more holistic approach, Lankford et al. (2020) reviewed the existing literature on irrigation efficiency and created the Irrigation Efficiency Matrix (IEM), a physical and social scale-based framework to better understand the paradoxes and trade-offs in irrigation efficiency. Five scales and ten discursive elements are included in the framework, encouraging irrigation efficiency researchers to conduct transdisciplinary work, especially focused on canal lining/piping, with critical attention to scales, motives, and values to inform equitable and sustainable water resource decisions (Lankford et al., 2020). Powerful actors in scales four and five (e.g. managers, politicians, policy-makers) determine irrigation efficiency methods and implementation in scales one, two, and three (e.g. small farmers and water user associations), and irrigation efficiency “pitfalls” result when definitions of ‘efficiency’ are different across scales (Lankford et al., 2020). The authors urged 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).

Along these same lines, van Halsema and Vincent (2012) emphasize the importance of understanding the “diverse notions and values of water use efficiency and productivity factors within a scheme, at scheme, and catchments scale” (p. 14). The use of irrigation efficiency to inform water management decisions should be at the irrigation scheme or catchment scale in order to locate and identify the opportunities for enhanced water use efficiency as well as “the potential trade-offs in water re-allocation between diverse water users and uses” (van Halsema and Vincent, 2012, p. 9). Lankford (2013) views the reallocated water, or ‘savings’, in resource efficiency as ‘the paracommons’, or a competition for the resources salvaged when there are shifts in the efficiency of systems. The complexity, uncertainty, and interconnection of users in an efficiency system are on the same level as other elements of resource management like equity and resilience (Lankford, 2013). Cantor (2017), building upon Lankford (2013)'s concept of 'the paracommons', found that "the legal interpretation and implementation of ideas of waste in terms of water has material consequences that carry political and biopolitical implications" (p. 1024).

Increasing water 'efficiency' has the potential to result in positive results for a basin, but the adoption of irrigation efficiency policy requires the incentives of actors at all scales to be aligned and a clear understanding of the potential trade-offs and resultant winners and losers (Molden et al., 2010). Molden et al. (2010) highlights the need to align incentives of resource managers and society as well as providing a way to deal with trade-offs in the adoption of water productive improvements. Ostrom (2007) created a nested, multi-tiered framework to better understand complex socio-ecological systems, enabling researchers to study the ways in which the elements of a resource system, the generated resource units, the users, and the governance system are affected by and also affect the interactions in time and space. This framework allows for situating these interactions in the larger socio-economic, political, and ecological setting in which they are embedded. In an application of Ostrom's (2007) framework to irrigation systems, van Rooyen et al. (2020) argues that "dysfunctional irrigation schemes can be transitioned towards complex adaptive systems by offering appropriate technologies, a thorough diagnostic approach, wide stakeholder involvement, and careful selection of strong but achievable interventions" (p. 194).

Natural Science Approaches to Irrigation Efficiency

The physical trade-offs and consequences of irrigation efficiency have been studied by natural scientists though a variety of methods. One of the possible trade-offs of irrigation efficiency is reduced groundwater recharge. Irrigation practices and conveyance infrastructures have created artificially higher groundwater levels than what would naturally exist, resulting in reliance on an expected, 'natural', groundwater level. There are a limited number of studies dedicated to specifically the impact that irrigation canal piping has on groundwater systems. Examples of two studies focused on this consequence are Meredith and Blais (2018) and Arumí et al. (2009). In some Montana valleys, rural housing developments that use wells depend upon the 'inefficient' irrigation in the region (Meredith & Blais, 2018). When conservation efforts work towards leaving more water in-stream for environmental purposes, less water is leaked from canals or fields. Meredith and Blais (2018) used a groundwater model to show that canal leakage is the primary irrigation-related source of aquifer recharge in a particular flood-irrigated valley in Montana. The authors also found that assumed recharge rates from flood irrigation practices can greatly overestimate recharge (Meredith & Blais, 2018). The authors suggest that the focus for irrigation conservation efforts should be on irrigation methods rather than reducing canal leakage, as this is a valuable water resource for maintaining healthy aquifer levels. Arumí et al. (2009) found similar results in Chile's Central Valley, where almost 75% of groundwater recharge was sourced from irrigation ‘inefficiencies’ from canal seepage (52%) and irrigation loss on field (22%). These authors also warned against lining irrigation canals due to the adverse consequences on groundwater supply. Both examples highlight the lack of focus on, or perhaps knowledge of, the interconnected nature of surface and groundwater by those making the irrigation efficiency decisions.

In addition to decreased groundwater recharge, irrigation efficiency can cause an increase in water consumption. In a concise review, Grafton et al. (2018) stated that “increased irrigation efficiency rarely delivers the presumed public-good benefits of increased water availability” (p. 748). Multiple studies have quantified the increase in consumption of water at the basin scale after irrigation efficiency updates are put in place (e.g. Pfeiffer and Lin, 2014; Wheeler et al., 2020; Batchelor et al., 2014; Ward and Pulido-Velazquez, 2008). The majority of these kinds of studies made suggestions for how to achieve water conservation rather than irrigation efficiency paradoxes and trade-offs. These recommendations included approaches like increased regulation of water quantity and improved water accounting (Pfeiffer & Lin, 2014; Ward & Pulido-Velazquez, 2008; Richter et al., 2017; Grafton et al., 2018; Wheeler et al., 2020).

Critical Approaches to Water Management

Hydrosocial Lens

Attention has been given to the social and physical nature of water in the literature under the concept and theory of the hydrosocial cycle. Norgaard (1994) discusses how social changes and the organization of the water cycle co-determine each other. Swyngedouw (2006) describes hydrosocial research as an attempt to "transcend the modernist nature-society binaries" and portray the circulation of water as a "hybridized socio-natural flow that fuses together nature and society in inseparable manners" (Swyngedouw, 2009, p. 56). Linton and Budds (2014) argues that the hydrologic cycle separates water from its social context. To conceptualize the ways in which water and society make and remake each other, the authors propose the hydrosocial cycle "as an analytical tool for investigating hydrosocial relations and as a broader framework for undertaking critical political ecologies of water" (Linton and Budds, 2014, p. 170). Budds (2009) uses a hydrosocial approach to critically address the political role that scientific assessments play in resource management policy, with a focus on groundwater exploitation and reconfiguring uneven waterscapes. Following Bakker (2003), Kaïka (2003), and Swyngedouw (2004), Budd (2009) describes the hydrosocial cycle as incorporating "water's social relations alongside its physical materiality, through the socio-ecological concept of the waterscape", which has been conceptualized through a Marxist approach to understand the intersection between water, social power, and capital (Budds, 2009, p. 420). Boelens et al. (2016) introduced the concept of hydrosocial territories to argue that territorial disputes are not only related to struggles over natural resources, but instead they involve struggles over discourses, meanings, knowledge, and norms.

The studies above are just a few examples of research using a hydrosocial lens to better understand the hybrid nature of water to uncover the equity and justice implications of water management. Yet, there have been only a handful of studies focused on using a hydrosocial lens to better understand irrigation systems in particular, even though, as Swyngedouw (2009) notes, referencing Harvey (1996), there is nothing unnatural about constructed environments, including irrigation systems, because "hydraulic environments are socio-physical constructions" (p. 56).

The conceptualization of irrigation as a socio-natural hybrid dates back to the 1980s (Uphoff, 1986; Vincent, 1997). More recently, Mollinga et al. (2014) argued that a hydrosocial perspective "can be used to bring together in a single framework the different scales and dimensions of the socio-technicality and hydrosociality of irrigation" (p. 193). Also, importantly, uncovering the tensions and contestations within irrigation projects emphasizes time and technology, which can be lacking in political ecology studies, to add nuance to neoliberal irrigation reform (Mollinga et al., 2014). Mollinga et al. (2014) shows that irrigation canals within large-scale surface irrigation processes in south India are part of a hierarchical rearrangement of the hydrologic cycle, with seemingly equal water distribution of water in theory but not in practice. In Tasmania, Kumar et al. (2022) used a hydrosocial lens to examine how visions of the future for irrigation development shapes the interactions between water and society. Seemann (2016) analyzed the social factors underpinning irrigation policy in Bolivia and the reconfiguration of hydrosocial territories. The author found that technology, power relations, and legal systems can result in imbalanced distribution of resources and water rights in resource conflicts (Seemann, 2016). In an effort to improve water governance in multifunctional irrigation systems, Ricart et al.

(2019) used case studies to show how hydrosocial territories are altered and shaped by stakeholder engagement.

Critical Physical Geography Lens

In an effort to bring together social science and natural science, CPG works to combine "critical attention to relations of social power with deep knowledge of a particular field of biophysical science or technology in the service of social and environmental transformation" (Lave et al., 2014, p. 3). Rather than understand eco-social relations as a one-way path of human impact on the environment, CPG aims to provide a deeper understanding of the "complex power relations that shape and are shaped by the biophysical world" (Lave, Biermann, and Lane, 2018). Instead of following the methods of conventual research on the Anthropocene which focuses on large-scale modeling and simplified understanding of human-environmental interactions, CPG "breaks down the divides between conventional disciplines but also engages with fundamental questions about the conditions within which we find ourselves as a society and the role of scientific inquiry in shaping those conditions" in an effort to recognize the different definitions and meanings of the Anthropocene in day-to-day life (Lave, Biermann, and Lane, 2018, p. 4). CPG has been applied to water resource research on market-based impacts on stream management (Doyle, Robertson, and Singh, 2018), environmental justice implications of water quality regulations (Arce- Nazario, 2018), shifting social priorities and the evolution of fluvial systems (Ashmore, 2018), privatization of stream restoration (Lave, Doyle, and Robertson, 2010; Lave, 2012) and dam removal (Dufour et al., 2017).

Synthesis and Gaps

The trade-offs in irrigation efficiency have been studied through physical and social lenses, as described above. Using a political ecology lens and special attention to scale, researchers have emphasized the political motives and values embedded in the term 'efficiency' and the risks of using efficiency as a neutral term in water managers' vocabulary. The scale at which irrigation efficiency is planned and implemented is critical to understanding and preparing for the equity implications of water losses and gains in a hydrologic system with diverse water users with differing values tied to water efficiency. The study of irrigation efficiency through a political ecology lens sets the stage for critical irrigation efficiency research, yet there are no existing studies which look specifically at the subjectiveness of terms like 'efficiency' and 'beneficial' related to canal piping. Also, while existing irrigation efficiency studies are useful for understanding the theoretical basis for misunderstandings, confusion, and conflicts surrounding irrigation efficiency, there is a lack of focus on the steps in which these social factors materialize into changes in the physical landscape.

Physical and natural scientists have quantified the volume of water 'lost' and recovered in an irrigation system at different scales, emphasizing the importance of understanding the material trade-offs in irrigation efficiency. These studies are necessary to preparing for and mitigating against the unintended consequences that may occur in a basin after irrigation efficiency is implemented. Having a deep understanding of the diverse water users in a basin and the changing water pathways in an irrigation system is vital, yet the physical studies discussed above do not engage with any critical analyses of the social drivers underpinning the water management decisions which ultimately lead to the physical trade-offs. The knowledge politics and social dynamics of water conservation and irrigation efficiency are not taken into consideration when studying the physical hydrologic landscape, just as the material element is not taken into consideration in the political ecology and social science studies. In a study of river basin resilience and irrigation efficiency, Scott et al. (2014) argues that trade-offs are inevitable in socio-agro-ecological systems, yet researchers tend to neglect these trade-offs when narrowly focusing on a subsystem. While there are a considerable number of studies dedicated to irrigation efficiency and the paradoxes that result from implementation, there are a lack of integrated and transdisciplinary approaches, like CPG, with attention to both the physical implications of irrigation efficiency and the underpinning social and multi-scalar discursive factors.

Hydrosocial researchers are advancing critical studies of irrigation to better understand the nuance within capitalist and neoliberal irrigation projects around the world. Yet, besides Mollinga et al. (2014), there is a lack of focus specifically on irrigation canals as the subset of a system. When it comes to exploring social power relations which make up hydrosocial cycles, Budds (2009) notes how attention has been paid to policymakers and groups lacking access to water, yet researchers have paid “little (if any) attention to the role of hydrologists and water scientists” (p. 420). There is an opportunity to apply a hydrosocial framework to irrigation efficiency to better understand the ways in which science and water relate by “extending existing work on the production of ‘expert’ knowledge by technical water managers, and by exploring the production and use of hydrological data” (Budds, 2009, p. 420). Also, while the concept of the hydrosocial cycle is rooted in the understanding that water and society are internally related, there are few, if any, hydrosocial studies which bridge the gap between the natural sciences and social sciences to understand the materiality of irrigation systems alongside the political, economic, and cultural factors which co-constitute them.

In this work, I address these gaps by specifically focusing on irrigation efficiency and canal piping from a hydrosocial and CPG perspective. I bring together the social and physical dimensions of this popular water conservation project to provide a holistic assessment of the ways in which motives, values, discourses, and scientific knowledge intersect and influence the hydrologic landscape in the Upper Deschutes Basin. By focusing on the perspectives of water managers, this study addresses the need to understand irrigation efficiency from specific social scales, especially those with the power to make water resource decisions in a basin, to better prepare for and mitigate against the potential trade-offs which may be overlooked.

Setting and Background

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. As "one of the most well-known waterways in the western United States", 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, generating hydroelectricity, and recreation (DRC, 2008, p. 3). Land use in the Deschutes Basin is predominately agricultural, forestry, and wildland recreation (Deschutes Basin Board of Controls, 2019). The Upper Deschutes Basin, which is the area of interest for this study, encompasses approximately 4,500 square miles of the Deschutes River drainage (see Figure 1) (Gannett et al., 2001). The Upper Deschutes Basin is drained by the Deschutes River and its tributaries: the Little Deschutes River, Tumalo Creek, Squaw Creek, the Metolius River, and the Crooked River. The study area has been a region of volcanic activity over the past

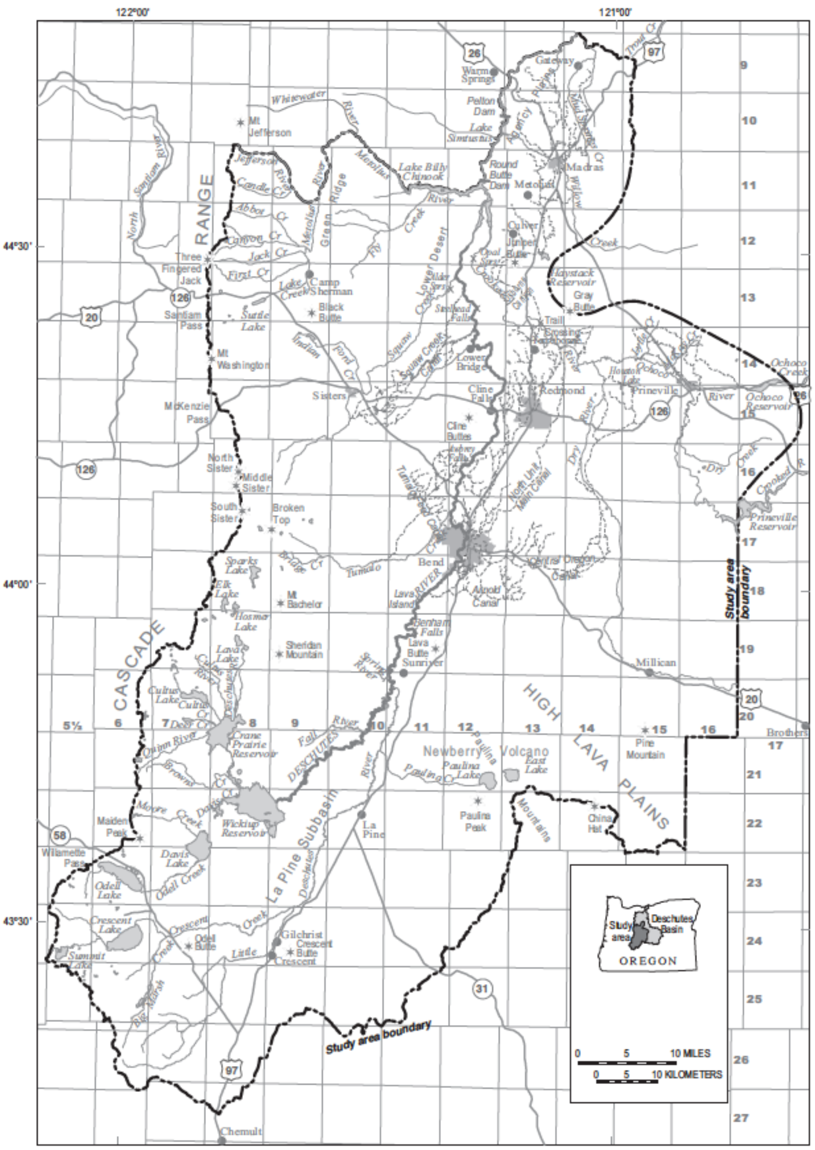


Figure 1: Map of Upper Deschutes Basin (from Gannett et al., 2001)

several million years resulting in geology dominated by volcanic, volcaniclastic, and volcanically derived sedimentary deposits (Gannett et al., 2017). The oldest rocks in the study area are of late Eocene to early Miocene age and part of the John Day Formation. In the northeastern part of the Upper Deschutes Basin, the Prineville basalt overlies the John Day formation and is a locally important aquifer (Gannett et al., 2001). The Deschutes Formation is the principal aquifer unit in the Upper Deschutes Basin and overlies the Prineville basalt. The Deschutes Formation ranges in thickness from zero feet to over 2,000 feet at its westernmost exposure (Gannett et al., 2001). The Cascade Range, composed of highly permeable quaternary aged volcanic rock overlies the Deschutes Formation and is the primary groundwater recharge area in the Upper Deschutes Basin (Gannett et al., 2001).

Major population centers where groundwater development is most intense in the Upper Deschutes Basin include Bend, Redmond, Sisters, Madras, Prineville, and La Pine (Gannett et al., 2001). The majority of the basin's population is around Bend, Oregon, which in 2019 had an estimated population of 100,421 residents (US Census Bureau Quick Facts: Bend city, Oregon, n.d.). In the past 30 years, the city 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 water from Bridge Creek, a small stream approximately 11 miles west of the city, and groundwater supply 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).

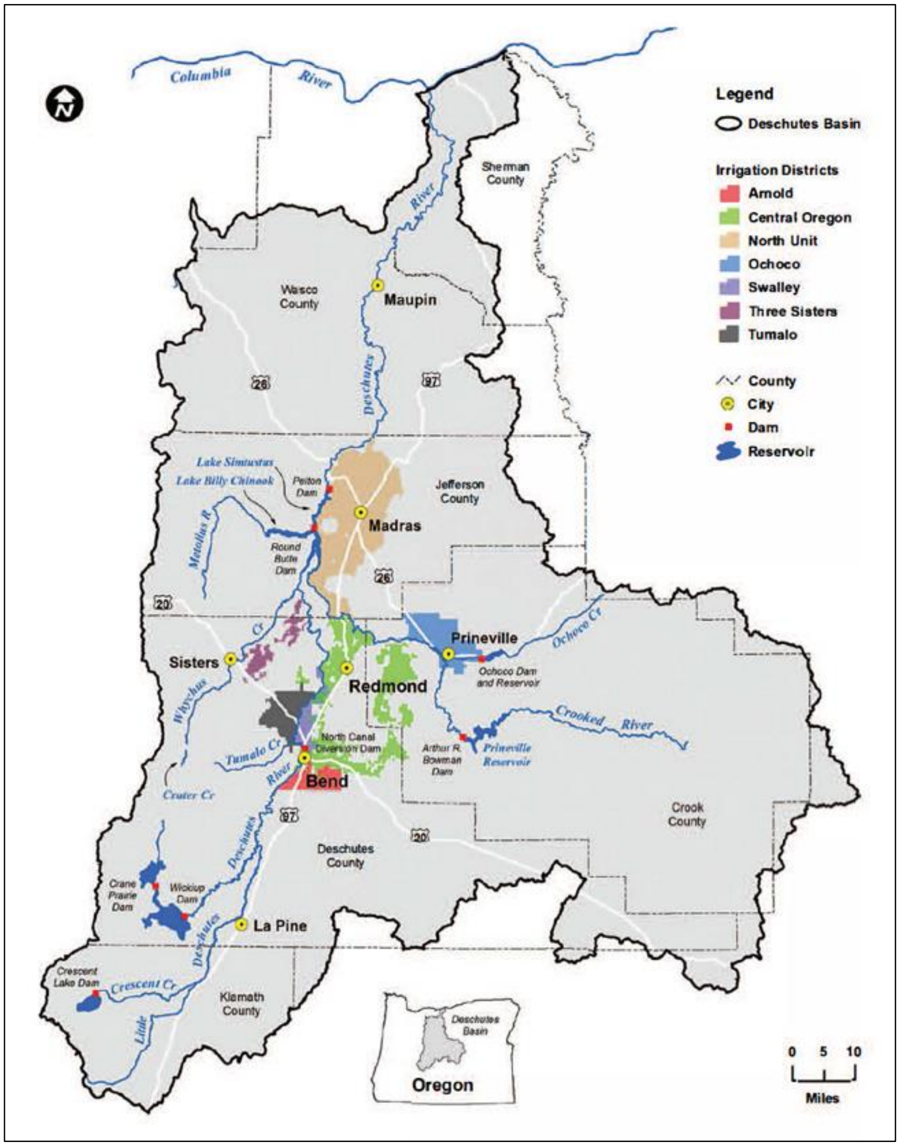


Figure 2: Eight irrigation districts in the Deschutes Basin and major rivers, reservoirs, and dams (from Deschutes Basin Board of Control, 2019)

The Deschutes Basin's hydrology has been altered dramatically by humans. In the late 19th century, the Homestead Act encouraged settler-colonial westward expansion into the region, forcing Indigenous peoples to lose access to land and water. In order to cultivate and manipulate the land to grow food, The Carey Act in 1894, combined with prior appropriation western water law, led to the construction of several hundred miles of irrigation canals by private irrigation companies to deliver and sell water rights to landowners for farming in the Deschutes Basin. Irrigation is by far the largest consumer of water in the basin, diverting approximately 700,000 acre-feet (2.3x10^11 gallons) from the Deschutes River and its tributaries annually (GSI, 2017).

Eight irrigation districts (see Figure 2) distribute the Deschutes River's water for use in agriculture. The irrigation districts hold the oldest water rights in the area with priority dates ranging from 1899 to 1916 (Deschutes River Conservancy, 2021). There are approximately 169,000 acres irrigated with surface water in the study area, with the majority of the water coming from the Deschutes River (Gannett et al., 2017). Central Oregon Irrigation District (COID) and North Unit Irrigation District (NUID) serve the largest acreage in the basin at 45,000 acres and 59,000 acres, respectively (Deschutes Basin Board of Controls, 2019). NUID has some of the most junior water rights on the Deschutes River, making it the most vulnerable to dry conditions. Irrigated agriculture forms a large portion of the basin's economy. In 2012, Jefferson, Deschutes, and Crooked counties produced crops with a combined market value of $71,938,000 (NASS, 2014), and the economic impact of agriculture in Deschutes and Jefferson counties was $351,000,000, with Jefferson County accounting for over twice that of Deschutes (Headwaters Economics, 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 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'Conner et al., 2003), which supports a range of summer-time recreational activities on the river. The increase in groundwater demand led to concerns about the impacts of groundwater withdrawal on surface water, leading to the passage of the Deschutes Groundwater Mitigation Program by the Water Resource Commission in 2002 (Deschutes River Conservancy, n.d.). New groundwater permits are required to acquire mitigation credits to offset the effects of pumping on surface water, highlighting the attention given to the unique interconnection of groundwater and surface water in the Upper Deschutes Basin.

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 Deschutes River's flow has been severely impacted by dams, storage, and diversions for agriculture (Deschutes Basin Board of Controls, 2019). The historic summer flows below Wickiup Reservoir (see Figure 1) averaged 730 cubic feet per second and winter flows averaged 660 cubic feet per second (DRC, 2012). Today, the minimum flow requirements below Wikiup Reservoir in the winter season (storage season from November through March) is 20 cubic feet per second. During the summer, the median flows have been recorded at 1,150 cubic feet per second (DRC, 2012). In the Middle Deschutes, irrigators legally divert approximately 90% of the river's water by the time it reaches the city of Bend, resulting in very limited flows and high temperatures (DRC, 2008). 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), putting the Basin's hydrological system in the political, economic, and social spotlight in recent years.

In an effort 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 (see Figure 3). 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 the adaptive management and conservation efforts required to meet the requirements for the endangered species over the duration of the 30 year take permits, which has the goal of increasing winter flows in the Deschutes from a current flow of 105 cubic feet per second to 300 cubic feet per second by 2028 (Deschutes Basin Board of Controls, 2019). Outlined in the plan are conservation options that are legally 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). The Upper Deschutes Basin study also outlined options for conserving water in the basin, including irrigation water conservation (e.g. canal piping and on-farm infrastructure upgrades), market-based approaches, and enhanced/new storage and ultimately conclude that water-market mixed with conservation efforts could prove effective (Bureau of Reclamation, 2019).

Irrigation canal piping is chosen as a means of reducing water usage because approximately 46 percent of water moving through the 720 miles of open-earth main canals leaks in the Upper Deschutes Basin, providing an estimated 379,000 acre-ft/yr of recharge to the study area in the mid-1990s (Gannett and Lite, 2017; Gannett et al., 2004). In 2013, this volume reduced by 72,500 acre-ft/yr, a reduction of 19 percent, due to canal piping conservation efforts (Gannett and Lite, 2017). Piping canals provides a way for irrigation districts to return water to the Deschutes River through the Allocation of Conserved Water Program without interfering with water rights and reducing rates of water consumption. As of 2018, 209.43 miles of the irrigation canals in the study area had been converted to pipe, leaving 862.60 miles of canals as open-earth (note: these values includes 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 is approximately 200,000 acre-ft/yr, which would cost an estimated $2.4 billion.

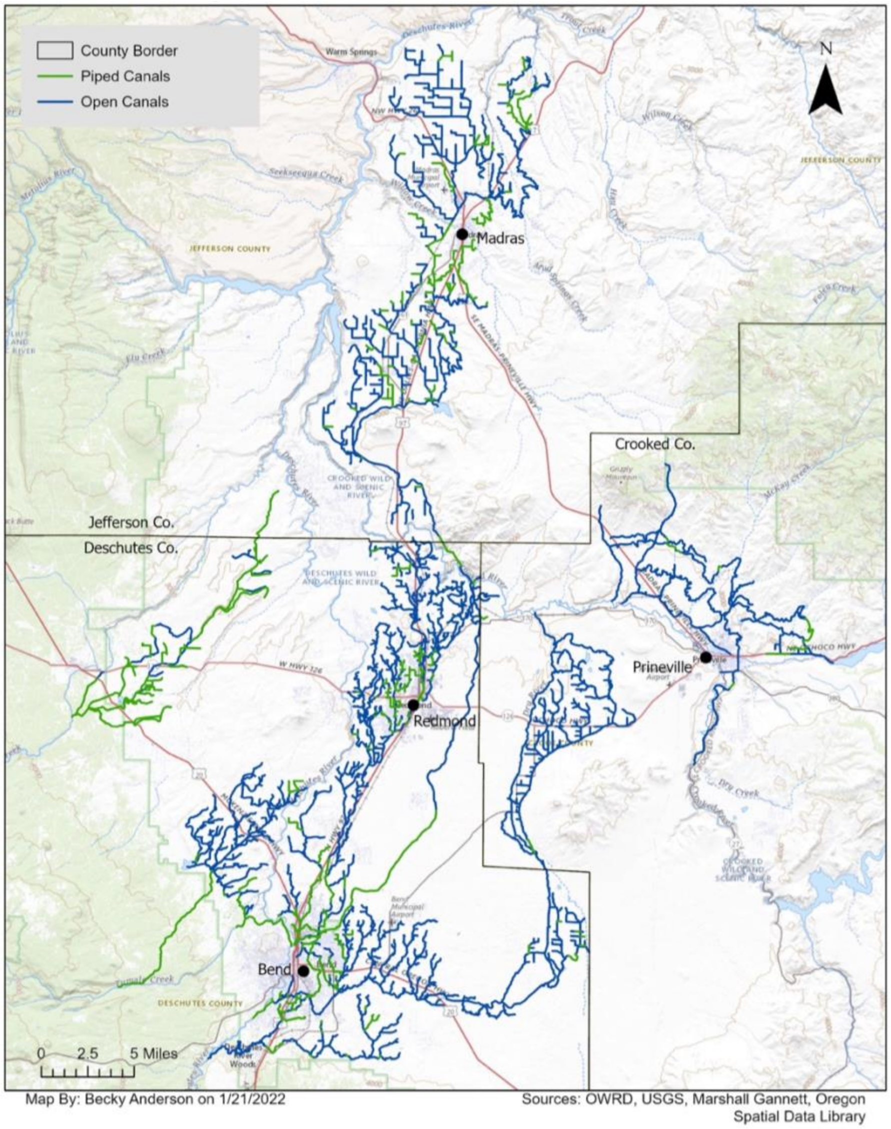


Figure 3: Irrigation canals in the Upper Deschutes Basin (as of 2018).

Yet, canal seepage has been found 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). The canal leakage supports 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). Broadly, groundwater levels in the study area have declined faster than what might be expected from climate variations alone (Gannett and Lite, 2013). The U.S. Geological Survey published a report describing the factors influencing these groundwater trends and their model (Upper Deschutes Basin Groundwater Model) attributed 10 percent of the groundwater decline to irrigation canal piping between 1997 - 2008. Groundwater recharge from leaking irrigation canals has elevated groundwater levels in the study area over the past century (Gannett and Lite, 2013), sparking public concerns about the potential negative impacts of piping canals on humans and ecosystems reliant on shallow groundwater. Hundreds to thousands of shallow wells were installed in the study area to a depth which was likely influenced by an elevated water table from irrigation canal leakage. Small-scale, localized water table fluctuations in the Upper Deschutes Basin have been shown to be impacted by recharge from local sources, including leaking canals (Gannett et al., 2001). Many wells throughout the irrigated central area of the study area in close proximity to canals experience fluctuations due to irrigation canal leakage, with an average of 1-10 feet of change in the water table seasonally (Gannett et al., 2001). In an extreme case, annual fluctuations caused by irrigation canal leakage of nearly 100 feet have been documented in the study area (Gannett et al., 2001).

Irrigation canal piping requires the cooperation and agreement of the numerous parties (Bureau of Reclamation, 2019), though it has not always received this. The Upper Deschutes River Basin Study (2019) noted that challenges to implementing canal piping include cost barriers and opposition to changing the nature of flowing, open canals that have been present for years. 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 by wanting canals to be designated on the National Register of Historic Places. 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) in order to stop or alter irrigation efficiency projects. On the *Save the Arnold Canal* website, one of the citizen-created websites against canal piping in the basin, residents claim that agriculture is not the only sector which benefits from canals, but that residents, wildlife, and plants do as well, and they feel that "the people who rely on over 500 existing wells that will be negatively impacted by piping have not been adequately informed by the District" (Save Arnold Canal, n.d.). Environmental impact statements are required for canal piping projects, and concerns expressed by the public in the comment section of a recent report from Swalley Irrigation District include worries about private wells going dry, negative impacts to wildlife and vegetation, negative consequences of decreased cold water recharge to streams, and costs of piping over other alternatives (FCA, 2018).

Research Questions

In this thesis, I examine the multiple dimensions of and perspectives on irrigation efficiency and canal piping through the following research questions:

1. How do actors involved in water conservation/management in the Upper Deschutes Basin define efficient water use and trade-offs in water conservation, and what factors most characterize these definitions?

2. How do these definitions relate to the support of or opposition to irrigation canal piping projects in the basin?

3. What does the spatial distribution of shallow wells in proximity to irrigation canals look like and can canal piping impacts on wells be analyzed with available groundwater data in the Upper Deschutes Basin?

In the next section I describe the methodology used to answer these questions.

Methods

To answer my research questions, I apply a mixed-methods approach including interview data collection and a spatial analysis of shallow wells in relation to canal piping. A mixed-methods approach is valuable because irrigation efficiency is embedded in socio-political processes, which creates real, physical impacts on hydrogeologic systems. Here, I describe each method in turn.

Qualitative Methods

Data Collection

To answer my research questions about how water managers define efficiency and how these definitions relate to support or opposition of irrigation efficiency projects, I conducted a set of semi-structured interviews with water managers.

To identify participants, I initially assembled a list of key stakeholders involved in irrigation canal piping through internet searches and review of water policy documentation in the basin. I reached out to these organizations and agencies via email, then used snowball sampling to identify the full range of water managers with knowledge and expertise on the hydrology and conservation of irrigation water in the Upper Deschutes Basin by asking interviewees for recommendations on who else I should speak with. I attempted to contact each person identified through this snowball sampling, although not all were interviewed due to lack of response and/or time constraints.

I chose water managers as the population of interest because this group produces knowledge and is tasked with deciding the management and policy strategies to be implemented, shaping "opportunities in the lower scales" for individual water users (Lankford et al., 2020). To allow for diversity in the sample, I used purposive sampling to create a sample of respondents that reflected the range of perspectives and institutions in the basin, including representatives from irrigation districts, state government agencies, conservation groups, water supply utilities, and research institutions (see **Table 1**).

Table 1: Interview Participants by Water Manager Type

Water Manager Type	Number of Interview Participants
Irrigation District Representatives	2
Federal Officials	1
State Officials	6
Nonprofit/NGO Representatives	7
Water Suppliers	1
University Researchers	1

I conducted 16 semi-structured in depth interviews with a total of 18 participants (15 interviews were one-on-one and one interview included three respondents) between August and November, 2021 (see **Table 1**). The interviews lasted between 30 minutes and two hours. The 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 (see Appendix B for the list of questions asked in the interviews). I conducted and recorded the interviews via Zoom, a teleconferencing software program. The recorded interviews were transcribed by Otter.ai, a speech to text translation software, then I reviewed and cleaned up the transcripts for analysis. The names of participants are replaced with pseudonyms to protect the identity and privacy of the water managers in the Upper Deschutes Basin (see Appendix C for more details).

Data Analysis

Utilizing a grounded, inductive approach (Charmaz, 2006) in combination with ‘flexible’ qualitative data analysis methods from Deterding et al. (2018), I initially coded each transcript both with open coding of line-by-line text and index coding of larger pieces of texts in MAXQDA Analytics Pro 2020. The open coding allowed me to identify themes inductively based on actual phrases or latent meanings in the data (Braun & Clark, 2006), while the index codes applied a top-down structure based on the interview questions and the broad themes already identified after completing the interviews. A few examples of the broad index codes were “Irrigation Efficiency Perspective,” “Canal Piping Trade-off,” and “Definition of Efficient Water Use.” This iterative process resulted in the creation of a coding structure with numerous inductive codes nested within the index codes. While completing the first round of coding, I wrote memos to keep track of connections across interviews to help with the identification of themes.

During the second round of coding, I went through each transcript again in MAXQDA to refine the codes and combine or nest similar codes for organizational purposes. In search of the major themes in the data related to my research questions, I followed Braun & Clark’s (2006) thematic analysis approach. Utilizing the analysis tools in MAXQDA, I compared the overlap between the inductive codes and the structural index codes, comparing the relationship between the frequent, interesting, and surprising codes across the entire dataset. Through this process, I identified five main themes that related to my initial research objectives of understanding the major factors influencing efficient water use perceptions in relation to irrigation canal piping. These themes include 1) incomplete groundwater knowledge, 2) natural versus artificial water, 3) balancing values, economic goals, and legal limitations in efficient water use, 4) scale and responsibility, and 5) education.

Quantitative Methods

In addition to collecting qualitative interview data on irrigation efficiency canal piping, I also conducted an analysis of shallow groundwater wells in the study area to integrate with the responses of water managers related to the potential trade-offs and consequence of irrigation canal piping. Shallow wells in the study are defined as wells with a completed depth of 300 feet deep or less following Gannett et al.'s (2001) separation of shallow wells as 100 to 300 feet deep and deep wells as generally 500 to 900 feet deep. To determine the extent of the vulnerability of wells, I analyzed the spatial distribution of shallow groundwater wells in the Upper Deschutes Basin nearby irrigation canals. I also analyzed the years of monitoring data available from shallow wells in the study area to explore the topic of adequate monitoring brought up by water managers in the Upper Deschutes Basin. Below is a detailed description of the methods used to achieve both analyses.

Shallow Well Spatial Analysis

I used well data from the OWRD to map shallow wells in the basin within each section (1 mile by 1 mile area). 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. A shapefile of irrigation canals, both piped and non-piped as of 2018, in the Upper Deschutes Basin was obtained from the OWRD and USGS (La Marche, personal communication, April 20, 2021) and was used to display the shallow wells in proximity to irrigation canals in the study area. The maps created by this analysis show three different values related to shallow wells near the irrigation canals in order to visualize and quantify how many wells are potentially at risk of shallow groundwater declines. First, there are maps of the number of shallow wells (300 feet and shallower) within each section. Second, there are maps of the average difference between the well depths and water table within each section, to determine the average number of feet of groundwater decline which would result in a shallow well going dry within a specified square mile area. Third, there are maps of the minimum difference between the well depth and water table within each section, displaying the most vulnerable well within each square mile. The maps are then compared side by side to USGS groundwater model results

(Gannett and Lite, 2013) of predicted groundwater decline caused by irrigation canal piping to determine areas with shallow wells that may be most vulnerable to the loss of seepage from canal piping.

To determine the distribution of shallow wells in the study area, I first organized and formatted three excel spreadsheets which contained all wells in Deschutes, Jefferson, and Crooked counties. The data was obtained from Marshall Gannett (Gannett, personal communication, August 8, 2021) and was downloaded from the Oregon Water Resources Department (OWRD) website. These datasets contain all wells located in the three counties up to 2018 and include information on the completed well depth (in feet), post static water level (in feet), well number, and location. I also obtained a shapefile of Townships, Ranges, and Sections (TRS) for the state of Oregon from Marshall Gannett (Gannett, personal communication, August 8, 2021). In order to combine the well data with the TRS shapefile in ArcGIS Pro, I created a “TRS” column in the excel spreadsheets and in the attribute table of the TRS shapefile.

Before I joined the well data with the shapefile in ArcGIS Pro, I first filtered the well data to include only the shallow wells. Two fields in the well data Excel spreadsheets were filtered: completed well depth and post static water level (water table). For completed well depth, I filtered to 300 feet or less and greater than 0 feet to exclude wells with no data. For post static water level, I filtered to greater than 0 in order to eliminate wells with no data. Wells with a negative difference between the depth of well and statice water level (depth of well minus depth to water table) were removed from the datasets because this would imply that the water table is below the depth of the well. This filtering process was completed for each county.

The filtered shallow well datasets for each county were combined and the only columns included in the combined dataset were county, well number, post static water level, completed well depth, TRS, and the difference between the well depth and the post static water level (this column is hereon referred to as 'difference'). At this point, each row in the Excel spreadsheets corresponds to a single well. To display the shallow wells per TRS in ArcGIS Pro, I created a Pivot Table in Excel with the row labels set to TRS. I then added in three columns to the Pivot Table: count of wells, average difference, and minimum difference. The Pivot Table was imported to ArcGIS Pro and joined with the TRS shapefile. Graduated symbology with various methods and classes were used to display the count of wells per section, the average difference between completed well depth and static water level per section, and the minimum difference between completed well depth and static water level per section. The difference factor is used as a proxy for vulnerability of the shallow wells in the study area. Two figures (Figure 6 and 7) present the number of shallow wells per section in the broader study area and also within the sections intersecting irrigation canals. Two figures (Figures 8 and 10) include the shallow well vulnerability of sections with shallow wells in the Upper Deschutes Basin study area and two figures (Figures 9 and 11) include only the sections which contain irrigation canals to highlight the shallow wells in proximity to the efficiency updates which are the focus of this study. The additional data (tables, percentages of vulnerable wells, etc.) were created by using the Table to Excel tool in ArcGIS Pro.

Shallow Well Monitoring Data Availability

I used data from OWRD' Groundwater Information System to map shallow wells with 'adequate' monitoring data in the Upper Deschutes Basin. While 'adequate' is a subjective term, I followed methodology from Albano et al. (2020) to help define the criteria in this study. First, I downloaded an Excel file of water level measurements from wells in the Deschutes, Jefferson, and Crooked counties from OWRD's website. This produced a dataset with over 15,000 rows of single water level measurements in each of the three counties. I then performed the first round of data filtering to find the shallow wells that meet the following criteria: a minimum of three water level measurements from the same month each year and the data spans over a minimum of 5 years within the range of 1985 – present. Water level measurements from the same month was included as a criterion to avoid seasonal fluctuation in groundwater levels due to natural trends and pumping of groundwater. Five years of monitoring data was set as the minimum for the purpose of finding more than short-term trends in shallow groundwater, and then the wells were sorted to a minimum of 10 years and a minimum of 20 years of water level measurement data to display the spatial distribution of the temporal range of shallow water level data in the study area. The data range was set to 1985 to present 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.

Wells which met these criteria were included in a separate spreadsheet and the columns included county, well log ID, first year of data, most recent year of data, total number of years of data, measurement month, and the difference between the most recent measurement and the first measurement (within 1985-present). To separate out the shallow wells (equal to or less than 300 feet), I used the OWRD well report query to find the completed well depth of each well. Any well with a depth greater than 300 feet was removed. The spreadsheet was then joined to a shapefile of well locations in Oregon, downloaded from OWRD's Groundwater Information System and two figures were created with this data. I made a figure of the years of available groundwater monitoring data at each shallow well (Figure 10) and a figure of the difference between the first and most recent water level measurement within, 1985 to present (Figure 11), to display the overall change in shallow groundwater levels during the period of irrigation canal piping in the Upper Deschutes Basin.

Results

In this results section, I discuss my qualitative and quantitative findings separately. I integrate the two types of findings in the discussion section that follows. In describing the results, I use both the 'Deschutes Basin' and 'Upper Deschutes Basin' because both spatial areas are included in the interviews as well as in the spatial analysis. As described in the setting and background, irrigation canal piping is a project occurring in the Upper Deschutes portion of the Deschutes Basin. At the end of the results, the USGS Upper Deschutes Groundwater Model is discussed, bringing the focus back to the Upper Deschutes Basin. The discussion and conclusion describe the results in terms of the Upper Deschutes Basin.

Qualitative Results

Incomplete groundwater knowledge

Water managers in the Deschutes Basin often expressed the difficulty associated with understanding the complexity of groundwater behavior. This challenge played a role in how respondents perceived the potential trade-offs of 'efficient' water management and how they respond to the concerns of shallow groundwater well users. The visual cues and ease of measurement of surface water are not associated with groundwater, which influences water managers' support for canal piping in the Deschutes Basin. John, an irrigation district representative, expressed this when describing his view on 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 the leaked water from the canals will return to the Deschutes River, which he referred to above as the "natural system," John was wary of considering the leaked water inherently beneficial to the hydrologic system. Later in the interview, John went on to debate at what point leaked water from a canal transforms from water "owned" by the district to water in an aquifer. He suggested that a shallow well intercepting water from leaky canals could even be considered "stealing" from the district, highlighting the complicated assumptions associated with mis-understanding groundwater.

Other water managers emphasized the unique nature of the Deschutes Basin's highly permeable and fractured volcanic geology as an additional factor adding to the uncertainty, suggesting that proving trade-offs caused by elimination of recharge from canals, like lowering aquifer levels and decreased spring discharge, is a daunting task. The concern of decreased spring discharge to the lower Deschutes River and Crooked River as a result of canal piping wasn't a large concern to water managers because, as Tom, a research hydrologist, said "springs aren't necessarily going to dry up, they're just going to have diminished flow" and went on to express that the point of uncertainty is what affect that will have on aquatic life reliant on cold water refugia.

The lack of groundwater understanding among water mangers influences not only how the potential consequences of canal piping are perceived in the

Deschutes Basin, but also their views on how public concerns about reduced groundwater recharge should be managed. When asked about these concerns, Robert, another irrigation district representative, responded,

> I think it [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.

Robert highlighted a lack of groundwater monitoring, a concern frequently raised by water managers in the basin. He also expressed that monitoring would aid in proving his belief 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 monitoring approach. Bill, a groundwater scientist, viewed the current monitoring in place as adequate for the "scale at which we do basin management," while others recognized the necessity of understanding the smaller-scale, localized effects of canal piping on groundwater levels.

Not all water managers agreed with Robert's view that public concerns about groundwater decline caused by irrigation canal piping are unwarranted. A range of respondents described how to handle the concerns of shallow groundwater decline related to canal piping. For example, Steve, 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.

Steve's response went beyond only monitoring to suggest that measures to address these trade-offs should be included within the piping projects themselves.

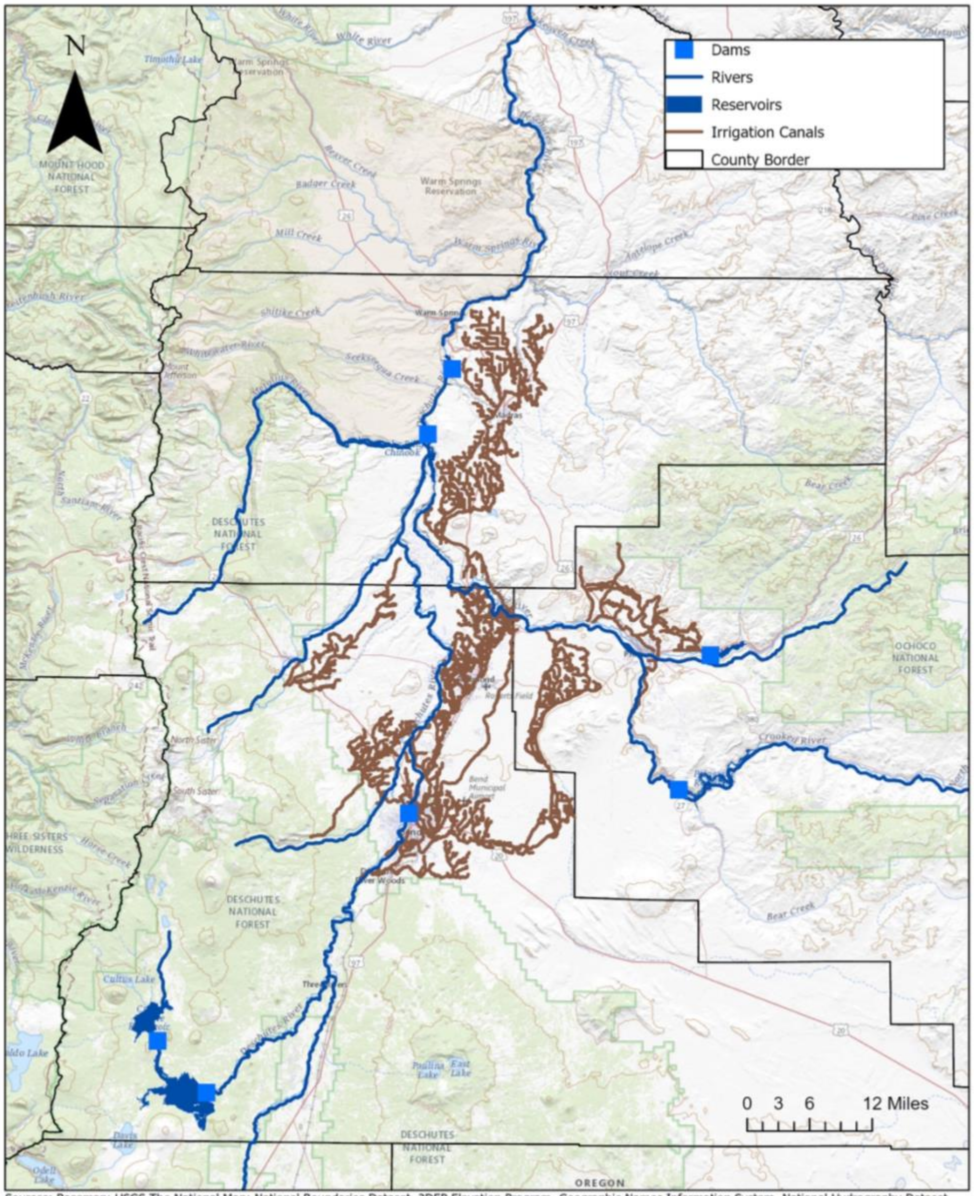
Tom, a research hydrologist, echoed the need for mitigating efforts because "there are winners and losers in the water management game," illuminating the potential burden placed on property owners who could face the reality of deepening their wells due to canal piping—a process that, in Tom's words, "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 whom I spoke with agree that canal piping should continue as a conservation effort to restore the heavily dewatered Deschutes River. Amelia, a conservation project manager, expressed with urgency the importance of piping canals, regardless of the uncertainties:

> But at the end of the day, we're never going to know until we take the leap and change course in management […] humans are so good at pretending that we know what we're doing, and we really don't have any idea […] I think we need to take in all the information that we have, but we still need to make decisions and move forward in management and adapt as necessary.

Water managers in the Deschutes basin are aware of the potential trade-offs to irrigation canal piping and acknowledge that there is limited data to fully understand the impacts. Regardless of this uncertainty, piping irrigation canals clearly conserves water for the Deschutes River and water managers see this as a benefit worth taking risks for.

Natural versus artificial water

When asked about their perspective on the groundwater recharge associated with irrigation canals, the majority of water managers in the Deschutes Basin raised the problem of “natural” versus “artificial” water. I found that water managers support irrigation canal piping because conserving the leaky water from canals and keeping that water in the Deschutes River is viewed by water mangers as an act of restoring the “natural system”. Figure 4 is a visual representation of this general discourse on surface water in the Upper Deschutes Basin. The ‘natural’ Deschutes River and its tributaries are represented as blue and the ‘artificial’ irrigation canals are represented as brown.



Sources: Basemap: USGS The National Map: National Boundaries Dataset, 3DEP Elevation Program, Geographic Names Information System, National Hydrography Dataset, National Land Cover Database, National Structures Dataset, and National Transportation Dataset; USGS Global Ecosystems; U.S. Census Bureau TIGER/Line data; USFS Road Data; Natural Earth Data; U.S. Department of State Humanitarian Information Unit; and NOAA National Centers for Environmental Information, U.S. Coastal Relief Model. Data refreshed August, 2021. ; OWRD, USGS, Oregon Spatial Data LIbrary

Map By: Becky Anderson 4/4/2022

Figure 4: 'Natural' (blue) and 'artificial' (brown) water in the Upper Deschutes Basin

The irrigation canal piping projects in the Basin are required by public funding contracts to leave the majority, if not all, of the saved water in-stream for the Deschutes River or its tributaries, with the goal of increasing summer flows to help the endangered species in the basin. Paul, a hydrologist with the State, highlighted how groundwater springs fed by leaky canal water are viewed as "artificial" in comparison to the Deschutes River:

> I think leaving water in-stream in the Deschutes itself is more important than protecting either artificially elevated springs, or anthropogenic springs, that wouldn't exist at all.

The non-existence of leaky canal water prior to European settlement in the basin is justification for supporting its elimination through piping to leave water in the Deschutes River in attempt to restore the "natural hydrograph."

Some water managers recognized the difficulty in managing water for a "natural" system when, according to Amelia, it's "such a nebulous thing." Jane, a water policy analyst, did not view piping canals as the only piece important to restoring the Deschutes Basin to its "natural" state:

> If you do want to go back to the natural system […] it's not just the canals and it's not just piping…it's the huge withdrawals that the [irrigation] districts are making… it's the storage in the winter time. There are many pieces.

Rather than seeing irrigation canals as the only "unnatural" element, Jane highlighted how humans have altered the hydrologic system in more ways than one. She makes the distinction between piping irrigation canals to conserve water for the "natural system" versus for a system already heavily influenced and intertwined with humans, highlighting the social nature of the Deschutes River (see the dams and reservoirs in figure 4). Large diversions of water from the Deschutes River for irrigation in the summer and the construction of dams to store water in the winter have resulted in the river existing, in Tom's words, "almost

180 degrees out of phase as to how it was prior to development." The Deschutes River experiences higher than historical spring and summer flows and lower winter flows because water is stored behind dams during the winter and released from the reservoirs and lakes along the river for irrigation in the spring and summer.

While there is debate about what constitutes "natural" water management in the Deschutes Basin, some participants acknowledged that there likely are ecosystems and groundwater wells that would not otherwise exist without the leaky canal water. Ryan, a conservation technician, expressed the reality of making water conservation decisions moving forward:

> The whole ecosystem that's evolved around that artificial water is real. You can't say it's not there and it has been there for maybe 100 years. So, that's the other piece, I guess… the impacts to both groundwater and habitat and ecosystems and everything is potentially to be changed in the efforts to be more efficient with our water management.

Ryan refers to the groundwater recharge from canals as "artificial", but he also acknowledges that it is real, validating the anthropogenic water landscape which may sustain both human and non-human water users. Bill, a groundwater scientist, debated whether water managers in the basin should be accountable for managing the artificial elements of the hydrologic system in the Deschutes Basin:

> Are we responsible for maintaining […] what is essentially a perturbed system? […] It's a little bit more of a philosophical question, but it's definitely something I've thought about because we do have this perturbed state […] and if we cut off the artificial seepage that does provide cool water habitat we can't expect that everything would be fine.

When it comes to making the call on whether or not to maintain the artificially elevated groundwater levels, Bill said "I'm glad I don't have to make that decision", emphasizing the complexity of making such a choice in water management. The role of Bill's agency is to support water-use development in the basin, which he acknowledges does not always go hand in hand with managing for a "natural" state. Bill points out that it may not even be a realistic possibility to manage for a "natural" system because "we're past a natural state…we can't expect to just take everybody out of the Deschutes Basin."

Despite some reflection on how best to handle the potential trade-offs that can occur when "artificial" irrigation canal leakage is eliminated, the overwhelming perspective of respondents is that keeping water in the Deschutes River is the ideal scenario. Phil, a state representative, compared the severity of the Deschutes River to the "artificial" groundwater when supporting canal piping:

> In my mind, because of how severe the streams have been impacted by the inefficient canals that it's an easy answer … we should be piping and lining canals as much as we can to help restore streamflow […] and the main driver of the groundwater system is the natural recharge. So maintaining an artificial recharge is not a prudent management decision.

Phil's attention to the leaky irrigation canals and not the large diversions of surface water for irrigated agriculture as the main cause of the severe impacts on streams in the basin showcases how some human activities can be viewed as more or less "artificial" than others. Also, since the regional aquifer in the Deschutes Basin is recharged predominately by precipitation, the influence of leaky canal recharge is not regarded as significant.

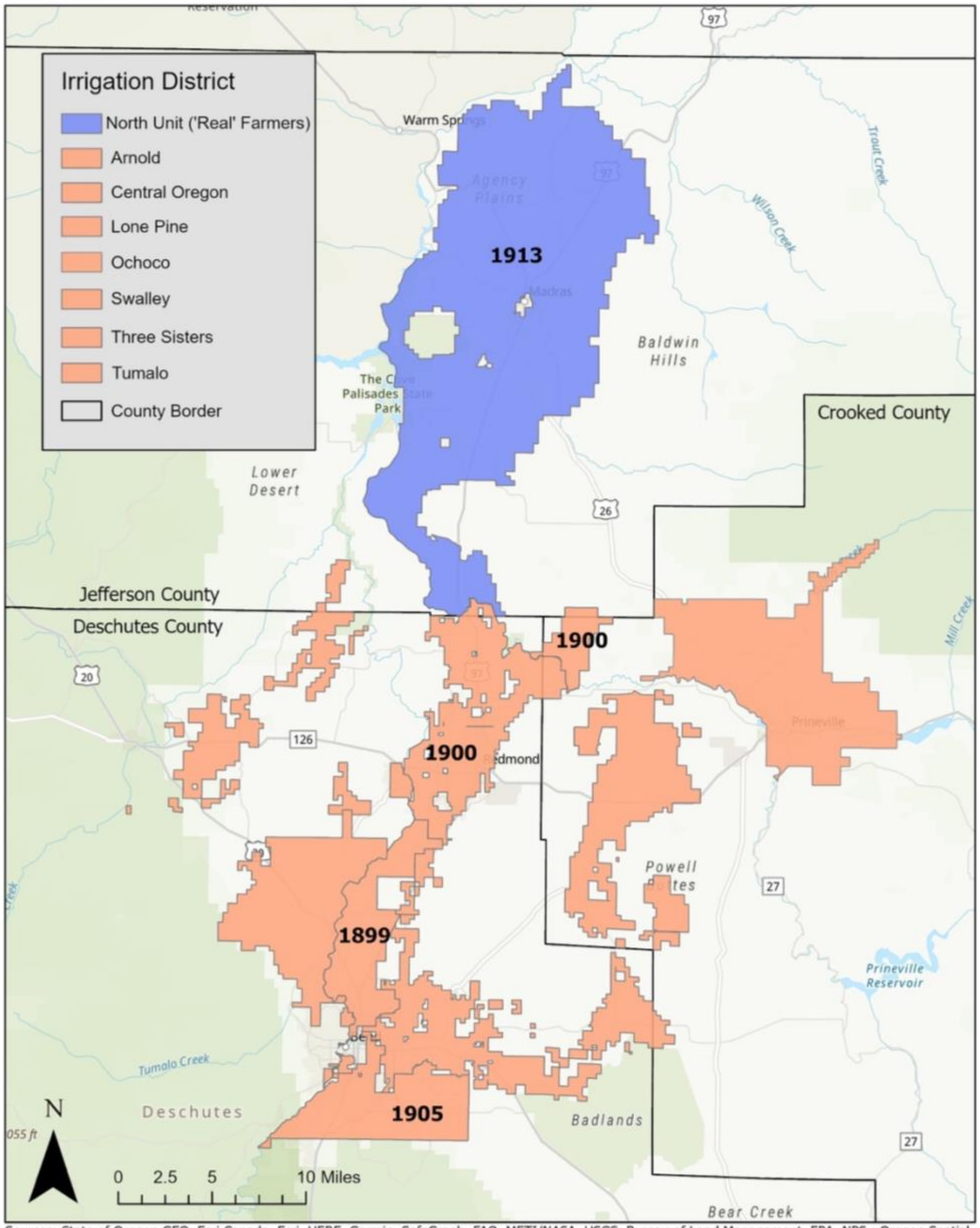
Because of these clear definitions of what is "natural" and what is not, water managers see eliminating "artificial" recharge as one of the leading answers to solving the water problems in the Deschutes basin. The Deschutes River and surrounding ecosystems are currently benefiting from this perspective among the water managers, while humans and non-humans who may rely on the groundwater recharge from leaking irrigation canals are devalued, begging the question of what values are embedded in water use efficiency in pursuit of a "natural" system?

Balancing values, economic goals, and legal limitations

When describing the necessity of irrigation canal piping, water managers in the Deschutes Basin raised the issue of who or what is worthy of the limited surface water. All respondents agree that canal piping is a necessary conservation effort, with varying degrees of limitations acknowledged, yet it became clear that conserving water for the "natural" river itself was not the only driving factor. Ryan, a conservation technician, explained another important consideration on the minds of the water managers in the basin:

> This year, in particular, there's a huge amount of concern because the North Unit Irrigation District in Jefferson County, has the youngest water right. But, they also have the most critical need in terms of commercial agriculture […] It's another philosophical question. The folks in Deschutes County, with their landscaping and their nice green grass and a couple llamas […] you get into this us versus them thing […] But Jefferson County water gets shut off first.

NUID in Jefferson County has the youngest water rights in the Upper Deschutes Basin, and water managers describe farmers in this district as "true" farmers, compared to some of the water users in the other irrigation districts in Deschutes County who have older water rights and are labeled as "hobby farmers" or "rhinestone cowboys" (see Figure 5). Ryan expressed frustration when describing the different ways in which the two groups use their water, especially when considering the more "critical" commercial agriculture users lose their water first during periods of drought.



Sources: State of Oregon GEO, Esri Canada, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, Bureau of Land Management, EPA, NPS ; Oregon Spatial Data Library
Map By: Becky Anderson 4/4/2022

Figure 5: Irrigation districts and their oldest water rights in the Deschutes Basin emphasizing 'real' farmers. (Note: this is a generalization from interview data. Not all farmers in Deschutes County and Crooked County were considered "hobby" farmers by participants in this study).

Respondents pointed out how a large number of patrons of the irrigation districts in the Deschutes County portion of the basin, which are described as "quite wealthy" newcomers, tend to use their share of water for aesthetic purposes or to maintain a small number of livestock, like llamas. On the other hand, the livelihood of water users in Jefferson County is dependent upon water from the Deschutes River. The "livelihood" versus "hobby" use of water has created tension in the basin over where the limited surface water should go and what is deemed as 'productive' and 'beneficial' use of water in the basin.

The conflict between different types of irrigation water users, both of which are considered "beneficial use" by the State, is a significant element involved in how water managers in the basin define efficient water use and describe the benefits of irrigation canal piping. When describing the ideal future for water conservation and irrigation efficiency in the Deschutes Basin, Phil explains how the "real" versus "hobby" farmer debate is central:

> The ideal improvement will be to pipe the Central Oregon Irrigation District, because it's the biggest irrigation district and you're going to get the most bang for your buck […] Improving Central Oregon Irrigation District's efficiency, in turn will provide water for North Unit to preserve the truly agricultural district in this basin.

Phil went on to say that the COID diverts "massive amounts of water" to irrigated agriculture, which is why improving the efficiency of canals in this district would 'save' large quantities of water. Piping COID's canals is a top priority for water managers in the basin to help support the livelihood of "true" farmers in NUID, illuminating the embedded social values in irrigation efficiency. The focus in Phil's vision for the future of water conservation in the Deschutes Basin is not on reducing the large amount of water that goes to "hobby" farming; rather it is working around the legal water right system through infrastructure to make sure that commercial agriculture has enough water.

The use of irrigation canal piping as a method to shift water to the younger priority date water users in NUID is discussed by water managers as a significant benefit of these projects in the Deschutes Basin, yet some expressed frustration with the underlying water rights system. Henry, a representative from a conservation group, described how canal piping is not enough on its own:

> So in my perfect world, we would have a policy reform that allowed water to move more flexibly…we would implement the full range of conservation alternatives, the market based incentives, the on-farm and the canal piping and we would redistribute the water accordingly. And we would restore the stream flows at least up to the minimum flows that the State has set in all the creeks and all the rivers.

Rather than only move water through the less flexible infrastructure of irrigation canal pipes, Henry's perspective highlights how surface water in the Deschutes Basin needs to be managed holistically through multiple management strategies, including changing the policy of water allocation. To Henry, the large consumption (and waste) of water by COID is a "huge equity issue", putting the "good family farms" in NUID at risk. Policy reform is the answer to this dilemma, according to Henry, because "I can't solve the river's problems very easily until we've solved the junior water right holders' problem because they have a real legitimate need."

Paul, a hydrologist for a state agency, also echoed this perspective, yet he did not have an optimistic outlook:

> The only alternative that I think has merit in terms of environmental benefit is if you just retired those lands… if you say well that doesn't make sense to support hobby farms by piping and…I get that, but I also think that the reality of it is that the districts have the right to take that water and we manage water under Oregon water law… so we could wish for a different management system, but I think it is kind of wishful thinking.

Water law is embedded in the water management system in the Deschutes Basin. Changing it is an unrealistic option to Paul because of the difficulty in initiating such a dramatic change. Sarah, a water policy expert, did not even entertain the idea of changing water rights allocations because "They ['hobby' farmers] have valid water rights. So that's kind of already passed." Even though the reality of the legal water system in the Deschutes Basin can be viewed as discouraging, many water managers in this study were hopeful that the collaboration and efficiency updates happening are a step in the right direction.

Irrigation canal piping is implemented by water managers in the Deschutes Basin as a mechanism to move water to meet societal values. Steve, a hydrologist for a conservation group, put it clearly that:

> We want to be prioritizing water uses where it meets our current societal values. And right now, some of our societal values are a little bit jumbled between water use for hobby farms versus water use for people who actually depend on it.

Steve highlighted, as others did, that the overwhelming value in this scenario is found in commercial agriculture, which supports the livelihood of residents in the Deschutes Basin. A great deal of attention is also placed in restoring the Deschutes River streamflow, but it is intertwined with economic and equity concerns within the legal water right system itself. When factoring irrigation canal piping into this equation, the leaky recharge to the groundwater system, which may provide water to shallow wells and ecosystems, is pitted against providing water to “good family farmers”, making piping a clear choice to water managers in the Deschutes Basin.

Canal piping has also been met with resistance from property owners around the city of Bend because it takes away the valued scenic amenity of visible water flowing through canals and lowers property values of homes (Cantor and Ross, 2021). However, this value was not favored by water managers in the basin, with some describing it as “nimbyism” and a “low priority.” Tom, a research hydrologist, acknowledged that water management in the Deschutes Basin involves “reconciling everyone’s values and expectations” but also stressed the importance of factoring in climate change which could disrupt societal values associated with water.

Different values are involved in debates over irrigation canal piping in the Deschutes Basin. Water managers support piping canals because it is a mechanism to move water to where it aligns best with their values. The legal water allocation system in place does not match where they believe the water should be. Most frequently, the values of concern to water managers in the Basin are habitat restoration in the Deschutes River and economic stability in commercial agriculture. Water mangers hold the power to decide which values are worth preserving and which are not.

Scale and Responsibility

When I asked the water managers in the Deschutes Basin about their perspectives on irrigation canal piping and efficient water use in the basin, the topic of scale was a frequent element in their answers. For example, Adam, a representative from a water conservation non-profit, emphasized the importance of having conveyance and on-farm irrigation efficiency improvements together:

> I think the future is using a mix of conveyance infrastructure projects that allow irrigation districts to effectively move water to where it's needed […] then when it gets wherever that is, the user is able to use it effectively and efficiently. And so that often means having on-farm upgrades happening in parallel with some of these bigger system upgrades.

The switch from flood irrigation, which is regarded as inefficient and "archaic" by many water managers in the basin, to more "modern" methods, like drip irrigation, is viewed as a necessary improvement in tandem with canal piping in the Deschutes Basin. Amelia, a conservation project manager, highlighted how irrigation efficiency on the on-farm scale is dependent on the geographic location in question because spreading water in the Deschutes Basin "makes zero sense" because that water wasn't there before humans altered the landscape. In comparison, both Amelia and Phil, a state representative, acknowledged that flood irrigation in the Klamath Basin in southern Oregon can be less of a "disaster" because of the flat topography and less porous geology allowing for the water runoff from fields to be used from one field to the next. Flood irrigation in the Deschutes Basin soaks into the porous geology before it can be used by neighboring fields, meaning it is defined as a loss because it is not being used for its intended purpose of supporting crops.

If irrigation efficiency updates do not happen at the field scale but they do occur by canal piping, Ryan, a conservation technician, argues that this creates a missing piece:

> If farmer A doesn't take it [water] out of the canal, because he's irrigating efficiently, is that water really saved if farmer B has taken it and run it out over the edge of the cliff because he's still wild flooding? Maybe that's a philosophical question that I tend to leave to others.

The analogy provided by Ryan explains how he views the efficiency of moving water across the basin through canals, or conveyance scale efficiency, to be intertwined with on-farm scale efficiency. Water that is lost at the conveyance scale is viewed in the same light as water that is lost through flood irrigation and Ryan emphasized the importance of everyone “doing the right thing” for the surface water in the Deschutes Basin to be used efficiently at the basin scale. Jane, a water policy analyst, also views on-farm efficiencies as “a big piece of the solution” to restore the Deschutes River in-stream flow. The focus on eliminating on-farm water ”waste” to the same degree as the leaky canal water highlights how both are viewed as “artificial”, or water that is not supposed to exist outside of the “natural” Deschutes River.

Yet, not all water managers in the Deschutes Basin view water “loss” in canal piping and on-farm irrigation modernization techniques as the same issue that should be solved together. John, an irrigation district representative, described how taking a stance about on-farm irrigation efficiency modernization is outside the bounds of his position:

> But it's really not our place as districts to put a definition on efficiency. You'd like to see people out there sprinkler irrigating, you'd like to see people drip irrigating…you don't really like to see the flood irrigating, although there are advantages to that. But, it's not really my place to say it's right and wrong.

John makes it clear that his irrigation district should not play a role in influencing how water is managed at the field scale, rather his responsibility "ends at the delivery gate." This highlights how the irrigation efficiency system can be viewed as fragmented, with responsibility placed on different groups at different steps in the water delivery process. Lankford et al. (2020) note how different social, political, and economic objectives exist within the multiple scales of irrigation efficiency, creating different understandings of how irrigation efficiency ought to be managed. Robert, another irrigation district representative, elaborated on this perspective:

> For us as a district, we should be helping fish and wildlife. For individual landowners, they should be helping themselves and the other members of the district. […] If somebody does an on-farm efficiency program […] I think that [water] should stay and help other patrons.

Robert views irrigation canal piping as the responsibility of the irrigation district to help the ecosystems that depend on healthy in-stream flows and the water that can be conserved by water users at the on-farm scale should be redistributed among the irrigators rather than stay in-stream in the Deschutes River.

The irrigation district representatives' lack of responsibility to enforce water conservation on the on-farm scale was a source of tension with other respondents. Henry, a representative from a conservation group, viewed the district's sole focus on canal piping as a problem:

> The senior districts who really don't have any incentive to do anything anyway, basically hold everybody over the barrel and say, "Oh […] let's do conservation together…you just bring us $100 million, we'll solve the problem for you, no problem". But these are the same districts who have zero culture of conservation within their districts about how they actually use water. […] They're not actually trying to tell people to use less water. […] In fact, they do the opposite. They go and tell people to dump water on their land to protect the water right. And it is criminal.

Henry disagrees that the irrigation districts' responsibility ends at the delivery gate and argues that they are not truly invested in conserving water, rather they will pipe canals with taxpayer money but not make an effort to change the "culture" of water use in the Deschutes Basin and even "force" water on patrons. Here, irrigation canal piping by the districts is viewed by Henry as a superficial effort of conservation, only saving a portion of the significant volume of water used by irrigators but not addressing the more fundamental issues of values and water use behavior which underly the infrastructure updates. Henry argued for multiple conservation efforts, including retiring lands and water rights, mixed with market-based approaches to meet the needs of the endangered species in the basin and restore the Deschutes River rather than only canal piping.

Jane, a water policy analyst, had a similar perspective to Henry, but instead focused her attention on the State:

> Honestly, I think its lack of political will is what it is. […] They [the State] could be setting efficiency standards by basin, and as you know, we're seeing a changing climate […] I think that there will be more and more political pressure on the State to really grapple with this because they have the authority to do it.

Rather than concentrate only on canal piping and on-farm modernization to increase the Deschutes Basin's water use efficiency, Jane saw the State's lack of "political will" to define and enforce more rigorous efficiency standards as one of the most pressing issues. Jane went on to describe how the canal piping proposed in the Habitat Conservation Plan (Deschutes Basin Board of Controls, 2019) doesn't provide enough water for the endangered species in the basin reliant on the Deschutes River. Because of this, she argues that the State should step in and manage and enforce against water "waste" rather than leaving it to the districts and irrigators to handle on their own through technology and infrastructure, once again introducing the importance of the legal water right system. Jane's call on the State to enforce more uniform water use standards illustrates the frustration some water managers are feeling in response to different definitions of efficiency used at different scales within the Deschutes Basin as well as different perspectives about who is responsible for 'saving' the water in the irrigation system.

Education

Education is intertwined with uncertainty in groundwater knowledge and scale and responsibility of irrigation efficiency in the Deschutes Basin. Water managers expressed different topics of education and different groups to which the education should be aimed at when describing how to be more efficient with water use. While irrigation canal piping and on-farm efficiency updates are a priority to water managers in the Deschutes Basin, they emphasize that without educating the public, obtaining efficiency goals may not be possible.

Some water managers in the Deschutes Basin view education as a way to ease the worries of the public who are concerned that irrigation canal piping will have negative consequences, like impacting springs, shallow wells, and ecosystems. Phil, a State representative, described how a lack of education to the public plays a role in this:

> There are also some folks that […] have a very limited background on the hydrogeology of the basin. And all they hear is that "oh, […] we're putting warm water in the river […] with this streamflow restoration and we're depleting the springs." Well, if you go back and you look at the relative magnitude of how much the recharge would be on a particular spring from a section of canal that's being piped […] it's probably less than 1/100 of a percent. So, for me it's not a very hard decision to make. But there are concerns out there… dropping the water table is a scary thing to some people.

Here, education is suggested to be used as a tool by the State to lower the concern about unintended consequences of canal piping. To the public, lowering groundwater levels in the basin as a result of irrigation canal piping provokes fear, which according to Phil, is not a necessary fear because the affects will be minimal. Yet, going back to the topic of adequate monitoring, this is up for debate.

In addition to minimizing public concern about irrigation canal piping affects in the Deschutes Basin, Bill, another scientist with the State, believes that groundwater well users need to be better educated on their own water systems. When asked about the frequency of calls to the State about dry wells, Bill explained that he hasn't heard of many except for some in the southern portion of the Deschutes Basin near Crescent, yet it is a big problem in other areas of Oregon. He went on to explain that he receives calls from well users who have lost access to groundwater and when asked basic questions about their well system (e.g. How deep is it? When was it drilled? Have you ever looked at it?) many times the well user does not know the answers. “We’re trying to educate well owners”, expressed Bill.

Along with educating well users about their system, some water managers brought up the issue of groundwater quality. When I asked about the potential risk to shallow groundwater users from piping irrigation canals and reducing recharge, the reduction in water quantity was not the sole focus. Adam, a representative from a water conservation non-profit, voiced his concern over groundwater well users currently drinking irrigation canal recharge:

> Do you really want to be drinking irrigation water? The answer is probably not. […] Unless it's very near the end of system, it's usually contaminated […] whether it's nutrients, manure, fertilizer [or] pesticides.

Some water managers used this position as another reason to support irrigation canal piping, because residents of the basin should not drink contaminated irrigation canal water. Yet, this wasn’t a universal opinion. For example, Tom, a research hydrologist, noted that drinking shallow groundwater recharged by irrigation canals is “actually fine because it’s basically river water.” Regardless of the debate surrounding the health hazard of drinking water from shallow wells near an irrigation canal, which in itself brings up an important question of access to clean drinking water in the Deschutes Basin, it was noted by Bill that he suspects most of the public is ignorant to the water quality of their shallow wells, prompting another area of needed education.

Less related to irrigation canal piping directly, water managers also urged for educating irrigators about taking steps toward water efficiency beyond irrigation efficiency. Robert, an irrigation district representative, explained how educating his patrons is an important part of efficient water use:

> What I would like to see internally to help our system probably work better is people […] growing different crops [and] finding out how much [water] they should be using per year and then only using that […] we have a lot of people that are of the old school thinking of, “well, my certificate says five and a half acre feet, I'm going to use all of it” when in reality, their crop only takes three and a half [acre feet].

The discussion around crop choice and using only the amount of water needed for that specific crop came up often when I asked water managers about what efficient water use means for the Deschutes Basin. It became clear that education is key to this process, as many water managers were concerned about irrigators using more water than is necessary. Ryan, a conservation technician, also expressed this concern, but suggested that education is needed because “irrigation districts call them [patrons] up and say you have to green this up or we’re taking your water right away.” This is in direct contrast with what Robert is suggesting that his irrigation do to educate his patrons on using less water.

The debate related to irrigation districts pushing water on patrons, which was a common theme in my interviews with water managers in the Deschutes Basin, was addressed by Jane, a water policy analyst:

> Oregon is different than a lot of the other western states…we're not a partial forfeiture state. So, as long as a district is ready, willing, and able to put the water to beneficial use […] then they don't lose their water right. […] But when you're in these discussions, even as recently as two years ago, with executive directors of irrigation groups and the Farm Bureau and other

> groups, they would say, "No, we'll lose our water". […] So long story short, I think there needs to be a lot of education on the ground on that.

Jane explained that water users in Oregon do not risk losing their water right if they are not using their full amount of water on their permit or certificate. Yet, many water managers expressed concern that irrigation districts are "forcing" their patrons to use more water than needed. Jane made it clear that education on this subject is necessary in the Deschutes Basin if water managers want to see efficient water use.

Lastly, water managers in the Deschutes Basin noted that the interconnection of surface water and groundwater, the basic principal of this study, is not as well-known as it should be. Irrigation canal piping, and other surface water conservation projects, have a direct impact on groundwater resources in the Deschutes Basin and groundwater use impacts surface water. Steve, a hydrologist, expressed that educating the public on this topic is a difficult part of his job:

> One of the biggest challenges of working in groundwater is trying to get people to understand the connection between groundwater and surface water […] a lot of our colleagues at our state agencies understand this pretty well, but it really is missing from the public perception […] It's not widely known that groundwater and surface water are the same thing.

Educating the public, and maybe even some professionals in water management, about the interconnection of surface and groundwater in the Deschutes Basin is a vital step in using water efficiently, according to Steve.

Summary

Water managers in the Deschutes Basin understand the benefits and potential trade-offs of irrigation canal piping based on both physical and social dimensions. Overall, the potential trade-offs of irrigation canal piping are not at the forefront of water managers concerns. Instead, managing water in a way that fits with the water managers' knowledge and values, which can be conflicting, is the focus of the respondents in this study. There is clearly confusion and uncertainty about how piping irrigation canals will impact the hydrologic system and increased monitoring is viewed as an important tool to both better understand the trade-offs and to reassure the public. Education is also a key element in moving the Deschutes Basin forward in efficient irrigation water use but there are conflicting views on the current level of education and monitoring occurring in the basin. Importantly, education on efficiency goes beyond canal piping. Underpinning irrigation canal piping are social values tied to economic agriculture and beliefs on "beneficial use" in the Deschutes basin, with concepts of what is "natural" water and "artificial" water, separating the system into distinct pieces. The infrastructure of irrigation canal piping is viewed as a mechanism to work around rigid water law to provide water to the uses deemed as "beneficial" by water managers. Yet, the scale at which irrigation efficiency is implemented in the Deschutes Basin and the responsible party for enforcing efficient water use is disputed and a source of tension among water managers.

Quantitative Results

Shallow Well Spatial Analysis

According to the OWRD Groundwater Information System, there are a total of 17,505 wells with a completed depth of 300 feet or shallower in Deschutes, Jefferson, and Crooked Counties, as of 2018 (see Table 2). The majority of these shallow wells are found in Deschutes County (~72%), with less concentration in Crooked County (~22%) and Jefferson County (~6%). The average completed depth of shallow wells in the three counties is 103.32 feet (see Table 3).

Table 2: Number of shallow wells (<300 ft.) in study area

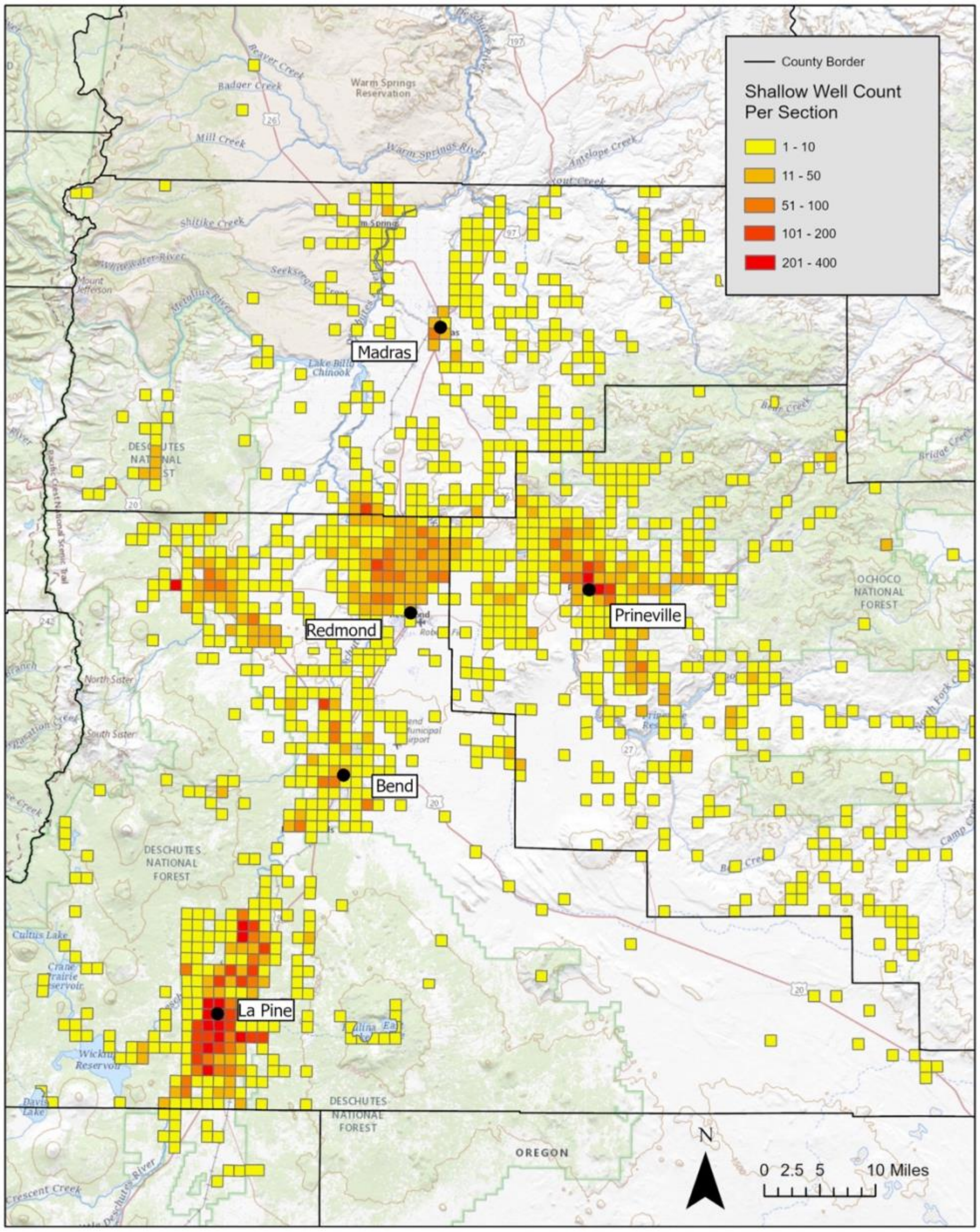
County	**Number of Shallow Wells**
Deschutes	12,609
Jefferson	1,062
Crooked	3,834
Total	**17,505**

Table 3: Shallow well (<300 ft.) depth statistics in study area*

Statistic	**Well Depth (feet)**
Average	103.32
Minimum	1.0
Median	65.00
Mode	40.00

*Three counties: Deschutes, Jefferson, and Crooked

Using sections (1x1 mile area) as the unit of analysis, Figure 6 presents the number of shallow wells within each section in the broad region of the Upper Deschutes Basin. Yellow represents the lowest concentration of shallow wells and red represents the highest concentration. A high concentration of shallow wells exist around the city of La Pine in the southern portion of the study area. There are also higher concentrations of shallow wells north of Redmond and around Prineville. Several sections around Bend, Sisters, and Madras also contain a higher number of shallow wells. Within all three counties, the number of sections (square miles) containing at least one shallow well is 1,351 (see Table 4). Specifically, 350 sections intersecting the irrigation canals contains at least one shallow well, with 149 sections intersecting piped irrigation canals and 315 sections intersecting open irrigation canals (see Table 4). Figure 7 shows a closer look at 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. There are 315 sections intersecting irrigations canals with static water level data. Sections intersecting irrigation canals around Prineville, north of Redmond, and to a lesser extent around Bend, have the highest count of wells equal to or less than 300 feet deep.



Map By: Becky Anderson on 1/7/2022

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

Figure 6: Count of shallow wells (<300 ft.) per section in Deschutes Basin Area

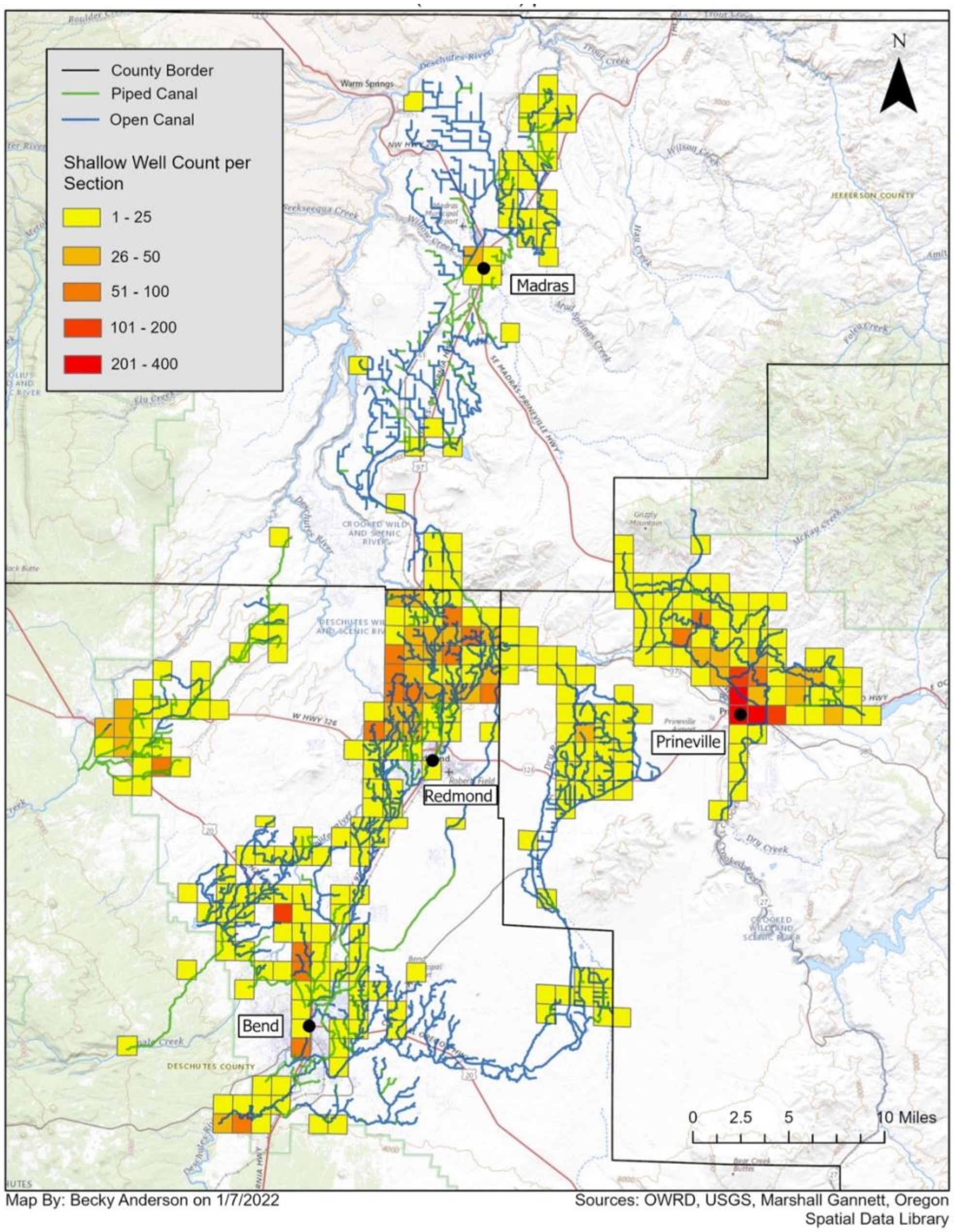


Figure 7: Count of shallow wells (<300 ft.) per section intersecting irrigation canals

Table 4: Number of sections with a minimum of one shallow well (<300 ft.)

Area	Number of Sections (1x1 mile) Containing at Least One Shallow Well
Three Counties	1,351
Intersecting All irrigation canals	350
Intersecting Piped Irrigation Canals	149
Intersecting Open Irrigation Canals	315

*Note: Sections intersecting an irrigation canal within 100 feet were included. Some sections contain both piped and open canals and thus the same section can be counted in both categories.

The vulnerability of the shallow wells in the study area, defined here as the difference in feet between the completed well depth and the static water level (also known as water table), is presented in Figures 8-11. The average difference between the shallow well depth and static water level in the larger study area is 72.55 feet. The mode value for shallow well vulnerability in the study area is 30 feet (see Table 5 for more statistics). The average vulnerability of shallow wells in each section in the larger study area is shown in Figure 8. Red sections have an average vulnerability of 0-10 feet, making them the most susceptible to going dry when groundwater levels change. Yellow sections have an average vulnerability of 101-300 feet and are the least likely to experience issues with accessing groundwater. Figure 9 presents a closer look at the average vulnerability in sections intersecting irrigation canals in the study area.

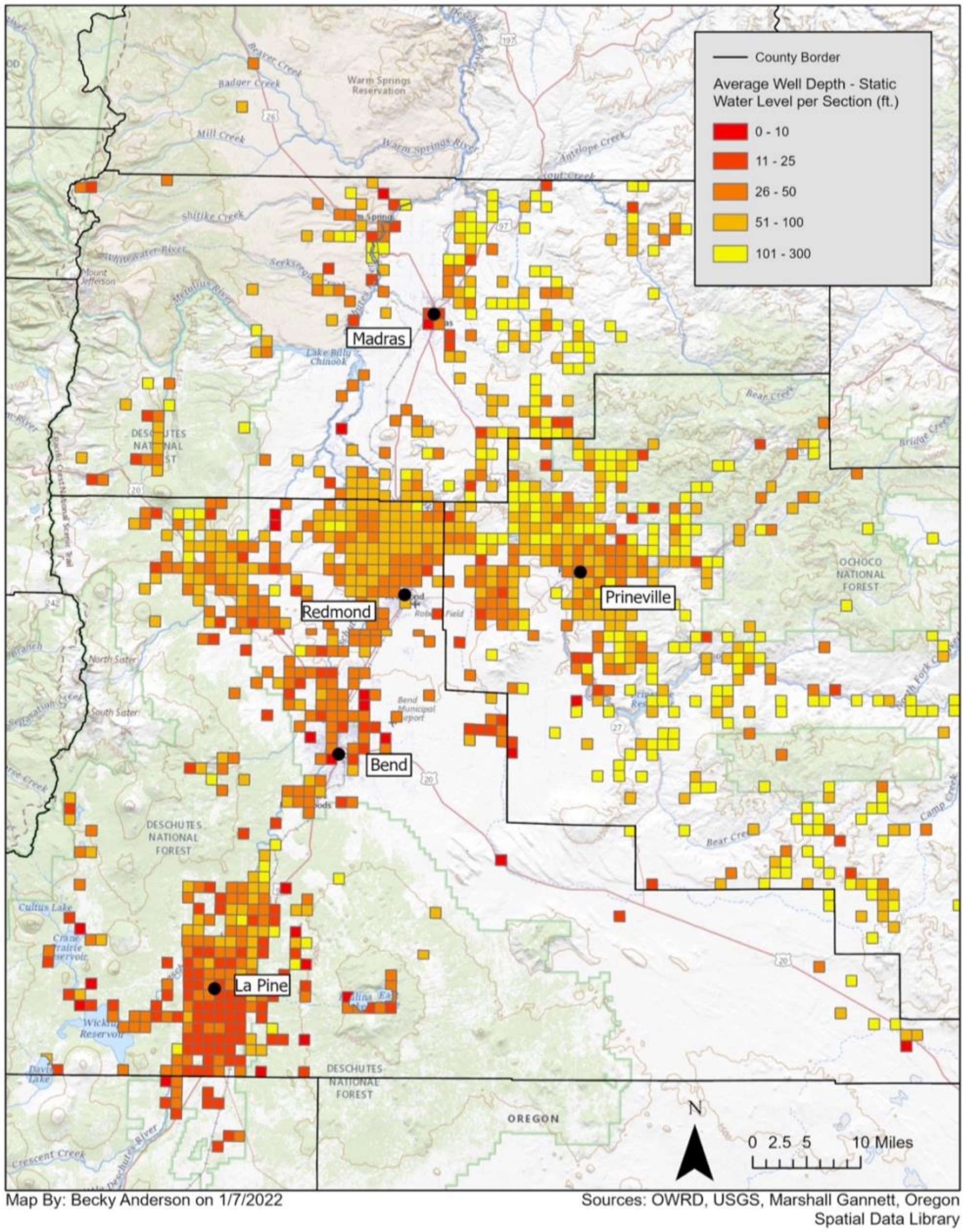


Figure 8: Average shallow well (<300 ft.) vulnerability per section in Deschutes Basin area

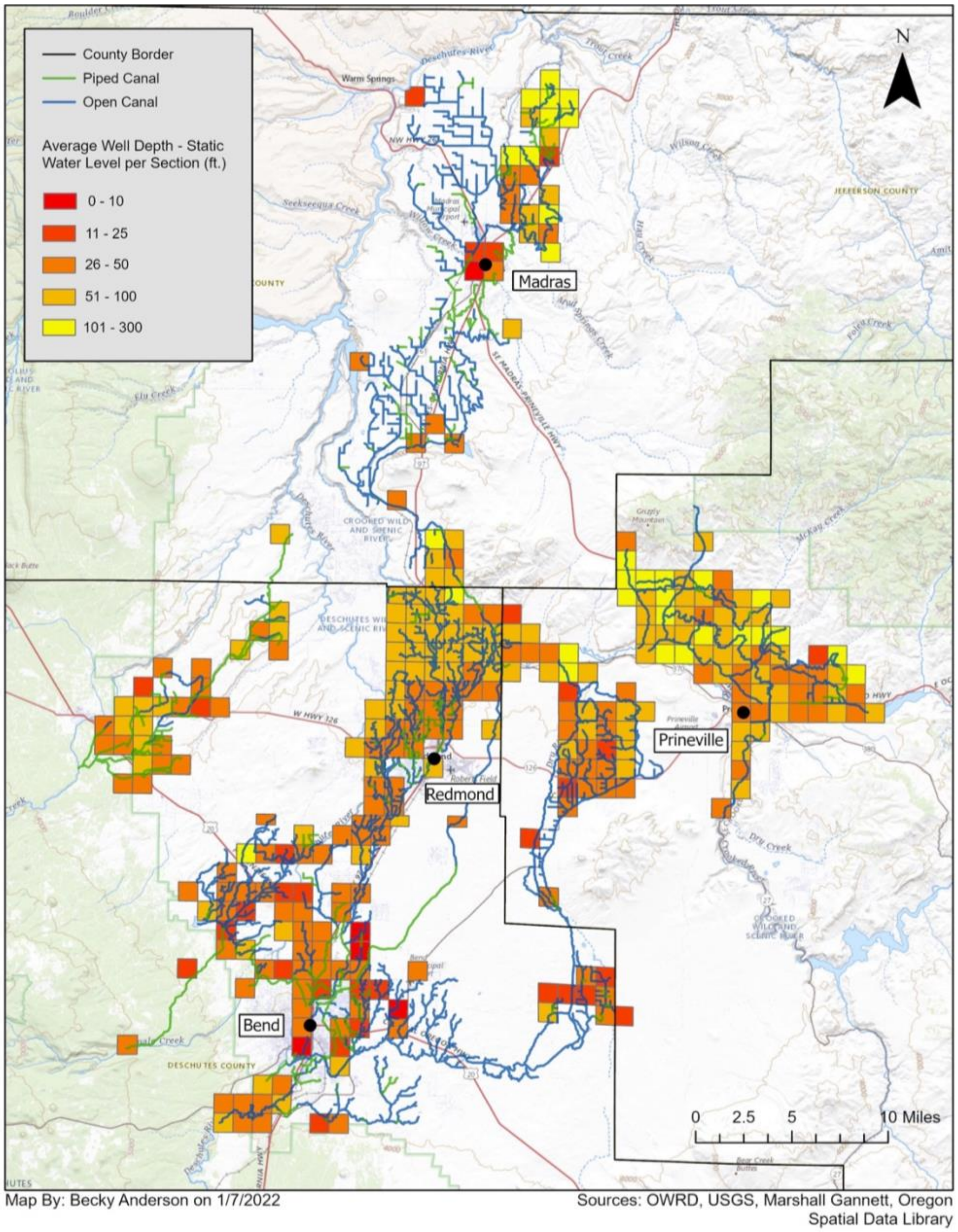


Figure 9: Average shallow well (<300 ft.) vulnerability per section intersecting irrigation canals

Within the broader study area, the average vulnerability per section is mixed, with the vulnerability seeming to decline further to the east based on the greater number of sections labeled as yellow in Crooked County (Figure 8). Bend, Madras, La Pine, and Redmond all have sections in the vicinity with high vulnerability, with sections near Bend and Madras seeming to have the highest concentration of high average vulnerability (sections with 0-10 feet difference between well depth and static water level). Looking closer at Figure 9, there are less sections with a vulnerability in the range of 101-300 and more in the range of 0-100. There are multiple sections to the east and north of Bend with an average vulnerability between 0-10 feet. To the west and north of Redmond, sections have a vulnerability in the range of 26-100 feet. Sections near Prineville also appear to have an average vulnerability in the range of 26-100 feet. Sections immediately surrounding Madras in the northern study area have an average vulnerability between 0-50 feet.

The minimum vulnerability of shallow wells in each section in the larger study area is shown in Figure 10. Red sections have a minimum vulnerability of 0-5 feet, making them the most susceptible to going dry when groundwater levels change. Yellow sections have a minimum vulnerability of 51-285 feet and are the least likely to experience issues with accessing groundwater. A section with a least one well with a minimum vulnerability greater than 50 was grouped into one category to highlight the sections with higher vulnerability (less than 50 feet). Figure 11 presents a closer look at the minimum vulnerability in sections intersecting irrigation canals in the study area.

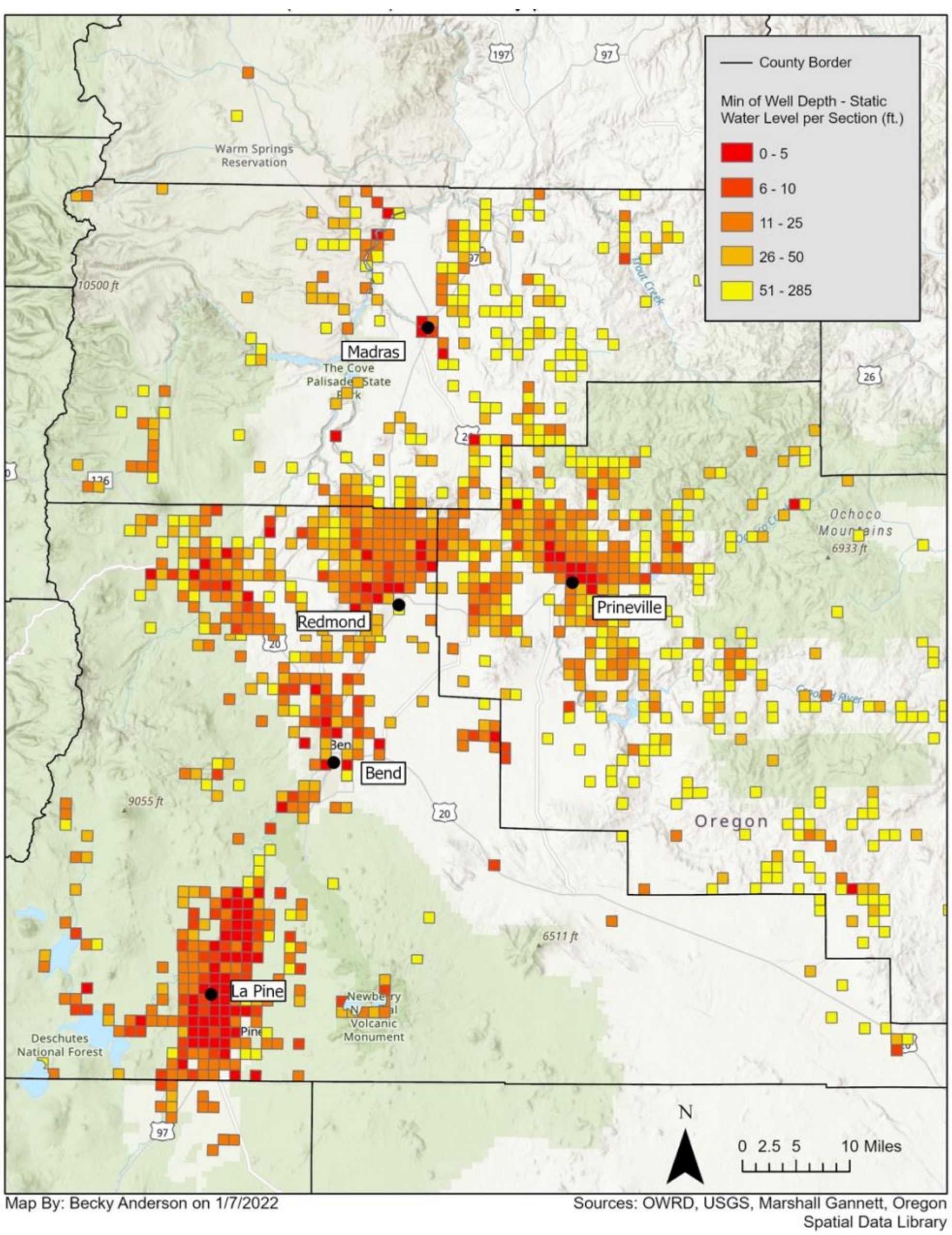


Figure 10: Minimum shallow well (<300 ft.) vulnerability per section in Deschutes Basin area

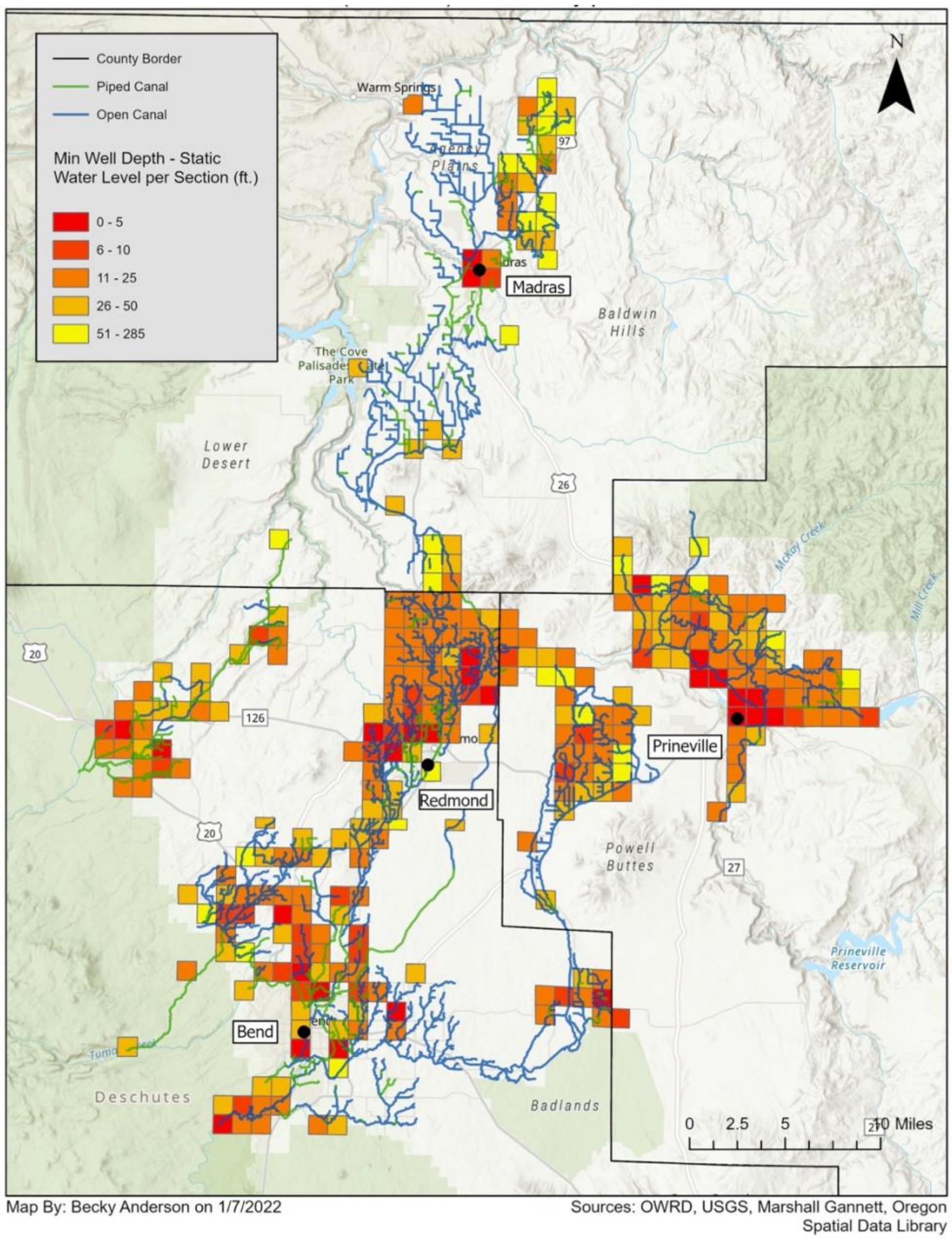


Figure 11: Minimum shallow well (<300 ft.) vulnerability per section intersecting irrigation canals

For the broader study area, the pattern matches the average vulnerability in that the minimum vulnerability of sections seems to be more severe in the eastern half of the basin, especially around the cities (Figure 10). Further east in Crooked

County past Prineville, the minimum well vulnerability is within the range of 51-285. Numerous sections around La Pine, Bend, Prineville, and Madras contain shallow wells with a minimum difference between well depth and static water level between 0-25 feet. Figure 11 provides a more detailed look at the minimum vulnerability of shallow wells intersecting irrigation canals, both piped and open. Again, it appears there is a mix of minimum vulnerability with a higher concentration of more vulnerable wells around the cities in the basin.

Table 5 presents the statistics of shallow well vulnerability in sections intersecting irrigation canals in the basin. For the average of the average vulnerability of shallow wells in sections intersecting irrigation canals, a range between approximately 51 feet to approximately 57 feet exists. For the average minimum vulnerability of shallow wells in sections intersecting irrigation canals, a range between approximately 22 feet to 32 feet exists. Table 6 presents the percentage of sections with a range of average and minimum vulnerability values near irrigation canals (total sections intersecting canals with water table data = 315). Over half (61.17 percent) of the average vulnerability in sections intersecting irrigation canals is equal to or less than 50 feet, yet only a very small percentage of sections intersecting canals have an average vulnerability equal to or less than 10 feet (2.56 percent). The majority (89.84 percent) of the minimum vulnerability in sections intersecting irrigation canals is equal to or less than 50 feet, and 49.84 percent is equal to or less than 20 feet. Approximately one fifth (18.41 percent) of sections intersecting irrigation canals have a minimum vulnerability less than or equal to 10 feet, and 8.89% have a minimum vulnerability less than or equal to 5 feet.

Table 5: Average and minimum shallow well vulnerability statistics in sections intersecting irrigation canals

	Sections Intersecting All Irrigation Canals (ft.)	Sections Intersecting *Piped* Canals (ft.)	Sections Intersecting *Open* Canals (ft.)
Average Vulnerability*			
Average	**55.83**	**51.29**	**56.83**
Minimum	0.00	8.83	0.00
Maximum	194.75	194.75	164.60
Median	49.00	44.40	49.17
Mode	50.00	50.00	50.00
Minimum Vulnerability*			
Average	**28.88**	**31.16**	**22.40**
Minimum	0.00	0.00	0.00
Maximum	162.00	162.00	283.00
Median	21.00	20.00	15.00
Mode	20.00	20.00	10.00

*Vulnerability = Well Depth (ft.) – Water Table (ft.)

Table 6: Percentage of sections intersecting irrigation canals with shallow well (<300 ft.) vulnerability

Vulnerability	≤ 5 feet	≤ 10 feet	≤ 20 feet	≤ 50 feet
Minimum Vulnerability				
Number of Sections	28	58	157	283
Percent of Sections	8.89%	18.41%	49.84%	89.84%
Average Vulnerability				
Number of Sections	3	7	21	167
Percent of Sections	1.01%	2.56%	7.69%	61.17%

*Number of sections intersecting canals (with vulnerability data) = 315 (as of 2018).

Shallow Groundwater Monitoring Data Availability

Figure 12 presents the location of shallow wells (300 feet deep or shallower) with groundwater level data that spans over a minimum of 5 years within the period of 1985-present. The well locations also have water level measurements from the same month of the year, preferably March, to avoid seasonal fluctuations. Figure 12 presents the locations of these wells based on the extent of data available. There are a total of 76 shallow wells in Deschutes, Jefferson, and Crooked County which meet the data requirements. Within 1 mile of the irrigation canals, there are 22 shallow wells which meet the data requirements. Table 7 presents the number of wells with groundwater monitoring data in the broader study area and within 1 miles of irrigation canals

The spatial distribution of shallow wells which meet the minimum requirement of data is not even throughout the study area. Shallow wells with monitoring data are clustered around Sisters in the eastern portion of the study area and Prineville to the west. Some shallow wells with groundwater data are the north around Madras and in the center of the study area near Redmond. There are no shallow wells which meet the data requirements near Bend.

Table 7: Number of shallow wells (<300 ft.) with 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 Mile of Irrigation Canals	22	1	12	9

*Deschutes, Jefferson, and Crooked

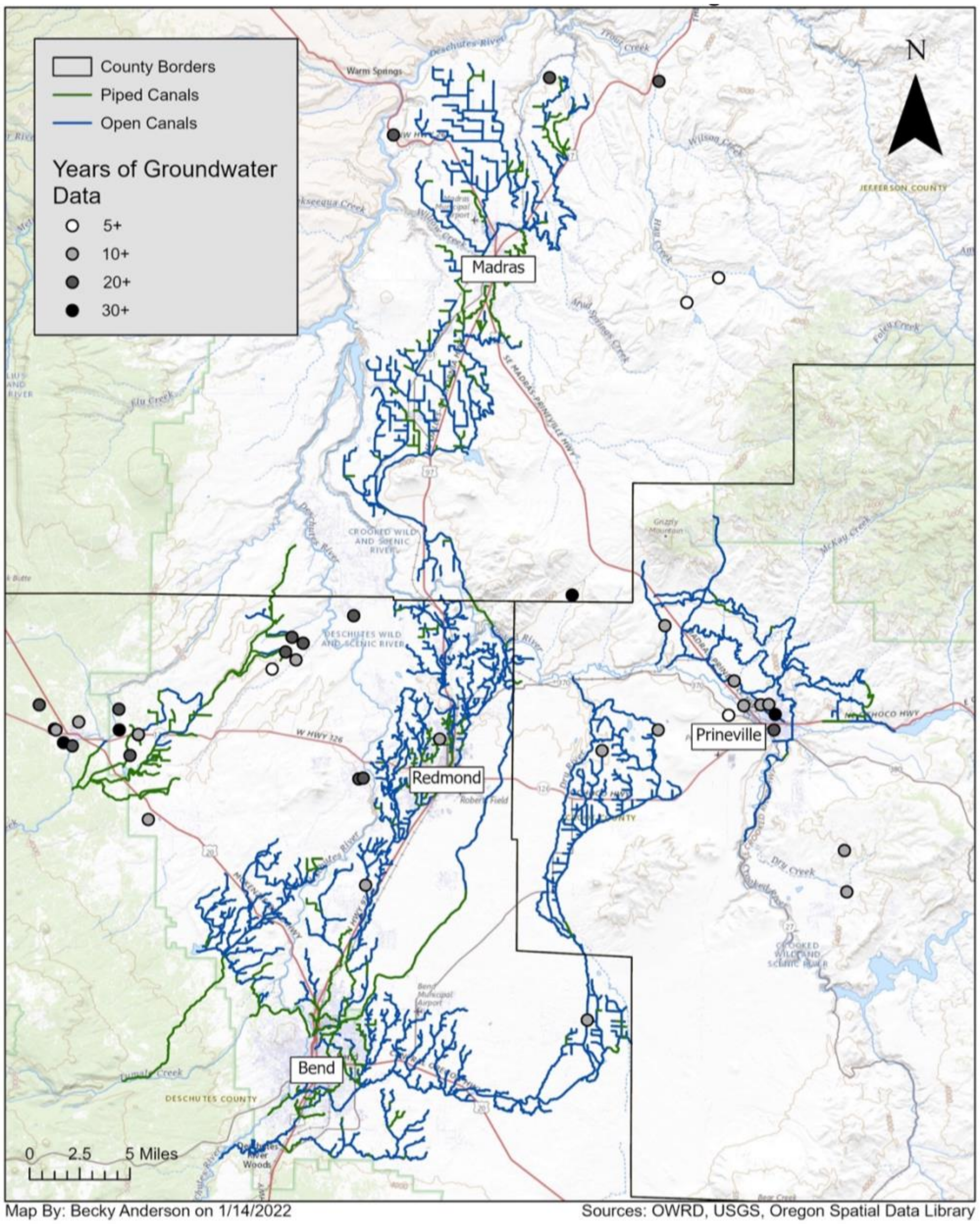


Figure 12: Location of shallow wells with monitoring data

Figure 13 presents changes in groundwater level from the first to last measurement at each of the 22 well locations which met the data requirements within 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 present. Shallow wells represented as orange, pink, and red experienced a decline in groundwater levels. It appears that the shallow groundwater levels in wells near canals around Prineville in the western portion of the study area have either experienced both increases and declines in groundwater. There are very few shallow wells near Bend, but the two closest wells, both represented as yellow on Figure 13, increased by less than one foot each. Half of the 22 wells are within 1 miles of piped irrigation canals. Of these 11 shallow wells, 7 show declining groundwater levels. The areas of the study area where groundwater changes have declined the most in proximity to piped canals is around Sisters and Redmond. Only one shallow well with adequate data exists near Redmond and groundwater declined by 51.4 feet between 2000 and 2020 groundwater at this location. Of the eight shallow wells around Sisters in Figure 13, six have declined by an average of 8.5 feet. For the rest of the study area, the spatial distribution of the wells make it difficult to discern any larger patterns in shallow groundwater levels related to irrigation canal piping, especially around Bend where the greatest number of canals have been piped. Appendix D includes a table of the groundwater level changes and the years of measurements for the 22 shallow wells near irrigation canals in Figure 13.

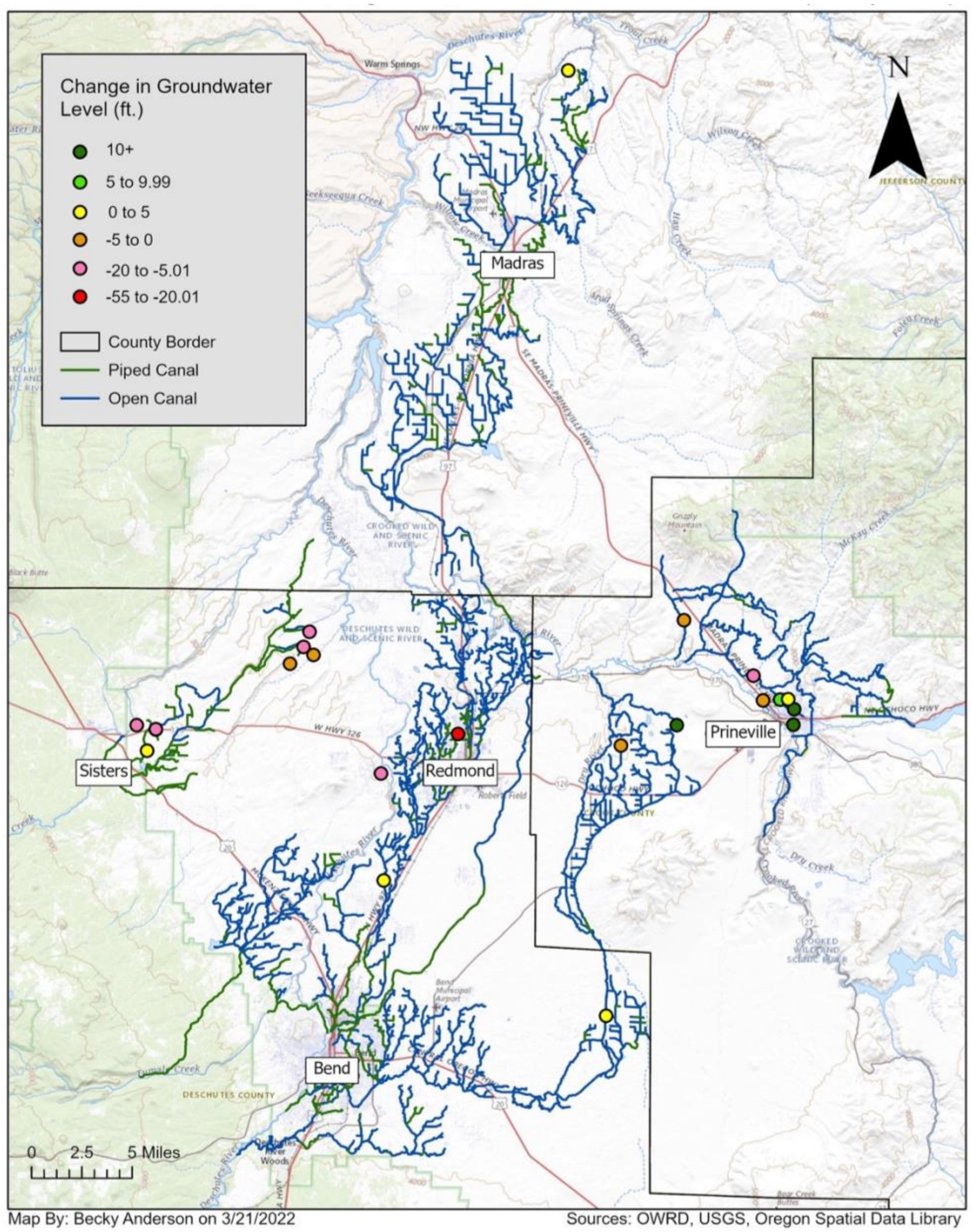


Figure 13: Shallow groundwater level change between first and last measurements (between 1985 to present)

Comparison of Shallow Well Spatial Analysis to USGS Models of Irrigation Canal Seepage Impacts

Comparing the results of the spatial analysis of shallow wells in the Upper Deschutes Basin with previous analyses and groundwater models can shed light on the areas in the study area most at risk of negative impacts to shallow wells from irrigation canal piping. 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 includes canal piping up to 2008, which is a limitation considering the irrigation canal data set used in the figures above was updated in 2018 after significantly more canals had been piped. Regardless, utilizing previously run groundwater model simulations is a useful tool to predict areas of greatest shallow well vulnerability.

Below are two figures of the model simulations: Model 1 and Model 3. Model 1 presents the simulated water level changes in the first 100 feet below the water table (Figure 14) and Model 3 simulates the water level changes deeper in the aquifer system between 200-300 feet below the water table (Figure 15). These maps were created by subtracting 2008 water levels from model runs which held post 1994 canal leakage at the 1994 rate (Gannett and Lite, 2013). Also included in the maps is the estimated decreases in annual canal leakage due to irrigation canal piping in acre-feet per year for each segment of canal. The shallow well spatial analysis above (Figures 6-13) only included wells that are 300 feet or shallower and the average water table is approximately 60 feet. Most of the shallow wells in the above analysis would only be affected by changes in the first 100 feet of the water table while others may feel the effect of deeper water level changes in the aquifer at 200-300 feet below the water table.

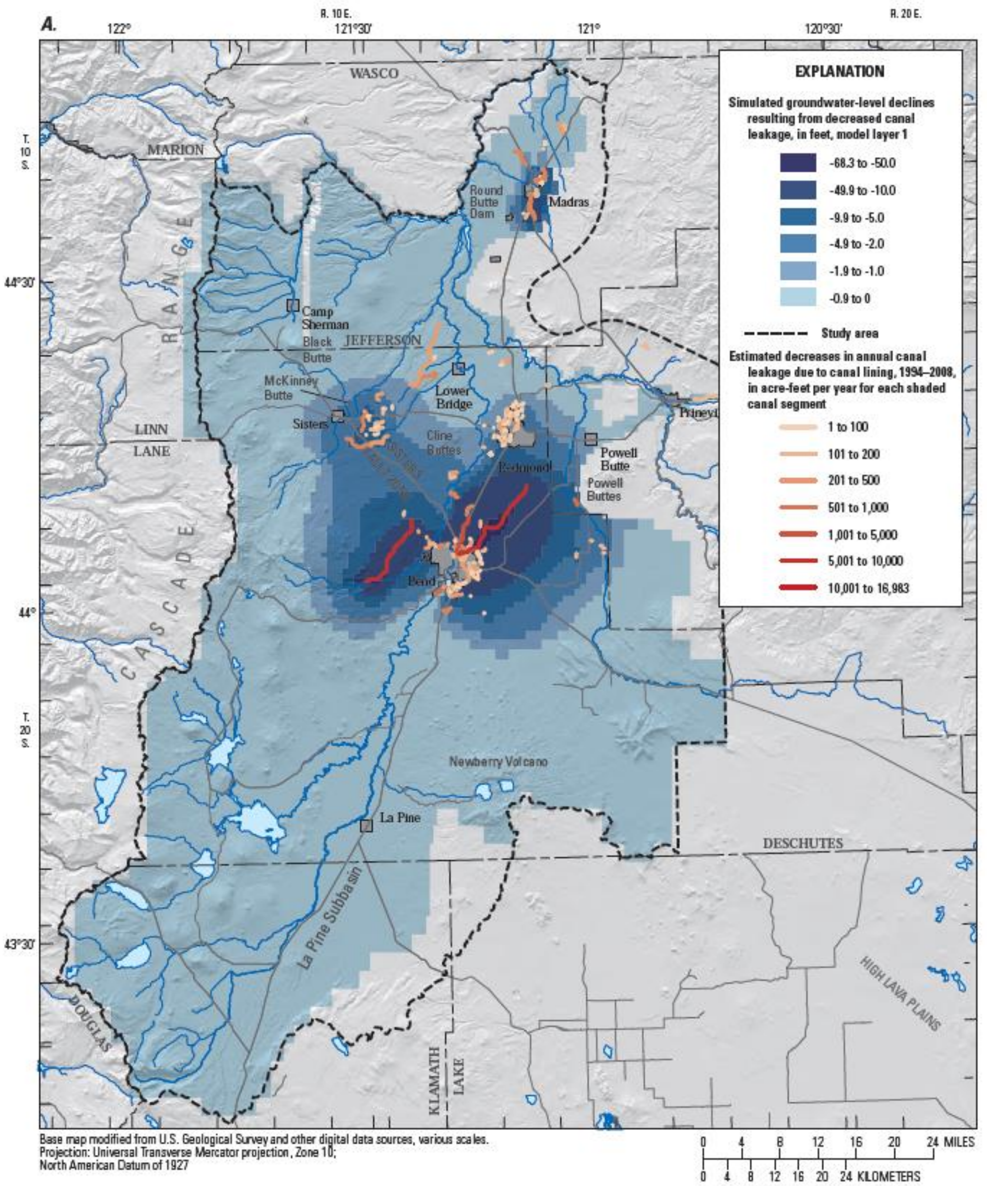


Figure 28. Upper Deschutes Basin, Oregon, showing estimated decreases in annual canal leakage due to canal lining between 1994 and 2008, and simulated groundwater-level declines resulting from decreased canal leakage. (*A*) model layer 1; (*B*) model layer 3.

Figure 14: USGS Upper Deschutes Basin Groundwater Model 1 - Canal Piping Impacts (from Gannett and Lite, 2013)

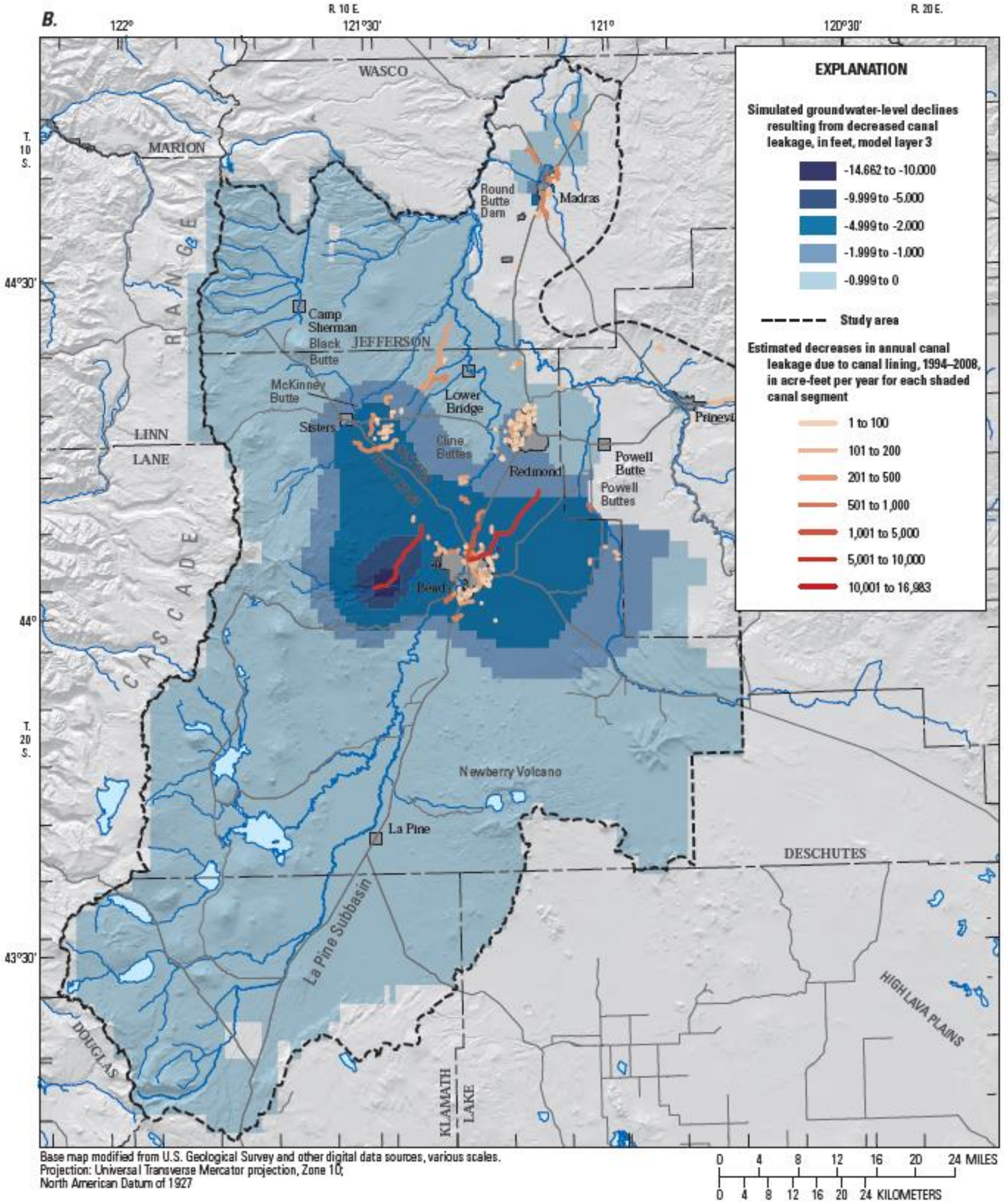


Figure 28.—Continued

Figure 15: USGS Upper Deschutes Basin Groundwater Model 3 - Canal Piping Impacts (from Gannett and Lite, 2013)

Model 1 (Figure 14) shows that simulated groundwater level declines in the first 100 feet of the water table resulting from decreased canal leakage are between 0 to 68.3 feet, with greater declines closer towards canal segments near

Bend. In the region between Sisters, Redmond, and Bend, the model simulated a groundwater decline of approximately 5 feet. Further towards Bend, the simulated groundwater decline increases. Area just northeast and northwest of Bend are shown to decline by 10 to 50 feet, with the most severe simulated groundwater decline resulting from canal piping occurring northeast of Bend. The model also simulated significant groundwater level decline around Madras in the northern portion of the study area.

I compared these results to Figure 6 and Figure 7 and found that there are a significant number of sections with shallow wells in between Sisters and Bend and between Bend and Redmond, but few to the northeast of Bend, where the greatest groundwater level declines were simulated to occur. In ArcGIS Pro, I selected the sections roughly between Sisters, Redmond, and Bend to find approximately 4,000 shallow wells in this area of the study area within 273 sections. In the northern study area near Madras, there are approximately 230 shallow wells within the area with greater simulated groundwater level decline due to canal piping.

I then compared Figure 14 to Figure 8 and Figure 9, to determine where the vulnerable shallow wells are in Upper Deschutes Basin in relation to the USGS simulated groundwater decline from canal piping. The majority of the sections between Sisters, Redmond, and Bend have an average vulnerability (well depth – static water level) between 0-50 feet with higher average vulnerability around Bend. The most at risk area appears to be to the northeast and northwest of Bend, where there are many sections with average vulnerability between 0-50 feet within the area in Figure 14 where the simulated groundwater decline is between 5 to 68.3 feet. The sections with shallow wells around Madras also have an average vulnerability between 0-50 feet and are within the area where simulated groundwater decline in the first 100 feet of the water table is between 5 to 68.3 feet. The same pattern can be seen when comparing the simulated groundwater decline from model 1 with the minimum vulnerability in each section with shallow wells in the study area (Figure 10 and Figure 11). Within the area around Bend, Redmond, and Sisters, there are 24 sections with a minimum well vulnerability equal to or less than 5 feet (~9%), 53 sections with a minimum well vulnerably equal to or less than 10 feet (~20%) and 141 sections with a minimum well vulnerability equal to or less than 20 feet (~52%) (See Table 8 for details of minimum and average vulnerability of wells in sections around Bend, Redmond, and Sisters). This means that at a minimum, 24 sections contain at least one shallow well that would be predicted to go dry (or already has gone dry) based on the USGS model in the area between Sisters, Bend, and Redmond. The area simulated to decline by 5 to 9.9 feet in Model 1 (Figure 14) covers a large portion around Bend and south of Redmond, meaning another 53 sections contain at least one well that is at risk of going dry.

Table 8: Percentage of sections between Bend, Redmond, and Sisters with shallow well (<300 ft.) vulnerability

Vulnerability	≤ 5 feet	≤ 10 feet	≤ 20 feet	≤ 50 feet
Minimum Vulnerability				
Number of Sections	24	53	141	249
Percent of Sections	8.79%	19.42%	51.65%	91.21%
Average Vulnerability				
Number of Sections	3	7	21	167
Percent of Sections	1.01%	2.56%	7.69%	61.17%

*Total number of sections in this area = 273

Model 3 (Figure 15) shows that the deeper simulated groundwater level declines as a result of canal piping (between 200-300 feet below water table) are more subdued between 0 to 15 feet, with declines becoming greater closer towards canal segments near Bend. Similar patterns can be seen when comparing Figures 6-11 to Figure 15, with the exception that the greatest simulated groundwater decline is to the west of Bend rather than to the northeast of Bend. There are not many, if any, sections with shallow wells in this area of greatest simulated groundwater decline (Figure 6). Still, a significant number of sections are within the region between Sisters, Redmond, and Bend, as discussed above. Those sections with an average vulnerability or minimum vulnerability less than 5 feet would be at risk of going dry based on the USGS model results.

Lastly, I compared Figures 12 and 13 with Figure 14 to determine the extent of shallow groundwater monitoring in the areas with greater simulated groundwater decline due to canal piping. I found that there is a limited amount of shallow groundwater monitoring data in the areas with the greatest simulated decline between Sisters, Redmond, and Bend and also in the northern study area near Madras. There are 11 wells with a minimum of 5 years of groundwater level data within the region with higher simulated groundwater decline due to canal piping between Sisters, Redmond, and Bend in Figures 12 and 13. No shallow ground water wells with monitoring data are located near the simulated groundwater decline around Madras.

Summary

There are a significant number of shallow wells (300 feet or shallower) in the three counties within the Deschutes Basin. In terms of spatial distribution nearby irrigation canals, the sections with the greatest concentration of shallow wells are around Prineville, north of Redmond, and around Bend (see Figure 6 and Figure 7). The average and minimum vulnerability (completed well depth – static water level) of sections near irrigation canals are somewhat randomly spatially distributed, appearing to be higher around the cities in the basin (Bend, Madras, Redmond, Prineville, and Sisters). Over half (61.17 percent) of the sections with shallow wells which intersect irrigation canals have an average vulnerability equal to or less than 50 feet. Approximately half (49.84 percent) of the sections with shallow wells which intersect irrigation canals have a minimum vulnerability equal to or less than 20 feet. There are only 22 shallow wells within 1 mile of irrigation canals that have adequate groundwater monitoring data (see methods) and the average change in water table is a decline of 2.82 feet. It is not feasible to determine basin-wide or localized trends in shallow groundwater due to the lack of monitoring data publicly available from OWRD, but it appears there are visible declines in shallow groundwater nearby the piping occurring north of Redmond and around Sisters (see figure 13). When comparing USGS simulated shallow groundwater changes as a result of canal piping, it becomes clear that the area between Bend, Redmond, and Sisters, as well as around Madras, likely already did or will experience groundwater declines. These declines could impact up to approximately 4,230 shallow wells.

Discussion

Irrigation efficiency piping and the Deschutes' hydrosocial changes

Irrigation canal piping in the Upper Deschutes Basin has been studied by the USGS through the Upper Deschutes Basin Groundwater Model (Gannett and Lite, 2013), and more recently by using GSFLOW integrated model (Gannett et al., 2017), both of which predict changes in the hydrologic system as a result of canal seepage. This impact on groundwater is estimated to be responsible for 10 percent of the overall groundwater decline in the central portion of the basin (Gannett and Lite, 2013). With the knowledge that canal piping will have an impact on the interconnected hydrologic system, water managers in the Upper Deschutes Basin incorporated social factors beyond the physical, scientific data of canal piping when defining 'efficiency' and 'beneficial use' and when describing their views on the trade-offs involved in canal piping. Studying irrigation canal piping through a critical, hydrosocial and scale-based framework revealed diverse social, political, and hydrologic perspectives on the Upper Deschutes Basin irrigation system (Lankford et al., 2020). The following discussion highlights how irrigation canal piping changes the hydrosocial cycle and territory of the Upper Deschutes Basin, and contributes to an understanding of how irrigation efficiency is situated within broader goals in water management and the ways in which irrigation efficiency benefits as well as overlooks specific water users.

Natural water discourse

Irrigation canal piping in the Upper Deschutes basin reconfigures the physical flow of water according to social values and discourses surrounding water use. Water managers in the Upper Deschutes Basin devalue ‘artificial’ canal seepage while valuing water in the ‘natural’ Deschutes River system, creating a dichotomy between the two types of water and at the same time raising questions about how to best manage such a system. The effort to distinguish between water paths that are ‘natural’ and ‘artificial’ by water managers in the Upper Deschutes Basin has the intention of restoring ecological function of the river system, which aligns with what Gleick (2000) refers to as the “changing water paradigm” which incorporates ecological value into water management. Yet, the act of managing water for a ‘natural’ system in the Upper Deschutes Basin separates humans from nature, preserving the modern hydrological cycle (Linton, 2008), which is commonly understood to be a neutral scientific concept but has been critiqued as a social construct with political consequences (Linton and Budds, 2014). The separation of the hydrologic system into ‘natural’ and ‘artificial’ categories goes against the encouragement of a hydrosocial hybridity lens (Linton and Budds, 2014), which acknowledges that water and society are internally linked rather than external factors separate from one another (Swyngedouw, 2004). Crifasi (2005) emphasizes the importance of understanding perceptions of ‘natural’ freshwater ecosystems and the definitions used to describe them because they influence the ways hydrosocial hybrid systems are viewed and managed. In the Upper Deschutes Basin, returning water to the Deschutes River by piping canals is described by most water managers as synonymous with returning water to the ‘natural system’, which has many benefits for the Deschutes River, yet this perspective may overlook the heavy human influence on the river system by way of dams, storage, and irrigation water diversions (see Figure 4 in results) and in doing so, places the attention on irrigation canal seepage as the primary type of ‘artificial’ water in the basin.

Perceiving water as ‘natural’ or ‘artificial’ in the Upper Deschutes Basin influences the support of canal piping by water managers for the purpose of restoration and conservation, specifically for the endangered species in the basin. At the same time, this discourse puts some water users in the basin, like shallow domestic well users and groundwater dependent ecosystems, at risk of being devalued because of their reliance on ‘artificial’ water supply. As discussed in the results section, there are over 17,000 shallow wells in the three counties within the larger Deschutes Basin and approximately 4,230 wells within the areas simulated by The Upper Deschutes Groundwater Model (Gannett and Lite, 2013) to experience aquifer declines as a result of canal piping. Fifty percent of the sections within the area around Bend, Redmond, and Sisters have a minimum well vulnerability equal to or less than 20 feet, and 20 percent of the sections have a minimum well vulnerability equal to or less than 10 feet. This means hundreds, if not thousands, of shallow wells in the areas simulated by the USGS model (Gannett and Lite, 2013) to be most impacted by canal piping are at risk of going dry if aquifer levels drop as simulated. When looking at all of the sections intersecting irrigation canals beyond the areas in the model (see Figure 9 and

Figure11), I found that the average vulnerability across all sections interesting irrigation canals is 55.83 feet. This value implies that only a very large decline in groundwater evenly across the entire study area would impact the average shallow well, but almost 10 percent of the 315 sections intersecting irrigation canals have a minimum vulnerability of only 5 feet. This means there are a considerable number of shallow wells in the Upper Deschutes Basin that face negative consequences of shallow groundwater decline, especially in the areas north of Redmond, around Bend, and around Prineville. If water managers in the Upper Deschutes Basin choose water management projects based on an understanding that canal seepage is 'unnatural' but the dammed Deschutes River and irrigated agriculture in the desert are part of a 'natural' system, then shallow well water users, who are already vulnerable to future water uncertainties (e.g. drought and climate change), are placed in an even more vulnerable position. This raises concerns about equity and access to water in an arid basin in the Anthropocene, where most water is in some way regulated by humans.

The Upper Deschutes Basin's irrigation system is a part of what Swyngedouw (2009) calls a socio-physical construction which is "actively and historically produced, both in terms of social content and physical-environmental qualities" (p. 56). The process of socio-environmental change is rarely neutral, increasing the sustainability of some social groups or environments while undermining others (Swyngedouw, 2009). Using a hydrosocial lens helps to shed light on the importance of looking at irrigations systems and irrigation efficiency in the Upper Deschutes Basin in a holistic, hybrid way to better prepare for and mitigate the unintended consequences of canal piping. This is especially important to the water users, both shallow wells and ecosystems, who are potentially reliant on water that is considered ‘artificial’ water and to better understand the underlying values and motives for fragmenting the irrigation system into ‘natural’ and ‘artificial’ segments.

It is also important to situate the ‘natural’ versus ‘artificial’ water use discourse surrounding irrigation canal piping within the broader social, cultural, and economic transitions occurring in the larger Deschutes Basin. From an exurban political ecology lens, Olson (2016) describes the changing landscape of the Deschutes Basin over the last 50 years, from “an economy based on timber production to one centered on amenity development and outdoor recreation” (p. 132). Restoring the Deschutes River is driven by the critical condition of the river itself and the resulting endangered species, but outdoor recreation and amenity tourism are an increasingly important part of Central Oregon’s economy (Vineyard, 2021). While this wasn’t the main focus of this research, another significant approach to understanding the binary between ‘natural’ and ‘artificial’ may be traced to the changing idylls at the urban-rural interface.

Values and tensions motivating canal piping

By interviewing the actors in the Upper Deschutes Basin with the power to make water resource decisions, I was able to uncover not only the discourses underpinning irrigation efficiency canal piping occurring in the upper portion of the basin, but also the political and economic values which dictate the support for canal piping infrastructure. Lankford et al. (2020) described ten entry points or motives in irrigation efficiency, including but not limited to hydrological, economic, social, and political. Water managers in the Upper Deschutes Basin greatly value conserving water for the Deschutes River ecosystem to restore the hydrologic system and critical habitat, but supporting economic agriculture in NUID, who have some of the youngest water rights in the basin, is also a vital component of their definition of efficient water use. The focus on securing water for "economically viable" uses reflects how water moves "increasingly in accordance with flows of capital" (Linton and Budds, 2014). According to water managers, water in the Upper Deschutes Basin should go to the 'real' farmers and not the 'hobby' farmers (see Figure 5 in results), emphasizing how economic commercial agriculture is valued while using older irrigation water rights for non-economic purposes is devalued. In a future where there may be less water, the desire to put the water to the most 'beneficial' use makes sense to support the livelihood of farmers in the basin while also conserving the 'non-beneficially' used water for the Deschutes River, yet canal piping is only a piece of the complex struggle to reconfigure the hydrosocial cycle to meet the needs of multiple water users.

Water managers in the Upper Deschutes Basin expressed frustration and tension around the legal water right system, specifically prior appropriation. The surface water rights on the Deschutes River which go to 'hobby' farms and commercial agriculture are technically both considered 'beneficial' use by the State, yet one is viewed as waste by water managers. This aligns with Hiner's

(2016) observation that legal aspects and the ethical-ecological elements which are not covered by law (e.g. what is perceived as fair resource use) can clash in contested ecologies at the rural-urban fringe. The act of piping irrigation canals in the Upper Deschutes Basin is a way to physically move water to where it is valued without changing the legal system in place, which many water managers noted how changing the water right system is “wishful thinking”, or not a realistic approach to conserving water. In this sense, irrigation canal piping reconfigures the hydrosocial territory (Boelens et al., 2016) of the Upper Deschutes Basin by shifting the water flow through technology based on socio-economic and cultural-political factors motivated by tensions around which type of water use fits within the rural landscape (Hiner, 2016).

The goal of delivering a small portion of the conserved water from canal piping to the NUID farmers reflects the values of the water managers in the Upper Deschutes Basin, one of multiple social scales involved in the hydrosocial network. The concerns that have been expressed by the public about the declining aquifer levels and decrease in spring recharge due to canal piping were not high on the list of priorities of water managers in the Upper Deschutes Basin because maintaining the ‘artificial’ water, or in other terms the ‘wasted’ water, is not part of the projection for the organization of the hydrosocial territory (Boelens et al., 2016). This is because the canal seepage is not a part of the water managers’ vision for “ways of patterning local livelihoods, production and regional economic and socionatural development” (Boelens et al., 2016, p. 5). In a political ecology study of waste and resource use efficiency in California, Cantor (2017) showed how “waste or unreasonable use” of water are situational and subjective concepts, but the water users, both human and non-human, who rely on the material flows of water that are labeled as waste face having “their lives and livelihoods marginalized” (p. 1205). In an effort to reorganize the hydrosocial cycle and territory in the Upper Deschutes Basin, water managers encourage irrigation canal piping to improve the livelihood of both human and non-human water users, while at the same time marginalizing others by defining certain water uses as waste, and in doing so neglects “water’s complexity and relationality” (Cantor, 2017, p. 1204).

Another source of tension among water managers in the Upper Deschutes Basin is the lack of uniform efficiency rules and regulations, or even uniform conservation “ethics.” This was closely related to frustrations about which actors in the basin are responsible for implementing efficiency updates. Some respondents were frustrated with other water managers for using large sums of public money to pipe canals but not encourage conservation in other ways. The scale of irrigation efficiency (e.g. on-farm updates vs. conveyance updates) was viewed differently by water managers in the Upper Deschutes Basin, with some emphasizing the need for the two to be implemented in parallel to conserve as much water as possible for the Deschutes River ecosystem. Others, namely the irrigation district representatives, held the position that the water conserved by on-farm efficiency updates should be used among the irrigators rather than being conserved as in-stream flow. This discrepancy highlights how the water ‘lost’ at different physical scales of irrigation efficiency in the basin are attached different meanings by different actors. This aligns with Perry's (2007) argument that the meaning of water use efficiency is not applied uniformly in irrigation systems, resulting in confusion.

The differing views on the meaning of efficiency and how canal piping fits within the larger goals of irrigation efficiency in the Upper Deschutes Basin introduced conflict about which groups are responsible for implementing and enforcing efficient water use. One of the respondents from an irrigation district described their responsibility "ending at the headgate", while other water managers expressed frustration with the ways in which water is used after it reaches the headgate and the ways in which irrigation districts enforce the wasteful use of water. When hydrosocial territories are transformed, as is happening in the Upper Deschutes Basin through canal piping, "scales and the ways they connect require continual re-production and are therefore subject to negotiation and struggle" (Boelens et al., 2016, p. 5). The physical scale of irrigation efficiency, as well as the social scales involved in making canal piping decisions, are not currently aligned in the Upper Deschutes Basin, resulting in the clash between different water users and actors. Canal piping is only a piece involved in the multi-scalar, complex irrigation efficiency goal in the Upper Deschutes Basin. The potential trade-offs resulting from the elimination of groundwater recharge was not as much of a concern to water managers in comparison to finding agreement on which part of the system need attention and who is responsible to implement the changes.

Groundwater monitoring and education: neutral or political?

Groundwater monitoring is an important part of understanding canal piping according to water managers in the Upper Deschutes Basin, yet there was not clear agreement about the reasoning for monitoring and the scale at which to collect data. Intertwined with groundwater monitoring was education, which was also a topic that water managers had different perspectives on. Groundwater monitoring was discussed as a need to both ease the worry of the public (e.g. concerns of dry wells or loss of ecosystems) and to determine what the real impact currently is and will be in the future with continued canal piping in the Upper Deschutes Basin. A few water managers even stated that monitoring is necessary so that the trade-offs of canal piping can be mitigated against and strategies can be included in the permitting process to address water users that are negatively impacted. The high cost of deepening a groundwater well was addressed by some respondents in this study, which emphasized the equity and environmental justice implications of irrigation efficiency trade-offs. The view that the potential negative consequences of canal piping should be better understood and proactively mitigated against aligns with the call by Sadoff et al. (2020) for integrative approaches that identify and minimize trade-offs in water management.

Minimizing unintended consequences is ideal in water management, but in the Upper Deschutes Basin, there does not appear to be a straightforward way to go about this with irrigation canal piping. An important factor contributing to this is the lack of consensus among water managers about the scale at which groundwater monitoring should be collected. Irrigation canal piping effects will likely be very localized in the basin nearby the canals themselves (Gannett and Lite, 2013). Some interviewees felt that the current scale of groundwater monitoring in the Upper Deschutes Basin is adequate, while others noted that the small-scale changes in aquifer levels, especially the shallow aquifers, are not well understood. While not a common response by water managers, the concept of collecting more groundwater data to prove to the public that there will be very little, if any, trade-offs due to canal piping came up in the interviews. This viewpoint showcases how water managers can have individualized understandings of the hydrological processes involved in canal leakage, regardless of the availability of monitoring data as evidence. The use of groundwater monitoring at specific scales of interest or as a way to validate an existing belief about the hydrological system can be power-laden and political (Foucault, 1980; Boelens and Vos, 2012).

The spatial analysis I conducted of shallow wells with groundwater monitoring data from ORWD's Groundwater Information System shows that there is a serious lack of groundwater data in the study area, especially near the irrigation canals and also in the areas predicted to experience the most intense effects of irrigation efficiency. Some localized patterns can be detected around Prineville and Sisters (see Figure 13), but overall, small-scale changes in the shallow aquifer system likely go unnoticed by the current monitoring system in place, especially around Bend and Madras where more piping has occurred. In proximity to piped canals, the limited data that does exist show significant declines in groundwater around Sisters and Redmond (see Figure 13 and Appendix D). 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 has the potential of impacting a significant number of shallow wells, as described in the previous sections. For some water managers in the Upper Deschutes Basin to view increased groundwater monitoring as a means to reinforce an individualized understanding of a hydrologic system with a clear lack of data highlights the "political-strategic nature of truth production" described by Foucault (1980) which includes factors like methods of observation and the procedures for investigation (Boelens and Vos, 2012, p. 17). Boelens and Vos (2012) describe that there is a conflict over truth in the field of water control and that truth claims are "used politically, but also work unconsciously" (p. 18). In the Upper Deschutes Basin, the lack of monitoring of shallow groundwater does not appear to be an entirely neutral, a-political act yet it also is not something water managers are actively doing, either.

The lack of shallow groundwater data does not come as a surprise after uncovering the values and discourses embedded in efficient water use and canal piping in the Upper Deschutes Basin. The seepage from irrigation canals is viewed as 'artificial' and water lost to the seepage is not going towards the most valuable water uses in the basin, potentially leading to it being under monitored. Also, a lack of a clear and universal understanding of what efficiency means to water managers in the Upper Deschutes Basin, as discussed above, opens the door to varying levels of attention and monitoring of irrigation water use at different physical scales, raising specific research policy question while hiding others (Lopez-Gunn et al., 2013; Lankford et al., 2020). The debate on the amount of shallow groundwater monitoring in the Upper Deschutes Basin, and the purpose it should serve, is an important factor when analyzing how water managers understand water use efficiency and trade-offs related to canal piping. By drawing on Lankford et al.'s (2020) irrigation efficiency scale-based framework, I found that the social factors embedded in water managers' perspectives on irrigation efficiency canal piping have likely contributed to the lack of shallow groundwater data in the Upper Deschutes Basin, corroborating the authors' viewpoint that debate around efficiency has "hampered fuller research and monitoring of IE [irrigation efficiency]" (p. 17).

Alongside monitoring, water managers in the Upper Deschutes Basin also encouraged increased education about efficient water use to achieve efficiency goals. Yet, like monitoring, there were different education points and different groups in the basin as the target, including residents, like domestic well users, and even water managers themselves. Similar to monitoring, some water managers view educating the public about the hydrologic system and the prediction that canal piping plays a smaller role than climate and pumping when it comes to groundwater decline (Gannett and Lite, 2013) as a way to ease the public's worry. The discussion on education went beyond only focusing on the trade-offs of canal piping to water use more broadly in the Upper Deschutes Basin. There is tension among water managers about the actors in the basin who are not educating the public enough about conserving irrigation water, which revolves around the issue of using up the full water volume on irrigators' legal water rights, even if their crop, or pasture, doesn't require all of it. The "use it or lose it" culture is embedded in the Upper Deschutes Basin water culture, even though one water manager pointed out that Oregon is not a partial forfeiture state, meaning that water users will not lose their water right if they do not use all of the water. Some respondents noted that specific groups, namely irrigation districts, still encourage irrigators to use more water than necessary to maintain their water right, while the irrigation district representatives I spoke to are aware of and thinking about how to educate their patrons about using only the water that their crop needs.

The different perspectives and conflicting views on knowledge, monitoring, and education about efficient water use in the Upper Deschutes Basin among water mangers aligns with the prior discussion about tensions around responsibilities and legal water rights. Changing the hydrosocial system of the Upper Deschutes Basin to become more efficient though canal piping has introduced different discourses, values, and definitions of efficiency, creating confusion about how to educate both the public and water managers. Ultimately, the discussion on education highlights again that the potential unintended consequences of irrigation canal piping was not at the forefront of water managers priorities in the Upper Deschutes Basin; instead, the perceived need to rally support for conserving water for the higher-valued water uses (e.g., Deschutes River ecosystems and commercial agriculture) is a driving force for education.

Sociopolitical and biophysical intertwined in canal piping

When I asked water managers in the Upper Deschutes Basin about their perspective on canal piping trade-offs, the uncertainty in the hydrologic system played a large role in the unanimous support for irrigation efficiency. The canal seepage that recharges the aquifer system and eventually discharges to the Deschutes and Crooked Rivers is hidden and elusive. Water managers expressed their support for canal piping because physically seeing the water stay in the Deschutes River and restoring the ecosystem is rewarding and encouraging. 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' goes shapes how water managers view canal piping, aligning with one of Lankford et al.'s (2020) dimensions which includes the complexity of understanding groundwater as an influence on views of efficiency losses, wastes, and savings.

Like most landscapes in the Anthropocene, the Upper Deschutes Basin hydrology has been heavily altered by humans. The water that leaks from irrigation canals did not exist in the basin prior to white settlement in the late nineteenth century, and the physical characteristics of this water, combined with its non-natural origin, impacts how irrigation efficiency is understood and promoted. This results in the physical shifting of the hydrosocial system in the basin by changing the material flows of water, directly connecting the material landscape to socio-political factors. Many interviewees compared the Deschutes Basin to the Klamath Basin in central Oregon when describing their perspective on canal piping trade-offs. In the Klamath Basin, the geology is significantly different than the Deschutes, leading to the water lost from irrigation canals to move as surface runoff to other fields, for continued use in irrigated agriculture. Canal piping is not viewed as a necessary solution to the water shortages in the Klamath for this reason. Acknowledging that water is or is not 'lost' based on different hydrologic characteristics of systems at different scales is a critical component in avoiding the "scale paradox" defined by Scott et al. (2014) and illuminates again how the physical characteristics and flow of water shape definitions of efficient water use.

By using a CPG lens, in addition to a hydrosocial lens, to study canal piping, the "material landscapes, social dynamics, and knowledge politics together, as they co-constitute each other" can be studied and understood in response to the complex socio-environmental irrigation landscape in the Upper Deschutes Basin (Lave, Biermann, and Lane, 2018, p. 6). The 'wasted' water in irrigation is perceived as 'artificial' and it not valued because it is not going towards the water uses that society in the Upper Deschutes Basin values most, like restoring the Deschutes River ecosystem and providing water to 'real' farmers in commercial agriculture in Jefferson County. Asking water managers about their definitions of efficient water use and their perspective on the trade-offs of canal piping shed light on how different socio-political motives for irrigation efficiency causes confusion and tensions around the responsibility for implementing canal piping, shallow groundwater monitoring, and water conservation education in the Upper Deschutes basin.

While there is no clear answer to these debates, what was clear is that the potential unintended consequences of canal piping are not a focus in water management in the Upper Deschutes Basin, as evident by the lack of shallow groundwater monitoring in the study area, especially in close proximity to irrigation canals (see figure 12). The public has expressed concerns about their domestic wells and the ecosystems which appear to use the canal seepage and subsequent cold water spring discharge, yet water managers, or in other words the actors at the higher social scales defined by Lankford et al. (2020) and those with ‘expert’ technical knowledge (Budds, 2009), have the power to dictate how the hydrologic system is controlled and monitored, thus setting the standard for what water ‘loss’ and ‘waste’ means. These standards are both socio-politically and bio-physically motivated based on the physical characteristics of groundwater as well as discourses, values, and knowledge politics linked to what efficiency means to water managers in the Upper Deschutes Basin.

Knowing the complex social factors and power relations underpinning irrigation canal piping in the Upper Deschutes Basin provides a deeper understanding about the causes and motives for the lack of shallow groundwater monitoring. Water managers in the Upper Deschutes Basin defaulted to the USGS Upper Deschutes Groundwater model when describing their perspective that irrigation canal piping will have minimal, if any, negative impacts on other water users in the basin reliant on the canal seepage. Yet, this model is only a simulation, and there has been more canal piping since the time the UGSG study was completed. Respondents often relied on the USGS model result which predicts 10 percent of the groundwater level declines to be caused by canal piping (Gannett and Lite, 2013) when explaining their reasoning for their lack of worry or attention towards the unintended consequences without acknowledging the limitations of hydrologic models, which 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 environmental science is underpinned by political and economic factors and relying on this type of scientific data can overlook the small-scale material realities in the Upper Deschutes Basin (Budds, 2009; Lave, Biermann, and Lane, 2018), like water users impacted by groundwater decline near irrigation canals.

The combination of the ways in which water is valued and understood in the Upper Deschutes Basin, together with the ways in which groundwater somewhat mysteriously moves throughout the hydrologic system, have shaped the basin's attitude toward water management, resulting in the lack of shallow groundwater monitoring, aligning with Lankford et al.'s (2020) claim that irrigation systems are often empirically data-short. The use of scientific models and limited groundwater data by water managers is by default a political act because the level of monitoring and data that exists in the basin today is a reflection of the discourses, values, tensions around the legal water rights system, and conflicts about what efficiency means and who is responsible to implement irrigation efficiency. Hydrologic modeling, specifically modeling focused on groundwater changes, can be used by government entities to make water management decisions in accordance with its own interests, resulting in unequal water use patterns (Budds, 2009).

In the Upper Deschutes basin, water managers that are relying on only the USGS Upper Deschutes Groundwater model as evidence for minimizing the negative consequences of canal piping may be consciously or unknowingly enforcing their own interests of providing water for the ‘natural’ system and economic agriculture. The lack of available shallow groundwater data combined with the heavy reliance on basin-scale modeling may put shallow well owners at an increased risk of facing water shortages and the expensive reality of deepening their well. I have shown through a geospatial analysis of shallow wells in the Upper Deschutes Basin combined with existing simulations of groundwater decline that approximately 4,230 shallow wells exist in the areas around Bend, Redmond, and Sisters as well as near Madras, where piping effects are likely to be strongest (Gannett and Lite, 2013). Of the sections (square miles) intersecting irrigation canals, approximately 20 percent contain at least one shallow well with a vulnerability of 10 feet or less. Near the piped irrigation canals in the study area, shallow wells around Redmond and Sisters show declines in groundwater levels and there is no data to see what is happening to shallow groundwater patterns around the piped canals near Bend and Madras. The shallow well users in these areas, and potentially groundwater dependent ecosystems, are at risk of being ignored when basin-scale models are relied heavily upon instead of a robust monitoring system.

Conclusions

Based on my research, I conclude that canal piping infrastructure works to meet specific values held by actors with the power to influence and make water management decisions. Irrigation canal piping in the Upper Deschutes Basin was supported by all of the water managers and experts I spoke to in this study for the purpose of conserving water for the Deschutes River and also for economic agriculture in Jefferson County. Biophysical and social elements play a role in why irrigation canal piping is supported, and ultimately, the project of irrigation efficiency changes the hydrosocial cycle in the Upper Deschutes Basin by physically shifting the flow of water as well as creating tensions about responsibility and scale of irrigation efficiency implementation among water managers. The concerns that the public express about declining shallow groundwater levels as a result of reduced seepage after canal piping is not at the top of water manager's priorities at this time. Although, some respondents did encourage the need for awareness and mitigation strategies to reduce the severity of the potential negative consequences. Yet, even if water managers wanted to plan for the trade-offs impacting shallow wells and ecosystems reliant on the canal seepage, I have shown that insufficient shallow groundwater monitoring data exists to assist with this type of effort. In this way, the potential impacts to shallow wells in the Upper Deschutes Basin as a result of irrigation canal piping is currently a pitfall, or "hidden risks, biases, omissions and fault lines associated with not fully understanding IE [irrigation efficiency]" with the potential to become a paradox, or a “clear contradiction and/or when outcomes materially go against expectations” (Lankford et al., 2020, p. 2).

By using a hydrosocial lens to study irrigation efficiency canal piping, I have demonstrated the importance of giving attention to water’s broader social dimensions to provide a deeper understanding of the benefits and trade-offs in irrigation efficiency projects. Irrigation canal piping is not simply a method to return water to the Deschutes River. Rather, it is a piece within a larger, complex project of working around the legal water right system to shift water to the ‘natural’ hydrologic system and to enhance the livelihood of the ‘real’ farmers, all of which is embedded in the tensions around the exurban transition of the Upper Deschutes Basin. Unraveling the embedded values and discourses in how water managers define ‘efficient’ water use offers insight to the ways in which the social construction of water in the Upper Deschutes Basin improves conditions for some water users while overlooking others. Importantly, this approach to understanding irrigation efficiency has highlighted the potential for groundwater monitoring to be unknowingly political to meet the needs of values at specific scales while ignoring other scales, like small-scale shallow groundwater changes near irrigation canals.

Beyond understanding the water-society relations involved in irrigation canal piping, I also demonstrated the necessity of incorporating the social factors with a physical and spatial analysis of the vulnerability of shallow wells and availability of existing monitoring data. The lack of certainty in where canal seepage goes in the groundwater system influences the support of canal piping because seeing increased flows in the Deschutes River fits with the desire to restore the ‘natural’ landscape, yet the heavy human influence on the Deschutes River for irrigated agriculture was not often discussed by water managers. A study which only included the spatial analysis components of this research without the perspectives and knowledge of water managers would miss critical details about how the biophysical and socio-political are intertwined in canal piping efforts. Not taking an interdisciplinary approach puts the hundreds, if not thousands, of shallow wells in an even more vulnerable position than they already are.

Also, taking this approach highlights the current ways in which water conservation science is used in decision making. Water managers relied on the USGS Upper Deschutes Groundwater Model when describing why the potential impacts on shallow groundwater users was not a concern of theirs, even though there is a lack of current shallow groundwater monitoring to prove or disprove the model predictions. Making universal statements, like stating that only 10 percent of the cause for groundwater declines in the Upper Deschutes Basin is irrigation canal piping (Gannett and Lite, 2013), rather than relying on comprehensive and localized groundwater monitoring data, overlooks the current impacts to shallow well users, who may not have the financial means necessary to deepen their well.

A critical approach to studying the potential trade-offs of canal piping in the Upper Deschutes Basin has allowed for the navigation between the material and socio-political dimensions of water conservation “to reveal the power relations that intersect with biophysical dynamics to produce and reproduce political ecologies" (Budds, 2009). Using Lankford et al.'s (2020) IEM framework as guidance, I emphasize the importance of understanding the perspectives of actors at the basin scale (e.g. water managers) while not overlooking the perspectives and concerns of the public at localized scales within the Upper Deschutes Basin. It is important to note that this study differs from others focuses on equity and environmental justice in water in that the biggest winner is the Deschutes River itself, rather than a small group of human water users. Even though the intrinsic value of water is being progressed and protected, focusing on the tensions, confusion, discourses, and values embedded in water conservation for in-stream flow has shown the importance of looking at irrigation efficiency projects through a holistic and comprehensive lens to avoid and mitigate the unintended consequences to the greatest extent possible.

This study is a call for more attention to the material and social factors involved in irrigation canal piping in the Upper Deschutes Basin to better prepare for, or at a minimum be aware of, the water users potentially relying on canal leakage. On the material side, more shallow groundwater monitoring at the local level is needed to fully understand how canal piping is affecting the groundwater levels in the basin. It would be helpful if groups involved in understanding groundwater patterns in the basin (e.g. OWRD or the USGS) install shallow groundwater wells near irrigation canals before they are piped to collect groundwater level data before and after piping occurs, especially in the areas highlighted in this study where shallow wells are most vulnerable. This would aid in collecting detailed data to help understand the current impacts of canal piping on water users reliant on canal seepage. This information would play a critical role in informing where canal piping occurs, and the mitigation efforts needed to protect shallow groundwater and ecosystems nearby. On the social side, a diverse range of perspectives and knowledge is needed in water conservation projects, like irrigation canal piping, to understand the values and goals of not only those with the power to make policy and management decisions, but all water users in the basin to clarify the varying definitions and discourses that exist around water in the Upper Deschutes Basin. The concerns of the public regarding declines in shallow groundwater levels from canal piping should be incorporated into management decisions to find conservation methods that meet the needs of all water users in the basin. Alongside incorporating diverse perspectives in irrigation efficiency projects, education and outreach with the public should be a necessary component to canal piping to promote collaboration between the multiple types of water users in the Upper Deschutes Basin.

Addressing the Research Questions

Here, I revisit the research questions which guided this study. First, I found that **actors involved in water conservation and management in the Upper Deschutes Basin defined efficient water use** in a range of ways, but the major themes were focused on conserving water for the 'natural' system for the Deschutes River ecosystem and also to provide additional water to the 'real' farmers in Jefferson County. Efficiency, to the respondents in this study, is about getting water to where it meets the greatest societal values. In addition to social factors, the uncertainty in knowledge about groundwater and who or what is actually relying on the canal seepage plays an important role in shaping how efficiency projects are defined. Irrigation canal piping alters the hydrosocial system in a way that physically changes the flow of water to become more visible, as the majority of the conserved water stays in the Deschutes River.

Second, I conclude that **these definitions relate to the support of irrigation canal piping projects in the basin** because it is an act of working around the legal water right system to move water in ways that align with water managers' values. While conserving water for the Deschutes River and for commercial agriculture in the basin is improving the conditions for many water users, especially fish and wildlife, the support of canal piping based on both the biophysical and socio-economic factors described above introduces the conditions for other water users to be overlooked. Defining canal seepage as 'waste' and 'artificial' has likely influenced the level of monitoring and attention given to the water users who are reliant upon the leakage. Support of canal piping is backed by basin-scale USGS model predictions and not a robust shallow groundwater monitoring system, putting the thousands of shallow wells in the basin, and potentially groundwater dependent ecosystems, in a more vulnerable position.

Third, I found that the **canal piping impacts on shallow wells cannot be analyzed with the available groundwater data** in the Upper Deschutes Basin. By conducting the spatial analysis, I found there are a higher concentration of shallow wells around Redmond, Prineville, and Bend. The vulnerability of the shallow wells in proximity to irrigation canals is variable, with higher risk wells north of Redmond, around Bend, and near Prineville. When comparing these results to the USGS Upper Deschutes Groundwater model, the area between Sisters, Redmond, and Bend as well as around Madras are simulated to experience the greatest negative impact from canal piping, yet there is a lack of shallow wells with robust monitoring data to confirm this. Only 22 shallow wells met the criteria within 1 mile of the irrigation canals, and those wells near piped canals show declines around Sisters and north of Redmond, up to 50 feet. There are no shallow wells with enough monitoring data from the OWRD database to analyze trends around Bend, where the most extensive piping has occurred, leaving the shallow groundwater conditions in this area a mystery.

Reflections

It is important to not forget in a critical, political ecology and interdisciplinary study to be reflexive and aware of how this research is going to impact the world. The second tenant of CPG states that the social and bio-physical factors which shape what we study also influence why we study them (Lave, Biermann, and Lane, 2018). The questions I asked in this study and the lenses I used come from a combination of many elements, including the education I have gained in graduate school, my past work in groundwater consulting, my own personal biases, and my concerns about equitable water allocation in the face of climate change. The third tenant of CPG states that the research we do produces knowledge, which has "unavoidable political consequences" on the landscapes and the people we study (Lave, Biermann, and Lane, 2018, p. 5). My research on the Upper Deschutes Basin provides insight and a deeper understanding of the complicated, multi-scalar effort to conserve water which is inevitably political. These two tenants influenced the way this research was designed, conducted, and written.

It is crucial to acknowledge that I am an outsider in this study, as I do not live in the Upper Deschutes Basin. I am not a member of the community in which I conducted this research, and I analyzed the opinions, viewpoints, and beliefs of community members who experience and interact with water in the Upper Deschutes Basin in a myriad of ways each and every day. My analysis of the data is only one interpretation based on my own background and knowledge, as I mentioned above. Also, as a white person of European ancestry, studying the ways in which water is managed and controlled is inherently tied to colonialism and the erasure of Indigenous Peoples. Curley (2021) makes it clear that considering nature as ‘resources’ “is colonial constructions consistent with genocide, displacement, exploitation, and capitalism” (p. 79). Working within the social construct of viewing water as a resource in this study, I risk perpetuating the capitalist and development centered focus of colonial progress. Yet, utilizing a critical lens and analyzing the discourses, values, and motives in water conservation for the sake of informing a more equitable and comprehensive way of viewing water in the Upper Deschutes Basin is hopefully a step towards more critical political ecologies and decolonial focused research on this subject in the future.

This research project was my first experience collecting, analyzing, and incorporating qualitative interview data with physical geography. My background in earth sciences and hydrogeology provided me with a certain confidence in my quantitative abilities. Throughout the process of conducting interviews analyzing the qualitative data, and integrating the analysis with the spatial analysis, I was nervous about my lack of experience, but I learned how to think of science and the process of discovery in a new way. There was a lot of trial and error along the way, and I had to work harder than I anticipated to get through all of the data I collected. I realized early on that I could have only focused on the spatial analysis or the interviews with water managers for a thesis level project, but as I described in the conclusion, limiting myself to just one would not have told a complete story of irrigation efficiency canal piping trade-offs in the Upper Deschutes Basin. I grew as a researcher and learned that I am passionate about the process of using both social and natural science methods to inform each other in interdisciplinary studies to progress our understanding of water landscapes in the Anthropocene.

Limitations

- The irrigation canal dataset was last updated in 2018, leaving out the piping projects that occurred since then.
- The shallow wells (300 feet deep or shallower) in the vulnerability assessment is current as of 2018, leaving out shallow wells installed after 2018.
- The shallow wells are not categorized by well type and encompass all uses, including domestic, municipal, irrigation, etc. This means that the data does not just represent domestic well use.
- The shallow wells in the vulnerability assessment may include wells that have been deepened or abandoned since installation.
- Wells that are deeper than 300 feet may be screened in the shallower aquifer system and could provide more details about shallow groundwater conditions. I excluded these wells in this study due to the reality that most wells are drilled deeper to access deeper groundwater, yet there may be more data available than what is shown in this study.
- The trend analysis in this study is only the difference between the earliest and most recent groundwater measurement rather than non-parametric statistically significant values (e.g. Sen's slope or Mann-Kendall Trend).
- While this study includes perspectives from a range of water managers in the Upper Deschutes Basin, additional input from more respondents, especially the Confederated Tribes of Warm Springs, who are located

north of the study area, would have provided additional detail that was lost in this study (see more detail in Future Research).

Future Research

This research only scratches the surface to understanding and informing efficient and equitable water management and policy in central Oregon, and beyond. There are multiple pathways of future research that would add to this work. First, from a natural science standpoint, it would be useful to install shallow monitoring wells in the area indicated in this study to be the most vulnerable to irrigation canal piping to study current localized trends. Using non-parametric statistical methods to find the trends in groundwater data would provide a more robust and reliable understanding of the impacts to shallow wells, as well as ecosystems, reliant on canal seepage in the Upper Deschutes Basin. Also, conducting an assessment of the type of well and whether each well has been deepened or abandoned would allow for a better representation of the reality of vulnerable shallow wells. In addition to shallow wells, an assessment of groundwater dependent ecosystems in the basin that may be reliant on canal seepage would further inform the unintended consequences of the conservation project in the Upper Deschutes Basin.

In terms of continuing to understand the social factors underscoring canal piping, incorporating qualitative interview data from shallow well owners and other groups who are concerned or against canal piping would illuminate the differing values, discourses, and motives that are tied to water. I chose to only include water managers' perspectives in this study because they are the group enforcing and deciding how water is controlled and my goal was to better understand how trade-offs are being handled. Asking those who rely upon shallow wells in the basin the same questions about how efficient water use is defined would open up a different range of social values that may have been missed by only interviewing water managers. Also, as mentioned in the limitations, the Warm Springs Reservation is located just north of the Upper Deschutes Basin. Incorporating the perspectives of Indigenous peoples in proximity to the study area would greatly enhance a study on irrigation efficiency and offer critical insight into the ways in which we think about and relate to water conservation policy and infrastructure.

An interesting piece of this research that I would like to further dig into is the frustration around the legal water right system and the changing regional political ecology of the Upper Deschutes Basin due to both urban and rural forces. Future research should include a critical analysis of the legal framework and how conservation efforts, like canal piping, are working around prior appropriation. At what point will these infrastructure projects fall short of meeting all of the water needs in the basin? Can the legal water rights system be changed? It would also be important to look critically at how the combination of these efforts are benefitting some water users while marginalizing others and why. This study offers a foundation for this type of research by providing information on the biophysical and socio-political factors involved in canal piping, yet many other types of water conservation efforts exist. Using an exurban political ecology lens could allow for a deeper understanding of the discourses and values tied to irrigation canal piping and highlight the regional and global forces shaping the local.

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Appendix A: Table of Acronyms and Initialisms

Abbreviation	Name
COID	Central Oregon Irrigation District
CPG	Critical Physical Geography
IEM	Irrigation Efficiency Matrix
NUID	North Unit Irrigation District
OWRD	Oregon Water Resources Department
USGS	United States Geological Survey

Appendix B: Interview Questionnaire

Deschutes Irrigation Efficiency Interview Questions

1. What is your role at ______?

2. How have you been involved in irrigation efficiency or water conservation in the Deschutes River Basin?

3. What do you see as the most important water management issue in the region?

4. What is your definition of efficient water use?
    a. In your opinion, what is “wasted’ water or water “loss”?

5. Can you tell me a bit about your perspective on irrigation canal piping?

6. How does canal piping change the area?
    a. What is the impact on surface water?
    b. What is the impact on groundwater?
    c. What is the impact on ecosystems reliant on surface and groundwater?
    d. Who or what should/does benefit?
    e. How big of an area (both physical and social/human landscape) does a canal piping project affect?

7. What do you see as the positive aspects & benefits of this project? What do you see as the challenges or potential downsides?
    a. Are there concerns about groundwater/GDE’s? What about the population reliant on groundwater as a drinking water source?
    b. Have you noticed/observed/heard about any physical changes to groundwater levels and/or GDEs after piping occurs?

8. Who supports irrigation canal piping and who is opposed? Why?

9. What do you see as the ideal future for irrigation efficiency and water conservation in the Deschutes River Basin?

10. What else should I be asking that I didn’t ask? What else should I know? Who else should I be talking to?

Appendix C: Participant List by Pseudonym

Participant Pseudonym	Professional Positionality
Tom	Retired Federal Hydrologist
Adam	Conservation/Ag Non-Profit Representative
Sarah	State Water Policy Representative
Ryan	Conservation/Ag Municipal Corporation Representative
Paul	State Hydrologist
Phil	State Representative
Amelia	Conservation Non-Profit Representative
Bill	State Hydrogeologist
Robert	Irrigation District Representative
John	Irrigation District Representative
Jane	Conservation Non-Profit Representative
Henry	Conservation Non-Profit Representative
Steve	Conservation Non-Profit Representative

Appendix D: Changes in Groundwater Levels Near Canals

gw_logid	First_Measured_Date	Last_Measured_Date	First_Measurement	Last_Measurement	Difference (ft)
CROO0001577	1985	2020	78.86	66.72	**-12.14**
CROO0002133	1996	2018	26.52	9.82	**-16.7**
JEFF0000222	1995	2021	64.89	62.26	**-2.63**
DESC0002929	1987	2021	142.9	157.11	**14.21**
CROO0001453	2000	2019	21.3	16.3	**-5**
CROO0001521	2000	2019	33.1	32.3	**-0.8**
DESC0002098	1998	2020	138.9	147.1	**8.2**
DESC0002100	1998	2020	177.4	185.9	**8.5**
DESC0002102	1998	2004	209.66	212.83	**3.17**
DESC0003088	1994	2018	194.38	191	**-3.38**
DESC0003853	2001	2020	154	205.4	**51.4**
DESC0000050	1995	2018	208.82	201	**-7.82**
DESC0000051	1990	2005	100.42	102.83	**2.41**
DESC0053714	1995	2020	242	250.02	**8.02**
DESC0000992	2002	2018	186.3	201	**14.7**
DESC0004320	1994	2009	197.67	197.26	**-0.41**
DESC0005180	1995	2009	30.13	29.1	**-1.03**
CROO0000811	1994	2011	33.26	37.99	**4.73**
CROO0000434	2007	2017	8	8.17	**0.17**
CROO0050223	2006	2021	42.99	44.98	**1.99**
CROO0051607	2009	2021	18.49	27.31	**8.82**
CROO0003150	1995	2014	165	150.63	**-14.37**