Oregon's Water Supply at Risk: Assessing Natural, Built, and Social Hazards for Improved Risk Management

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Abstract: Water suppliers face multiple stressors including natural hazards such as floods and wildfires, aging infrastructure, and changing social demographics. In this work, we create a framework to assess natural, built, and social stressors for water suppliers using Oregon as a case study that exemplifies the Western United States. First, a database of water system, geographic, and demographic data was developed to assess the current state of water supply vulnerability in Oregon. The compiled database was analyzed to develop a holistic view of the state's water supply. Second, a network analysis was completed to reveal the interconnectedness of suppliers to assess vulnerability and redundancy. Finally, agglomerative hierarchical clustering analysis was performed to understand patterns of risk and define distinct water supplier typologies. Results indicate that there are diverse needs among water suppliers and risks across source areas. For example, some suppliers face a high risk of wildfires contaminating their source water, with 30-year burn probabilities of headwaters near 40%, while other suppliers serve growing populations whose needs may strain existing supplies. Many of the largest suppliers in the state, primarily located in the Portland metropolitan area, are connected through water transfers and a regional water consortium; however, the analysis elucidated several midsize suppliers that do not have as many resources or connections, presenting vulnerabilities. These suppliers may require further attention because they serve and supply a substantial population in more rural parts of the state. Lastly, the clustering analysis revealed four supplier typologies, confirming that many suppliers face similar stressors, although they are not necessarily geographically colocated. The results of our work indicate that future water supply resiliency and sustainability efforts could be further strengthened by collaborative efforts and knowledge sharing, particularly through non-neighboring partners, and by policies and programs developed to serve the unique needs of large urban, midsize regional, and small rural suppliers. **DOI: 10.1061/JWRMD5.WRENG-6905**. *This work is made available under the terms of the Creative Commons Attribution 4.0 International license, https://creativecommons.org/licenses/by/4.0/.*

Practical Applications: Water suppliers in Oregon and other Western US states face multiple stressors including natural hazards, such as wildfire and landslides, aging infrastructure, and changing demographics that impact drinking water supplies. This study finds that these stressors require different solutions across the state of Oregon, but that there are opportunities for increased collaboration, particularly across geographic boundaries. While the largest suppliers in the state (serving the Portland metropolitan area) are potentially well-positioned to meet water supply needs in the future, midsize suppliers that provide water to smaller cities may have vulnerabilities including a lack of supply redundancy, exacerbated as their service populations are likely to grow and they are often located in more rural parts of the state. The results suggest that future water supply resiliency and sustainability efforts could be strengthened by collaborative efforts and knowledge sharing, particularly through non-neighboring partners, and by policies and programs developed to serve the unique needs of large urban, midsize regional, and small rural suppliers.

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Introduction

Water supplies around the world face multiple stressors from changing human and natural systems. Population growth is amplifying the need for supply certainty at the same time as water supplies are threatened by phenomena including climate change, economic development, and urbanization (Gerlak et al. 2018; Zimmerman et al. 2008; Hajirad and Pourmohammad 2025). As threats persist and expand, there has been an increasing focus on improving water security, with particular attention to place-based (location-specific) needs (Gerlak et al. 2018).

In the Western United States, water supply systems face multiple hazards (Ward 2026). Such hazards may affect water supply at its source, with headwaters facing impacts from land use change (Ozment et al. 2016), lower snowpack retention (Mote et al. 2018), groundwater sources impacted by decreased recharge (Niraula et al. 2017), as well as various forms of contamination such as by nutrients and pesticides (Brown et al. 2011). Water supplies also face potential hazards at their point

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of use, with urban areas facing water security challenges such as population growth, inadequate infrastructure, and increased contamination (Hoekstra et al. 2018).

Threats to water supply are exacerbated by climate change. In the Western United States, over 70% of water supplies originate in forests (Liu et al. 2022). Catastrophic wildfires in forested headwaters are becoming more common as the climate warms (Bladon et al. 2014), putting water sources and supplies at greater risk (Robinne et al. 2021). In addition, wildfires can increase the occurrence and magnitude of landslides (Rengers et al. 2020), while climate models predict an increased likelihood of extreme rainstorms following extreme wildfires (Touma et al. 2022). Droughts, already a regular occurrence in the Western United States, are expected to increase across the country by 2050 (Strzepek et al. 2010). The Western United States has been experiencing more hydrological extremes with both drought and flood conditions over the last decade, and extreme water events are projected to become even more frequent as warming continues (Li et al. 2025). Furthermore, climate change is expected to exacerbate compounded natural hazards, adversely affecting both water quantity and quality (Mora et al. 2018). All US water utilities are exposed to at least one type of climate-related hazard, with around half at risk of large changes in hazards (e.g., heightened water supply stress) that could significantly impact system reliability (Lyle et al. 2025). Climate change is also expected to have adverse impacts on water quality, through increased spread of pollutants, changes in water chemistry through temperature increases, and changes in dilution patterns due to floods and droughts (Delpla et al. 2009).

These climatic events can strain water supply infrastructure (Fluixá-Sanmartín et al. 2018) and are expected to increase the costs of providing water (Hughes et al. 2010). High costs of service and maintenance can cause disparate impacts, because lower-income communities may not be able to afford safe water infrastructure or the investments that may be required to meet growing challenges. Increasing water scarcity due to climate change will become more difficult to combat (for example, using water storage and saving technologies) in areas with fewer resources (Islam and Winkel 2017).

Nearly all such water supply issues are present in the state of Oregon, which faces general challenges and those particular among Western US states. Wildfires (Day et al. 2021; McEvoy et al. 2020), landslides (Macleod et al. 2005), and the impacts of climate change, including increasing temperatures and changes in streamflow (Farley et al. 2011; Sproles et al. 2013), are common and growing challenges in the state. As in many other areas of the country, infrastructure hazards (McCarthy et al. 2009) and social stressors (Shandas and Parandvash 2010; Stone et al. 2007) also pose threats to Oregon's water supply. Unlike its neighboring states of California and Washington, however, Oregon also lacks a central agency or interagency system to oversee water-related issues (Grigg 2023; Oregon Secretary of State 2023). In addition, the state's water policy exacerbates inequities by prioritizing the needs of senior rights holders (Oregon Secretary of State 2023). Due to Oregon's history of racist and exclusionary policies toward Indigenous tribes, Black and Chinese Americans, and other people of color, these water rights policies continue to perpetuate racial inequities (Oregon Secretary of State 2023).

These governance issues can deepen water supply challenges and inhibit the ability of water supply agencies to respond to crises effectively and equitably. However, despite the clear challenges faced by the state, there has been a relative lack of focus on Oregon in the literature compared to other geographies in the Western United States (ProQuest 2024). As it becomes more pressing for both water suppliers and policymakers to address vulnerabilities and determine the best investments for promoting resilience, it is imperative to understand how these challenges vary across water agencies and parts of the state. This understanding would help promote more efficient communication and collaboration between suppliers facing similar stressors. State, regional, and local agencies also benefit from understanding the linkages, vulnerabilities, and potential interventions to better develop policy recommendations and best allocate shared resources across jurisdictions.

Background

In this study, we examine multiple factors (referred to here collectively as "stressors"), including hazards and socioeconomic factors, that could contribute to water system vulnerability across Oregon and can thus inform strategic investments and help prioritize policy needs. We define hazards as "phenomena or substances that have the potential to cause disruption or damage to humans and their environment" and vulnerability as "the degree to which a population, individual or organization is unable to anticipate, cope with, resist and recover from the impacts of disasters" (Wisner and Adams 2002). Importantly, vulnerability is socially constructed; in other words, social and economic factors impact the degree to which a community is vulnerable (Morrow 1999). Vulnerability is commonly considered to be one dimension of resiliency and risk (Hashimoto et al. 1982; Matthews et al. 2014). Here, resilience is defined as the ability of a socioecological system to recover and return to its previous state after facing any shock, risk, and uncertainties (Lanlan et al. 2024). Understanding hazards and exposure is critical for characterizing vulnerability, and multiple metrics may be necessary when comparing vulnerability across communities (Hummel et al. 2018).

Natural hazards, including wildfires, landslides, and droughts, are a growing threat to water supply systems, exacerbated by climate change. Wildfires in the Western United States are increasing in size and severity, which leads to increasing contamination of water supply by heavy metals, nutrients, and sediment (Bladon et al. 2014; Robinne et al. 2021). Wildfires can also impact hydrological processes, including streamflow and snowpack retention, producing excessive amounts of water during some periods and depleting the available water supply for later periods (Bladon et al. 2014). Other natural hazards can significantly impact water supply, as well: landslides can lead to spikes in suspended sediment, decreasing the potability of water (Geertsema et al. 2009), while droughts regularly reduce the quantity of available water in reservoirs (Cancelliere et al. 1998). Compounded hazards are also increasingly a concern; wildfires, for example, cause a heightened risk of mudslides and flash floods, resulting in a series of destructive hazards (Touma et al. 2022).

A second class of hazards relates to the built infrastructure that water systems rely on to deliver adequate and safe water. Infrastructure, including dams and reservoirs, pipes, aqueducts, canals, and water treatment systems, is necessary to purvey clean water but simultaneously can pose significant risks. Aging infrastructure can cause various forms of microbial, heavy metal, and chemical contamination (Allen et al. 2018; Grigg 2017). The risk of this increases over time as the infrastructure continues to degrade. When water supply contamination occurs as a result of natural hazards such as wildfires, treatment systems and gray infrastructure are often not equipped to handle this altered water supply, which can lead to further contamination from disinfection by-products (Hohner et al. 2016). Dams are of particular concern in the United States, with nearly 27,000 rated as posing a high or significant hazard by ASCE in a 2021 report (ASCE 2025). Aging dams threaten the continuity of water

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supply; for example, sediment trapping and stratification behind dams can negatively impact water quality (Scott Winton et al. 2019). In addition, as the Western United States experiences more extreme precipitation conditions due to climate change, flood risk may increase, and many dams are not built for these events. In California in 2017, for example, damaged spillway infrastructure combined with an extremely wet winter resulted in the evacuation of 180,000 people from the town of Oroville (France et al. 2018).

Finally, social stressors, examined through social and demographic metrics, also have implications for water supply vulnerability. In the United States, centuries of systemic racism and perpetuated inequalities have culminated in disparities in the availability and quality of water. These inequities have resulted in unequal access to funding for water infrastructure building and maintenance, varied enforcement of drinking water regulations, and a lack of political power to access an adequate water supply (Balazs and Ray 2014). A 2019 report from the National Resources Defense Council found that water safety violations are more likely to occur in communities with a higher proportion of racial and ethnic minorities and a higher proportion of nonnative English speakers (Pullen Fedinick et al. 2019). National water quality violations are also significantly greater in number in rural areas than in suburban and urban areas, and low-income rural areas experience more violations than high-income areas (Allaire et al. 2018). Infrastructure hazards are often closely linked with social stressors, because communities (including lower-income, rural, and minority communities) without safe infrastructure are unable to access safe drinking water (Balazs and Ray 2014). Natural hazards are often also linked with social stressors; for example, water systems that are exposed to wildfire upstream often serve populations that are more socially vulnerable (Wachter et al. 2025).

Focusing on these three classes of stressors (natural hazards, infrastructure hazards, and social stressors), we use spatial analyses to evaluate the challenges faced by suppliers both within their surface water source areas and their service areas. In addition, we present a network analysis to highlight dependencies among water systems that could exacerbate or mitigate risk. Finally, we use a clustering model to develop typologies of water systems by type of stressor, aiming to facilitate intersupplier communication and statewide policy interventions. By performing this analysis for Oregon, we hope to provide tangible tools for water suppliers in an understudied region while providing an approach and perspective that are applicable across the Western United States.

Methods

Information about Oregon's water supply system was gathered from publicly available data sources in the three categories already described: natural hazards, physical or infrastructure hazards, and social stressors. Natural hazards that we consider include land cover, impervious area, landslide risk, erosion risk, slope, and burn probability; infrastructure stressors that we consider are dam condition, land ownership, water quality violations, and system dependencies and redundancies; and social factors considered include the population served and racial and socioeconomic metrics (Table 1). We specifically focus on water systems that have surface water sources, which face greater vulnerability to many hazards than groundwater systems (Foster 2022) and about which there is a greater understanding of hazard impacts (Elliott et al. 2024). All analysis was conducted in ArcGIS or R version 4.3.1.

Public Water Systems and Surface Water Drinking Water Source Areas

Data on Oregon's public water systems (PWSs) was obtained from the Oregon Health Authority (OHA) (Oregon Health Authority 2022). Public water systems in Oregon are defined as drinking water systems that have 15 or more connections or serve 25 or more people. Characteristics include the population served, activity status (active or inactive), system type (community, nonpublic, nontransient noncommunity, or transient noncommunity; full definitions are provided in Table S1), number of connections, primary source type (surface water and groundwater), system dependencies (purchased water supplies), redundancies (number of primary and emergency sources), and number of water quality violations (system score and points returned to compliance). A Gini-Simpson index was calculated for each water system as a metric of water supply diversity (Gonzales and Ajami 2017b). Data were cross-checked to ensure consistency (e.g., that the sum of the different source types equaled the total number of sources).

In Oregon, surface water supply headwaters are delineated as Drinking Water Source Areas (DWSAs). Data on natural, infrastructure, and social stressors were linked to either the PWS (the system and population served) or their DWSAs (the geospatial source water area; e.g., landslide risk) (Table 1). A given PWS may have no associated DWSAs in this analysis (if they rely exclusively on groundwater) or may source water from one or more DWSAs. PWS and DWSA data were obtained separately, and thus, substantial data filtering, matching, and collating were required to develop a comprehensive database that could be used for analysis (Fig. 1).

As of August 2022, there were 5,520 public water systems in Oregon, and 3,317 of these were active. These active systems overwhelmingly rely on groundwater, with 90.8% using some form of groundwater—direct or purchased—as the primary source. Of the active PWSs, the majority (68.8%) are privately owned, and the next largest group (15%) are owned by local governments, with the remainder split between the federal government, state government, and mixed public–private ownership. Twenty percent are community systems, 38% are transient noncommunity systems, and 32% are "Oregon Very Small" systems (see definition in Table S1).

Public water systems that serve fewer than 500 people (considered "very small" as defined by USEPA, distinct from "Oregon Very Small") were eliminated from the analysis to focus on larger systems that represent the majority of the statewide water supply. This resulted in a total of 359 active, public water systems that serve 500 people or more (Fig. 1). These 359 water systems collectively serve 4.25 million people, which is greater than the 2020 Census population of Oregon (4.24 million). The discrepancy in population served is due to the inclusion of noncommunity systems such as schools, hospitals, restaurants, and campgrounds.

Data from OHA indicated that of the 359 public water systems that serve over 500 people in Oregon, 171 have surface water sources, including 120 that rely directly on surface water and 51 that only rely on surface water through purchases. Spatial delineations of surface water DWSAs were obtained from the Oregon Department of Environmental Quality (Fig. 2), which included 261 entries. Geospatial DWSA data included information on the PWS served, which was cross-checked against the PWS data from OHA for consistency. Any DWSAs that were only associated with a PWS serving fewer than 500 people were discarded, leaving 192 entries. Twenty-five inactive and/or emergency surface water sources or erroneous entries (e.g., groundwater sources) were also removed from the DWSA database. Ten permanent and four seasonal surface water sources were missing from the DWSA database. Other than surface water and groundwater, there is a third category of source

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Table 1. Metrics used to assess exposure

Stressor	Source	Metric(s)	Potential impact	PWS or DWSA
		Natural hazards		
Slope	Oregon Geospatial Enterprise Office (10-m DEM)	Percent rise	Steeper areas are more likely to erode following wildfire or extreme precipitation events	DWSA
Soil erosion potential	USGS, derived from NRCS STATSGO data	k-factor	Soil characteristics impact susceptibility to erosion, which can lead to increased turbidity and other water quality impacts	DWSA
Landslide potential	Oregon Dept. of Geology and Mineral Industries Data	Mean landslide risk	Landslides can directly damage infrastructure and impact water quality	DWSA
Wildfire risk	Pacific Northwest Quantitative Risk Assessment	30-year burn probability (spatial average)	Wildfires pose a risk to water quality, runoff timing, snowpack storage, and infrastructure integrity	DWSA
Land use—agriculture	National Land Cover Database (30-m raster of land cover)	Percent cultivated	High percentage of agricultural land use can impact water quality, demand levels, and timing	DWSA
Land use—urban development	National Land Cover Database (30-m raster of land cover)	Fraction of area that is impervious	High percentage of impervious area can impact runoff and flood risk	DWSA
		Infrastructure hazards		
System dependencies and redundancies	Oregon Health Authority	Total number of permanent sources	A greater number of sources can increase resilience	PWS
	Oregon Health Authority	Percent of sources that are purchased	Purchased sources can support resilience by providing additional or back-up supply, but dependence on other sources and institutions could also create potential risks	PWS
	Oregon Health Authority	Number of emergency sources	Having an emergency supply available can increase resilience	PWS
	Oregon Health Authority	Diversity of source types (Gini-Simpson Index)	A greater diversity of sources can increase resilience since different types are likely to be susceptible to different stressors	PWS
Water quality	Oregon Health Authority	System score	Higher score indicates more water quality violations in the last 5 years, suggesting challenges in providing adequate services	PWS
	Oregon Health Authority	Points returned to compliance (RTC)	More points RTC'd suggests the ability to recover from water quality challenges	PWS
Dams and reservoirs	Army Corps of Engineers National Inventory of Dams	Number of dams at high or significant risk	Dams are critical infrastructure for PWS, the failure of which could create significant service disruptions	DWSA
Land management	Oregon Department of Forestry	Percent privately owned	Private land ownership can create challenges, especially related to water quality, outside a PWS's control	DWSA
		Social stressors		
Population demographics	Oregon Health Authority	Total population Served	The larger the number of people served, the greater the potential impact of a service disruption	PWS
	US Census	Percent of the population that is nonwhite	Communities of color may have special considerations, including economic or language barriers, that PWS must account for when providing services	PWS
	US Census	Percent of the population below the poverty level	Poorer communities may struggle to fund investments that create resilience	PWS

Note: PWS = public water system; and DWSA = drinking water source area.

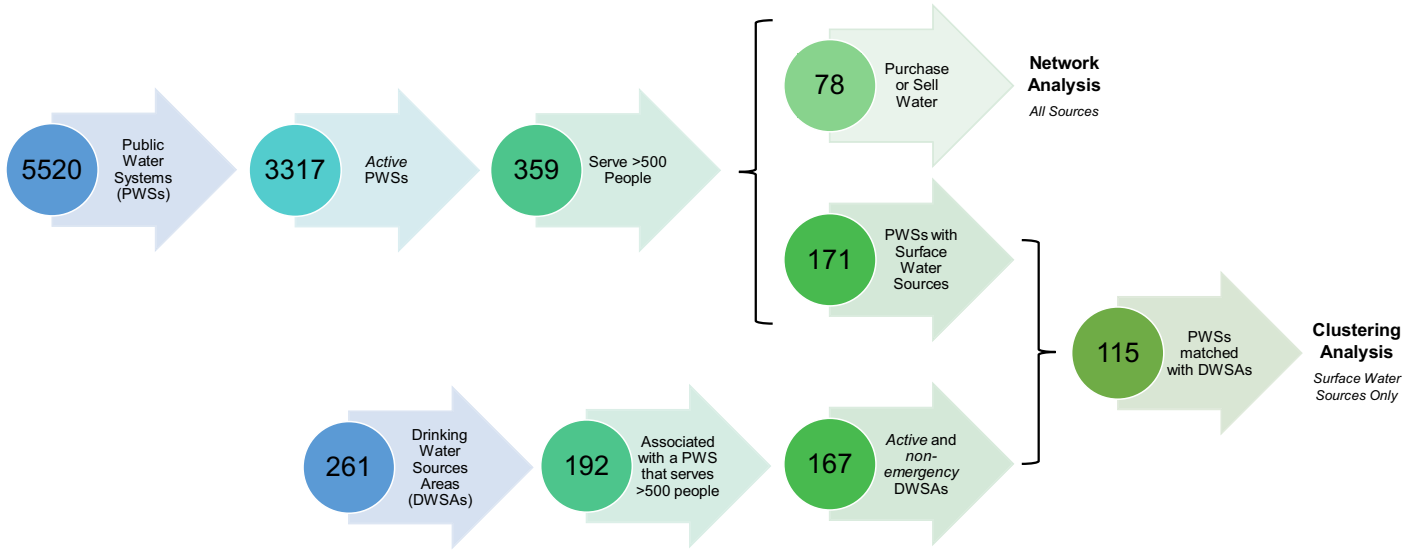


Fig. 1. Data-filtering process.

type, "groundwater under the influence of surface water" (GU), which included 36 sources for 13 PWSs in addition to one such purchased source. Ten of these GU sources were delineated in the DWSA database and were included in the analysis, while three were eliminated because they were inactive and/or emergency sources. This left 23 GU sources missing from the DWSA database. After cleaning, there were 167 total DWSAs included in the analysis, serving 115 different PWSs. Note that this means that five PWSs with surface water sources are not represented at all due to missing data.

Source areas were only associated with PWSs that draw directly from the watershed, not with any PWSs that subsequently purchase from those sources. This is because the number of purchased sources was considered as a separate metric (see Table 1), and it is not always clear which of multiple sources from a seller may be used to supply a purchasing PWS. All natural hazards and some infrastructure risks (number of high risk dams and land ownership) were assessed by DWSA using a spatial analysis. The metrics across all DWSAs serving a given PWS were then aggregated by taking the mean, maximum, or sum, depending on the metric, to give a single value for each PWS. The merged PWS and DWSA database included a total of 115 PWSs (Wolfand 2025).

In addition to PWS data from the OHA, US Census data (percent of the population that is nonwhite and below the poverty level) was used to understand the socioeconomic demographics of each PWS service area. A spatial analysis was conducted overlaying each PWS with census-designated places. Approximately 62.5% of water systems were located within a census-designated place, the remaining 37.5% were matched to the nearest census-designated place (with a maximum distance of 32.2 km). The metrics used were the percent of the population served that is nonwhite and the percent of the population below the poverty line.

Network Analysis

Mapping a water supply network is critical for understanding system interdependencies and vulnerabilities, because a water agency with multiple sources and a diversified supply is more resilient (Gonzales and Ajami 2017a; Palazzo et al. 2017). A network analysis was conducted to quantify patterns in water supply retailing throughout the state. A directed network map was created with PWSs represented as nodes and water-purchase or water-sale relationships represented as links. The analysis included all PWSs, regardless of whether they draw from surface or groundwater sources. Purchasers and sellers were identified by manually searching for each PWS in the OHA's online drinking water database. Of the 359 water systems in our analysis, 78 purchase or sell water and were thus included in the network analysis. Network metrics, including degree centrality [in-degree (DI) and out-degree (DO)], betweenness centrality (BTWN), and closeness centrality (CL), were calculated to provide quantitative insights into the supply network. We further examined network structure by identifying weakly connected components (COMP) and detecting communities of nodes (COMM) using the Walktrap community detection algorithm.

Clustering Analysis

Grouping water systems based on their features can show what stressors are faced by groups of suppliers, provide insight into commonly compounding hazards, and demonstrate where policy and funding interventions are needed. We clustered the 115 PWSs that were matched to DWSAs to reveal common vulnerabilities and understand characteristics for different interventions. The PWS and DWSA databases were merged into a final database with 17 variables. We used the Shapiro–Wilk normality test and found that, except for slope, the data were not normally distributed. Based on the nonnormal distributions, we performed a Spearman correlation analysis and removed variables with a correlation coefficient greater than 0.6 (percent cultivated land use and mean landslide risk). A principal component analysis (PCA) was not successful in dimensionality reduction, because it resulted in 13 principal components needed to explain at least 95% of the variance in the data. We proceeded without PCA and used agglomerative hierarchical clustering using complete linkage on min–max scaled variables. Euclidean distance was used as the similarity metric, and the dendrogram was cut to identify four PWS clusters. Hierarchical clustering was chosen due to the relative size of the data set (115 observations across 15 variables).

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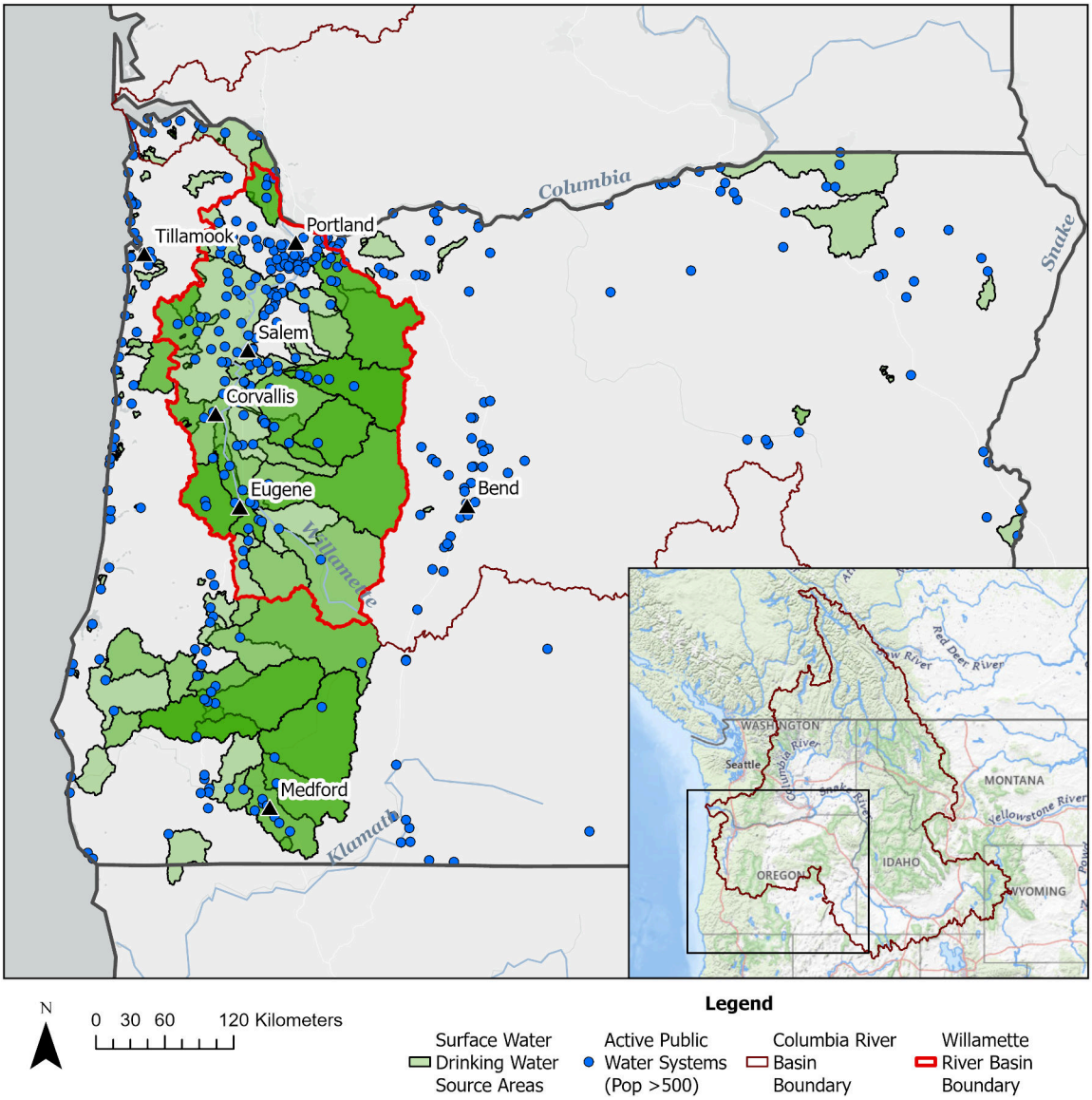


Fig. 2. Public water system (PWS) and surface water drinking water source area (DWSA) locations in Oregon. Note there are overlapping DWSAs. (Inset map image courtesy of Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS User Community.)

Results

Oregon's Water Supply Landscape

Eliminating very small systems from our database, the final list of 359 PWSs comprises 239 small systems (serving populations between 500 and 3,300); 56 medium systems (3,301–10,000 people); 58 large systems (10,001–100,000 people); and 6 very large systems (more than 100,000 people) [Fig. 3(a)]. Most (278) are classified as Community Water Systems (C) while 56 are transient noncommunity (NC) and 25 are nontransient noncommunity (NTNC). None are "Oregon Very Small" systems because, by definition, these systems serve very few people.

Approximately 55% of the water suppliers use groundwater as their primary source, while 32% use surface water, 12.5% use purchased surface water, and the remaining < 1% purchase groundwater as their primary source. This distribution skews considerably more toward surface water than the overall state's distribution, indicating how many of the very smallest systems rely on groundwater. The median number of water sources for each PWS is two, with 33% (119) having only one supply source and 24% (87) having two sources [Fig. 3(b)]. Of those water systems that have only one source, 57 are reliant on groundwater or groundwater under the influence of surface water, and 42 on surface water. A further 19 exclusively purchase surface water (the remaining one uses purchased groundwater). Finally, regardless of the number of sources, 188 PWSs are reliant wholly on some form of groundwater (direct or purchased), and 70 are reliant wholly on some category of surface water.

Most systems included in the analysis (252 or 70.2%) are owned and run by local governments [Fig. 3(c)], while the next-largest category is private systems (73 or 20.3%). The remainder are federal (4 or 1%) or state (29 or 8.1%) government-run, all but one of which are noncommunity systems that serve, for example, infrastructure related to national forests or state parks. Finally, there is one mixed public–private system (Chenowith Public Utilities District in Wasco County). This distribution also differs from the state as a whole since most of the "Oregon Very Small" systems, all of which were excluded from the analysis based on population served, are overwhelmingly privately owned (74.8%).

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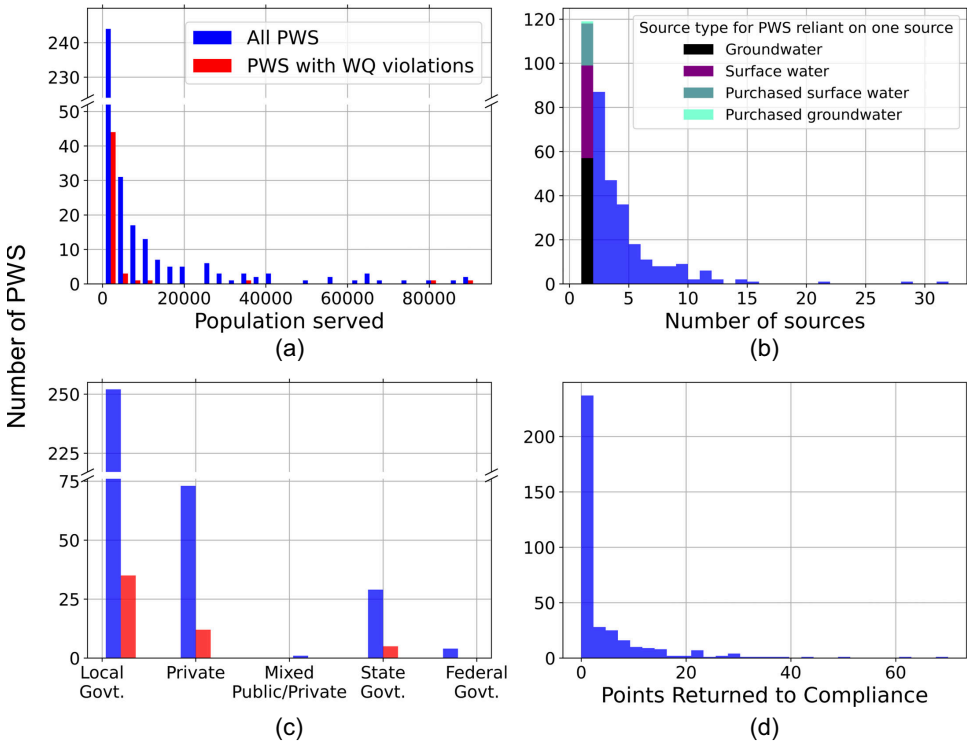


Fig. 3. Characteristics of PWS included in this study (i.e., excluding very small systems (population served < 500): (a) distribution by population served, excluding very large systems (population served > 10,000); (b) distribution by number of sources; (c) distribution by ownership type; and (d) distribution by number of points returned to compliance during reporting periods ending within the last 5 years.

Finally, we looked at the water quality indicators for each PWS, which are tracked by system score and points returned to compliance (points RTC'd). These give a sense of whether a PWS is managing to provide adequate service and their history of violations. System score represents unaddressed violations for monitoring periods ending within the last 5 years, with higher scores indicating more or more severe unaddressed violations. One point is given for most reporting violations, five points are given for more serious violations such as lead and copper violations, and 10 points are given for the most serious violations such as those related to *E. coli*. While points RTC'd alone could suggest recovery from an acute problem, a high system score alongside points RTC'd could indicate that a system struggles with chronic violations.

Overall, 52 of the 359 PWSs (14.5%) had a system score greater than zero, while six had a score between five and 10 (moderate quality violations or multiple reporting violations) and four had a score of 10 or above (severe quality violations or some combination of multiple lesser violations). Small systems were overly represented among PWS with violations: they numbered 44 in total, accounting for 84.6% of systems with violations, despite accounting for only 66.6% of the PWS included in this study. There were four each of the medium and large systems with positive system scores, but no very large systems with violations. The group consisted mostly of local government owners (35 or 67.3%), followed by private water systems (12 or 23.1%), followed by state government (5 or 9.6%), which follows a similar distribution to the larger group of PWS. However, all state government water systems with violations were noncommunity systems.

Just over half of the water systems in this study had points RTC'd (211 of 359 or 59%), but most (75%) of these had fewer than 10 points [Fig. 3(d)]. There was a small but significant correlation between system score and points RTC'd (Spearman's $r = 0.253$, $p < 0.001$), indicating that some systems may face recurring issues with water quality. For example, of the 10 water systems with a system score of five or more, all but one had points RTC'd and two had more than 40 points RTC'd.

Network Analysis

The network map of the 78 interconnected water suppliers (Fig. 4) and associated calculated metrics (Table 2) reveal critical information about Oregon's supply system. Twenty-three agencies sell to but do not purchase from others (DI = 0 and DO > 0), 42 purchase water from a single supplier (DI = 1 and DO = 0), 7 both purchase and sell (DI = 1 and DO = 1), and only 6 suppliers receive water from more than one other agency (DI > 1 and DO = 0), with no suppliers purchasing from more than two sources. These metrics indicate a low level of supply redundancy for many PWSs, where most systems are either reliant on one other supplier or themselves.

In the entire network, most relationships occur directly between suppliers without intermediaries (BWTN = 0). Only two PWSs have a nonzero betweenness (Lake Oswego Municipal Water and City of Hillsboro; BTWN = 0.000171), acting as bridges that can bypass direct linkages. Consequently, most of the network consists of components with eight or fewer interconnected suppliers and most often with only two connected systems. Closeness centrality showed minimal variation across the network, reflecting the presence of primarily disconnected systems. Approximately 48 (62%) of systems have undefined closeness values (CL = NA), indicating most systems are terminal purchasers. In fact, 20 different water supply "islands" exist (COMP range = 1 to 20) of which only 3 are interconnected to each other (COMM range = 1 to 22) while the rest remain isolated. This large interconnected system represents the Portland metropolitan area (metro area) systems, which is subsequently described. Based on these patterns, Oregon's water supply network can be broadly grouped into three categories: (1) suppliers in the Portland

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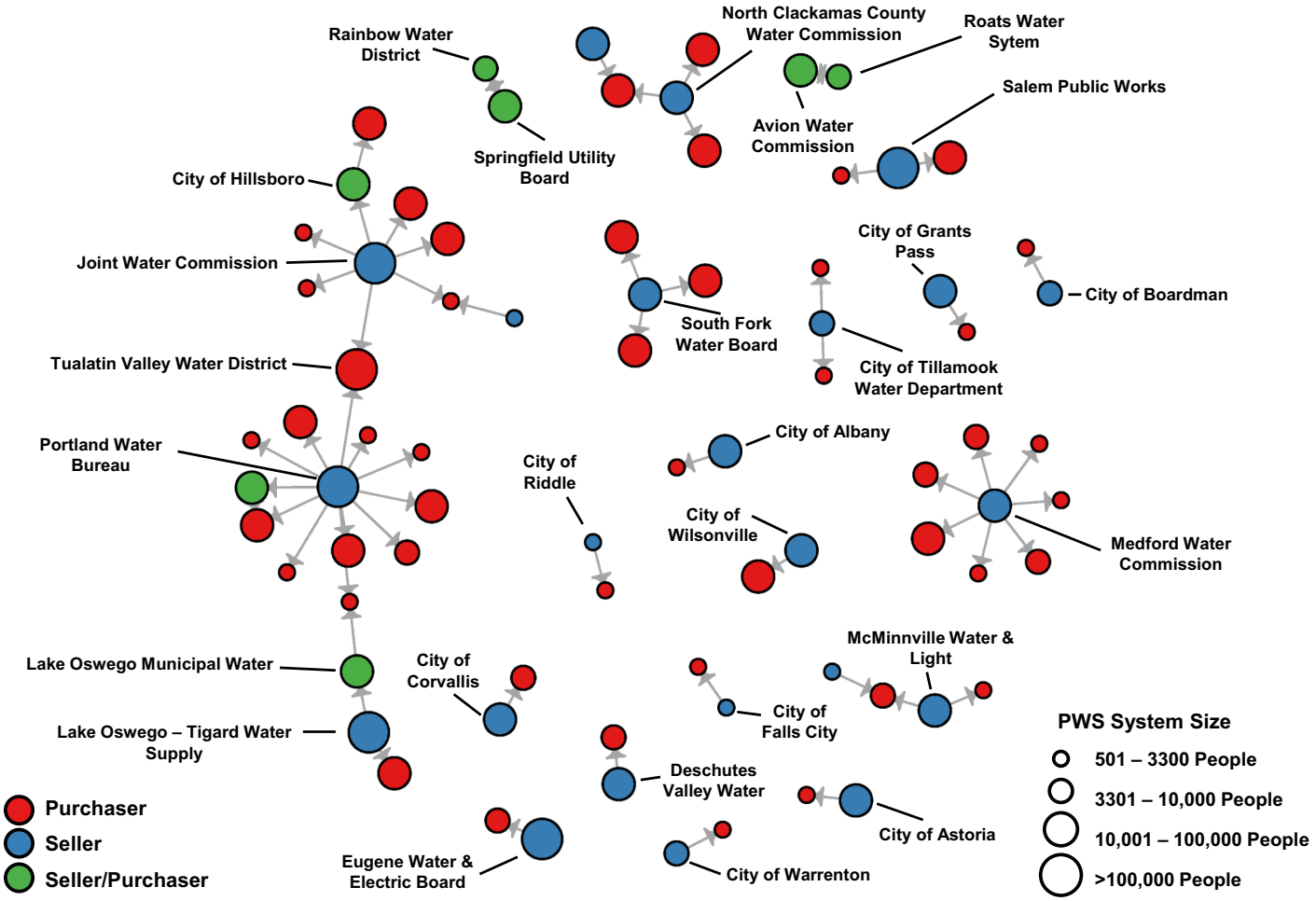


Fig. 4. Public water system network graph. Arrow pointing out represents "selling to." Size of the node is proportional to population served by each water system.

Table 2. Network metrics for water buying and selling relationships among 78 public water systems

Metric	Abbreviation	Median	Mean	Min	Max	Summary
Degree in (purchase)	DI	1	0.78	0	2	Most systems do not purchase
Degree out (sell)	DO	0	0.78	0	12	Portland Water Bureau is the largest retailer
Betweenness	BTWN	0	~0	0	0.000171	Very few bridging nodes
Closeness	CL	1	0.99	NA	1	Majority (48) of nodes are isolated (NA)
Components	COMP	—	—	1	20	20 connected subgroups of systems
Community	COMM	—	—	1	22	22 community clusters

metropolitan area (Portland metro area), (2) midsize regional suppliers, and (3) small rural suppliers.

Suppliers in the Portland Metro Area

Unsurprisingly, Portland Water Bureau is the largest retailer in the state, providing water to 12 other water systems (DO = 12), of which 3 also sell water to other water systems. The largest cluster within the network consists of the Portland Water Bureau, which is linked to the Joint Water Commission (tied for second-highest number of buyers, DO = 7) and Lake Oswego-Tigard Water Supply through the Tualatin Valley Water District and Lake Oswego Municipal Water, respectively. This cluster, serving the greater Portland metro area, is the largest connected component in the network and includes several of the systems with the highest degree values. It also serves the highest population areas within the state.

In addition to this large cluster, two other clusters, the South Fork Water Board and the North Clackamas County Water Commission, which each provide water to three other agencies (DO = 3), are also located in the greater Portland metro area, and each source water from the Clackamas River. This means that almost all of the large clusters (three or more links) in Oregon are in the greater Portland area. The exception is the Medford Water Commission located in southern Oregon, which provides water to 7 other suppliers (DO = 7), and is the largest non-Portland connected component.

Midsize Regional Suppliers

Outside of the Portland metro area, there are six PWSs that collectively serve more than 50,000 people, either directly or through seller connections (Table 3).

Medford Water Commission sells to seven other water systems that serve more than 500 people and 10 other water systems that serve fewer than 500 people (not shown in Fig. 4). Medford Water Commission, which sources water from the Rogue River and

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Table 3. Midsize suppliers outside of the Portland metro area

Public water system (PWS)	Number of PWS supplied, including themselves	Approximate population served	Surface water drinking water source areas (DWSAs)
Salem Public Works	3	215,935	North Santiam River → Willamette River
Eugene Water and Electric Board	2	180,080	McKenzie River → Willamette River
Medford Water Commission	8	135,659	Rogue River
Springfield Utility Board	2	68,400	Middle Fork Willamette River
			Thurston Well #2
City of Corvallis	2	60,670	Willamette River
			South Fork Rock Creek
			North Fork Rock Creek
			Griffith Creek
City of Albany	2	57,560	South Santiam River
			Santiam River

Note: Population served includes direct population as well as population supported by buying agencies.

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various groundwater sources, serves approximately 91,000 direct customers and 44,000 indirect customers.

The remaining midsize suppliers include some of the larger cities in Oregon beyond the Portland metro area, including Eugene, Salem, and Corvallis. All three systems are sellers to one to two other systems (DI = 0, DO >= 1), indicating their role as independent regional retailers. Notably, Eugene has only one source of water, the McKenzie River, but is planning to build a new treatment plant to establish the Willamette River as a backup source (Eugene Water and Electric Board 2024). Interestingly, one of the midsize suppliers, Springfield Utility Board, both purchases and sells water to the Rainbow Water District through shared groundwater sources, although Springfield Utility Board also sources surface water from the Willamette River. This reciprocal relationship places both systems among the seven systems statewide with dual roles (DI = 1 and DO = 1).

Small Suppliers

The remaining water systems that retail to others are relatively small (serving fewer than 50,000 people both directly and indirectly) and generally have low degree values. They typically belong to small, isolated network components, reflecting limited interconnectedness and redundancy. For example, the City of Falls City sells water to the Luckiamute Domestic Water Co-op, and the City of Tillamook sells water to the Long Prairie Water District and Pleasant Valley Water Company. However, the total population served, including those indirectly served, is less than 10,000 in each case.

Cluster Analysis

The hierarchical clustering analysis revealed four distinct clusters among the 115 included PWSs based on the natural hazards, infrastructure, and social stressors they face (Figs. 5–7; note that although the correlated variables were not part of the clustering analysis, they are still presented for each cluster). The geographic distribution of each cluster's DWSAs is presented in Fig. 8. The four groups can be characterized as follows.

Mixed-Use Private Property (Cluster 1, $n = 23$)

This cluster has by far the highest rates of private ownership (mean = 83% privately owned) as well as a considerable amount of cultivated land on average (7.8%). With the lowest average population served of any cluster (6,200 people), Cluster 1 generally represents smaller towns and surrounding agricultural land. Regions in Oregon with widespread agriculture and ranching, including the Willamette Valley and coastal areas, are heavily represented in this cluster, but the relatively large spread of impervious area indicates mixed land uses. It has the lowest average landslide risk (2.43) and slope (6.44%), representing relatively flat areas, but the highest mean k-factor (0.28), representing high erodibility. Consistent with the findings that smaller systems are overly represented among those with water quality violations, this cluster has the highest average System Score (1.3) and, discounting outliers (defined as beyond 1.5 times the interquartile range), the highest average number of points RTC'd (10.6).

Small-to-Medium Urban with Medium Wildfire Risk (Cluster 2, $n = 79$)

Clusters 2 and 3 are relatively similar, because both serve medium-sized populations. However, Cluster 2 has significantly lower fire risk than Cluster 3 and has a greater geographic spread, including wetter areas in the western part of the state. Nevertheless, many of these water systems still have a significant 30-year fire risk (average = 5.2%) and are in moderately mountainous areas with a higher slope and landslide risk. The spread of Gini-Simpson Indices is relatively large (0–0.67), representing some systems that pull from single source types (e.g., have access to plentiful surface water sources or that rely exclusively on groundwater), whereas others use multiple source types. Notably, almost all of the outliers in terms of the number of purchased sources—those with a high number of purchased sources—fall into this cluster.

Small-to-Medium Urban with High Wildfire Risk (Cluster 3, $n = 9$)

Like Cluster 2, Cluster 3 represents rural areas and small population centers, but this group is distinguished by having a much higher average wildfire risk than any other cluster (mean = 18.9%). This group represents natural landscapes in mountainous areas, particularly the Cascades, as indicated by the cluster's low impermeability (mean impervious = 0.38%) and low cultivated land area (mean = 0.05%) but high slope and landslide risk (11.3% and 2.7, respectively). It also has relatively low private ownership (mean = 18%), suggesting small towns surrounded by federal or state forested land, likely with significant Wildland–Urban Interface (WUI) area. The cluster's high average Gini-Simpson Index (0.5) suggests a mix of surface and groundwater sources within each PWS, a possible source of resilience to natural hazards.

Large Urban (Cluster 4, $n = 4$)

Cluster 4 is the smallest cluster, with four urban water systems: Clackamas River Water, the Joint Water Commission, the Portland Water Bureau, and the City of Wilsonville. These suppliers serve large, diverse, and relatively affluent populations. This cluster tends

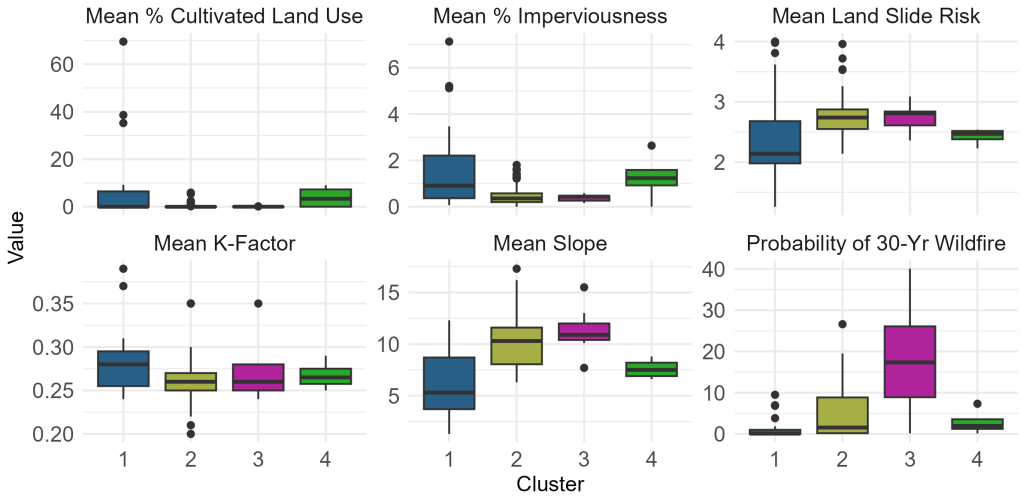


Fig. 5. Natural hazards by cluster.

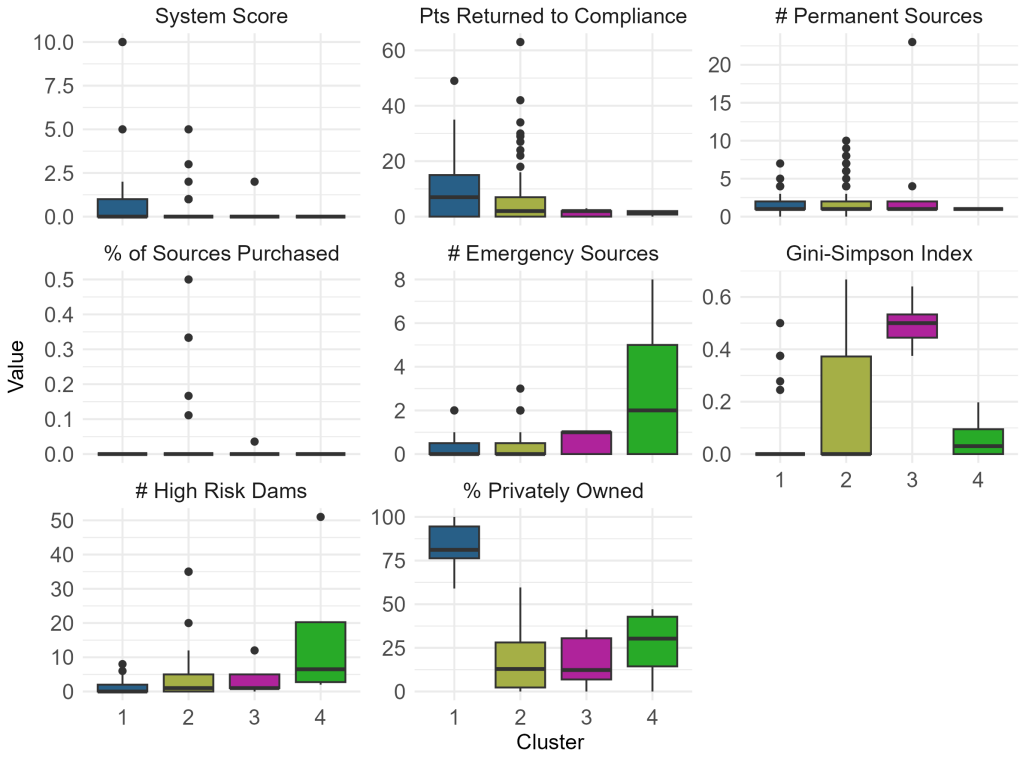


Fig. 6. Infrastructure stressors by cluster.

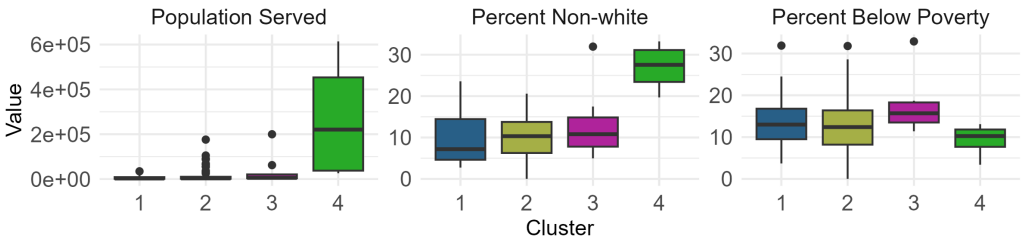


Fig. 7. Social stressors by cluster.

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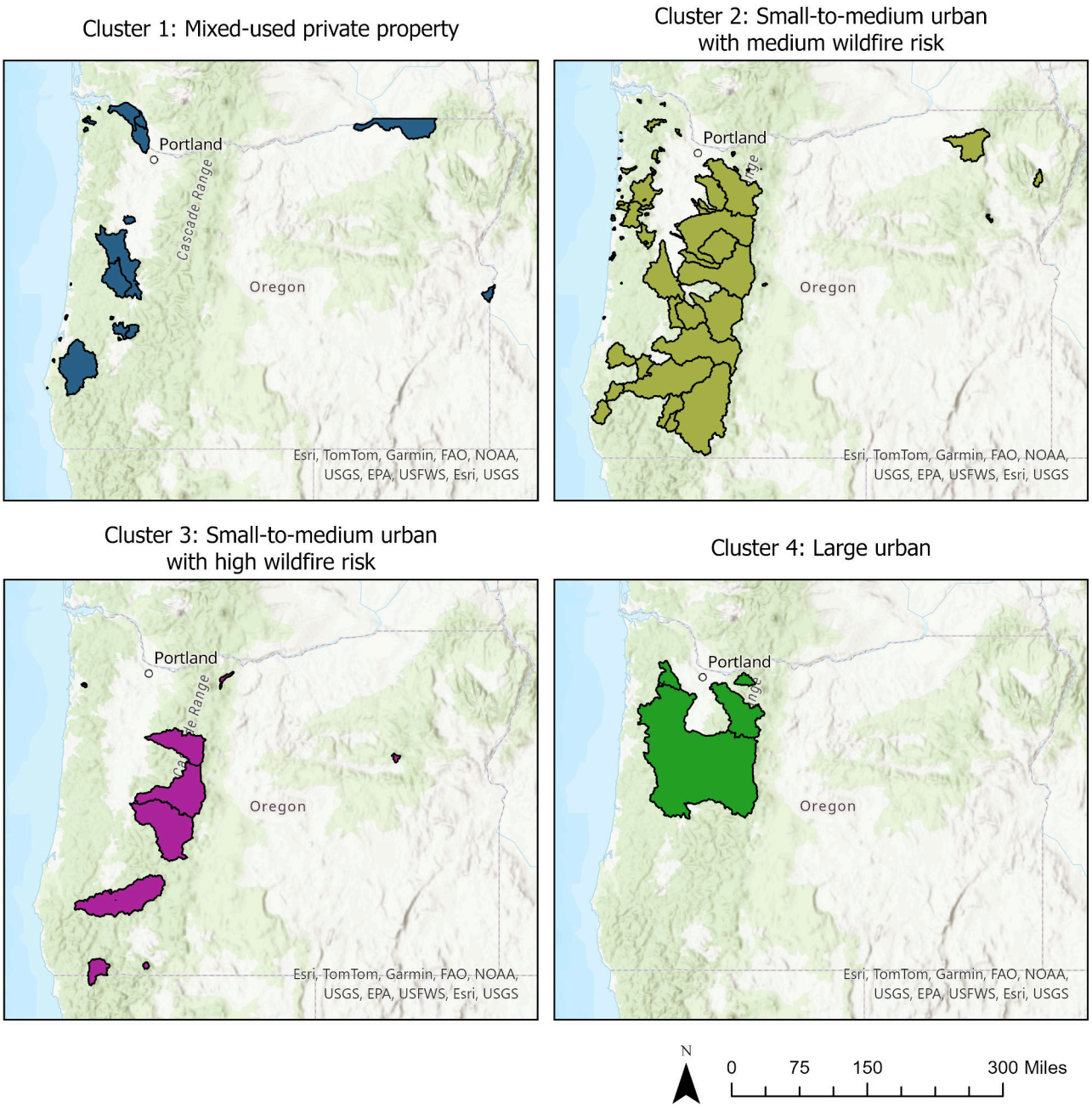


Fig. 8. Map of drinking water source area (DWSA) clusters. (Maps courtesy of Esri, TomTom, Garmin FAO, NOAA, USGS, EPA, USFWS, Esri, USGS.)

to have ample emergency sources and virtually no water quality violations. However, Cluster 4 still faces vulnerabilities, including a high number of at-risk dams (mean = 17 high-risk dams per PWS).

Discussion

Oregon Highlights the Diverse Challenges Facing Water Suppliers across the Western United States

Oregon's water supply system faces stressors similar to other regions throughout the Western United States, including wildfires, floods and landslides, changing populations, and aging infrastructure. This analysis represents an approach for mapping and assessing hazards and vulnerabilities across a diverse and decentralized public water system landscape, where only a few large water systems serve a disproportionate share of the population. The largest public water systems may have the structures and systems in place to manage potential stressors and hazards in the future, but a significant proportion of the population is served by midsize and smaller water suppliers, who may face greater resource hurdles and have fewer redundancies. The public water systems included in the network analysis serve a combined total population of about 3.16 million, or 75% of Oregon's total population. This leaves 25% of Oregon's population, around 1.1 million people (from a total population of about 4.24 million per the 2020 Census) (US Census Bureau 2020), relying on independently operating PWSs or private water supplies, which makes them more vulnerable to water supply disruptions due to a lack of system redundancy.

Within Oregon, most surface water source areas are undeveloped open space, with some cultivated (1.9% average) and impervious land use (0.75% average with 0–7.1% range).

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DWSAs have an average slope of 9.3% (range 1.3–17.3%) and a moderate-to-high risk of landslides. The average 30-year probability of wildfire across DWSAs is 5.5% with a maximum of 40%, although this is likely to be an underestimate of true risk, given the changing climate over the next 30 years. Our results indicate similar risks to those identified by a survey of Oregon water providers conducted in 2018 (Davis et al. 2021). In that study, survey respondents identified potential wildfire impacts (e.g., erosion and cover loss), turbidity/suspended sediment, forest chemicals such as herbicides, and increased wildfire risk as the most concerning water management issues. The study also highlighted the need for collaborative approaches, particularly small and informal partnerships (Davis et al. 2021).

The relatively siloed nature of Oregon's water supply also highlights the need for applied research that focuses on states with modest social, cultural, and financial resources. In such states, identifying opportunities for knowledge sharing and coordination is important, because these are relatively low-cost ways to reduce vulnerability. In contrast to Oregon, for example, California has received significantly more focus in terms of understanding water resource challenges, but it also has both a larger budget at the state level and a more extensive system of infrastructure that can promote redundancies during dry periods. Oregon's situation may more closely reflect that of other less-populated states with lower funding resources across the Western United States, which are all facing increased water resource challenges due to the effects of climate change, fragmented water infrastructure, and legacy land management practices.

Disruptions to the Portland Metro Supply Are a Potential Vulnerability, but Focus Should Not Come at the Expense of Midsize Retailers

Oregon's water supply landscape is relatively concentrated, with a few large water regional retailers serving most of the state's population. Only five water systems (Joint Water Commission, Medford Water Commission, North Clackamas County Water Commission, South Fork Water Board, and the Portland Water Bureau) sell or provide water to three or more other agencies; collectively, these five agencies either directly or indirectly serve approximately 2.1 million people, about half of Oregon's population. This diverse landscape calls for a tailored approach that can meet the needs of major public water systems for which source-water disruptions would impact a large number of people, without neglecting smaller water systems that may have fewer resources and supply redundancies.

All five of the large providers listed, except Medford Water Commission, are within the Portland metro area, where water sources are heavily concentrated in the Lower Columbia River watershed. While this covers a significant area with several tributaries, its importance for Oregon's largest urban area makes it critical for hazard mitigation. The region has already experienced acute stressors in the last several years, including the Camp Creek Fire in 2023, which burned less than 2 miles from the City of Portland's Headworks treatment facility (City of Portland 2023). Portland's water has historically not been filtered and is only subject to disinfection with chloramine. However, to comply with federal limits for cryptosporidium levels, a new filtration facility is being built and is expected to be completed by 2027 (City of Portland 2024).

Some coordination between water systems in the Portland metro area already exists through the Regional Water Providers Consortium, a network of 25 water suppliers that "provides leadership in the planning, management, stewardship, and resiliency of drinking water in the greater Portland, OR, metropolitan region" (Regional Water Providers Consortium 2024). All major suppliers (or their members, in the case of the Joint Water Commission and North Clackamas County Water Commission) are members of the Consortium. The Consortium's water source portfolio includes five major surface water sources (Bull Run Watershed, Tualatin River, Willamette River, Clackamas River, and Trask River) as well as groundwater sources and managed aquifer storage facilities. The first four surface water sources are within the Lower Columbia River watershed, while the Trask River drains into Tillamook Bay, located on the north Oregon coast. The Consortium focuses on conservation efforts, emergency preparedness, and regional coordination amongst water suppliers, with significant attention given to public outreach and engagement. Climate change, alongside other threats such as emerging contaminants, aging infrastructure, and supply chain challenges, was discussed in the Consortium's 2023–2028 five-year strategic plan, but the Consortium has not developed a specific strategic response (Regional Water Providers Consortium 2023).

Outside of the Portland metro area, midsize retailers represent significant hubs for water supply across the state and exhibit sufficient similarities that could indicate the potential for knowledge-sharing and collaboration. Collectively, the midsize regional suppliers identified in the network analysis provide water to 718,304 people, about 17% of the state population. Unlike the geographically clustered PWSs of the Portland metro area, these retailers are relatively siloed, with only Eugene and Springfield sharing a boundary between service territories. This limits their potential for creating supply redundancies through interconnections and calls for greater attention to creating diverse local portfolios.

All six midsize suppliers have at least one surface water source, while half (Medford, Salem, and Springfield) also rely on groundwater sources. Most draw water from the Willamette River or its tributaries. In the clustering analysis, all fall into either Cluster 2 or 3, indicating strong similarities in land ownership, land use, and population demographics. The primary difference is the level of fire risk, which is higher for Cluster 3 (Salem and Springfield). Given their geographic and source water similarities, as well as the overlap in their clusters, these agencies could benefit from shared learnings in natural hazard projections, risk mitigation and response plans, and conservation and resilience initiatives. At the same time, some critical needs, such as investment in physical infrastructure to protect water supply quantity and quality, will require irreducible resources to support comprehensive resilience for all midsize water systems.

Another critical factor for multiple midsize water systems is projected population change. Although Oregon's population is slightly declining, the cities of Medford and Eugene are expected to experience population growth over the next 20 years (League of Oregon Cities 2024; Population Research Center at Portland State University 2023), which may put pressure on existing infrastructure and require new development (Larsen 2023). Medford Water has a natural hazard mitigation plan that identifies wildfire, drought, earthquakes, and winter storms as "top-tier" natural hazards, while Eugene Water and Electric Board identifies earthquakes as a very high-risk hazard, and windstorms, winter storms, and wildfires as high-risk hazards (City of Eugene et al. 2020; Medford Water 2024). Increased population may exacerbate the risks posed by these hazards, not only through increasing demand but also because new development may be concentrated in higher-risk areas such as the WUI. At the state level, areas expected to experience population growth may be important targets for state resources.

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When Coordinating and Sharing Knowledge across the State, Spatial Proximity Is Not the Only Important Factor

The cluster analysis reveals similarities between public water systems that may not be geographically proximate. For example, Clusters 1 and 3 both represented DWSAs ranging from the coast, the Cascades Range, and the eastern part of the state. However, both within and across spatially diverse clusters, there are important opportunities for coordination and knowledge sharing. For instance, Clusters 2 and 3 highlight significant natural hazard exposure, namely wildfire risk as measured by the 30-year burn probability, but also landslide risk and average slope, which could indicate susceptibility to a compound hazard if rain follows a severe wildfire. Both are likely to benefit from investments in wildfire risk reduction and water supply resilience, such as the installation of backflow prevention devices in WUI structures. Cluster 3 also had the highest average percent of the population below the poverty line, which is critical for both the water systems in this cluster and the state government as a whole to consider in the formation of emergency response plans.

Having the same DWSA did not necessarily mean that two different PWSs would be placed in the same cluster, and significant spatial overlap is apparent between DWSAs in different clusters (Fig. 8). This suggests that PWS-related characteristics, such as population demographics and water quality indicators, were important in characterizing the clusters. Cluster 1, for example, faces several important infrastructure-related stressors. The cluster has a uniquely high average system score and the highest average number of points returned to compliance. The causes of these water quality challenges may differ across the cluster; for example, the cluster has a relatively high average percent of cultivated land and a relatively high percent impervious rate. With both metrics, higher values could lead to greater water quality challenges, but the former implies agricultural land use while the latter implies urbanization. However, Cluster 1 also has by far the highest share of DWSA land under private ownership, which could indicate a general challenge in protecting water quality due to a lack of access or land use controls. Policies and investment to support private landowner uptake of water quality protection measures—for example, planting cover crops, creating buffers around waterways, and supporting urban bioswales—could be cost-efficient ways of reducing water quality violations.

Finally, it is worth noting that a particular cluster has a broad range of values for a given stressor. Although Cluster 4 includes PWSs with some of the largest populations served, the range is large. Such broad ranges mean that average values, while useful, could obscure important variability that should be accounted for when forming strategic plans and partnerships among PWSs.

Recommendations for Future Work

Although the water system summary and network analyses included PWSs that source from groundwater, the clustering analysis was limited to PWSs linked to surface-water DWSAs due to the limited availability of groundwater source area data, particularly data on water quantity and future availability. Future work should further assess the vulnerability of groundwater supplies, because much of the state, particularly more rural areas, relies solely on groundwater sources. Such an analysis would also capture some of the very small PWSs excluded here, because they often serve only a few people through single groundwater wells.

The quantity of water sourced, indicating each system's water demand, was not included in this analysis. Only a subset (approximately 17%) of water rights holders in Oregon are required to report monthly water use, creating a highly limited view of water use in the state, despite water demand being a critical part of assessing the overall supply system (Oregon Water Resources Dept. 2024). Future work considering and comparing quantities of water sourced could shed more light on vulnerabilities within the system.

In addition, the social stressor data from the US Census is inherently limited in its ability to capture vulnerable populations such as unhoused individuals not connected to public water systems. Geopolitical factors such as changes in interstate and international water rights within the Columbia River basin may also impact water supply availability but were not considered. Access to Columbia River water is currently governed by a 2024 three-year interim agreement between the United States and Canada (Government of British Columbia 2026) and changes this agreement could influence future surface water availability in the basin. Future work could integrate more robust and nuanced social and geopolitical data. Future work could also incorporate more acute hazards (e.g., earthquakes and volcanic activity), long-term drought effects, and water quality impacts on surface water supplies.

Conclusion

By creating and analyzing a comprehensive geospatial database of Oregon's water supply system, we present an overview of the water supply stressors and hazards that contribute to vulnerability and resiliency across the state. Oregon serves as an example to highlight the diversity of characteristics and needs associated with public water systems, particularly in the Western United States, and this analysis represents an approach for vulnerability assessment and disaster readiness across a broadly heterogeneous and decentralized public water system landscape. A network analysis reveals that just five water suppliers serving the greater Portland area and sourcing water from the Columbia River basin account for about half the population of the state. However, while disruptions to the Portland metro supply are a potential vulnerability, focus on this vulnerability should not come at the expense of midsize retailers, which provide water to approximately 17% of the state's population, nor should it come at the expense of small retailers with no supply redundancy. In addition, when coordinating and sharing knowledge across the state, spatial proximity is not the only important factor. A clustering analysis revealed several suppliers with source areas that have similar 30-year burn probabilities, landslide risk, and average slopes, yet are not geographically proximate. Findings suggest that water supply resiliency may be enhanced by targeted policy efforts and knowledge sharing beyond traditional geographic and watershed boundaries.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available in a repository or online in accordance with funder data retention policies. The PWS database and DWSA shapefile are available for download at Wolfand (2025).

Reproducible Results

Kathleen Bieryla (University of Portland) and three reproducibility reviewers downloaded the materials from the repository, recreated the computing environments, and used the directions to reproduce results in Figs. 3–7.

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Author Contributions

Jordyn M. Wolfand: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review and editing. Tessa Maurer: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review and editing. Kimberly Q. Seipp: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Resources; Supervision; Validation; Visualization; Writing – original draft; Writing – review and editing. Ariella Chichilnisky du Lac: Methodology; Validation; Writing – original draft; Writing – review and editing. Sahas Sok: Data curation; Formal analysis; Investigation; Methodology.

Supplemental Materials

Supplemental material associated with this article are available online at: http://www.hydroshare.org/resource/1da00454bf3740149fc50efd83327814.

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