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Social Vulnerability and Water Insecurity in the Western United States: A Systematic Review of Framings, Indicators, and Uncertainty

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Key Points:

- This study determines the influence and uncertainty associated with indicators of social vulnerability to water insecurity
- There is substantial uncertainty about the strength and/or direction of many indicator relationships to water insecurity conditions
- Integrated studies are vital as conceptual framing of social vulnerability and water security define which indicators are measured

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Water insecurity poses a complex challenge for the western United States. Large populations are exposed and susceptible to physical and social factors that can leave them with precarious access to sufficient water supplies. Consideration of social issues by water managers can help ensure equitable supply. However, how social factors affect water insecurity conditions remains unclear. This paper reviews literature on how social vulnerability influences water insecurity in the western United States. Through a meta-analysis, indicators measuring how dimensions of social vulnerability influence water insecurity were classified and hierarchical clustering was used to characterize the relationships among these vulnerability dimensions for the largest water-users—the agricultural and municipal sectors. The study then assessed uncertainty associated with social vulnerability dimensions and their indicators. There is greatest evidence for the influence of demographic characteristics, socioeconomic status, and exposure. Indicators of these determinants were mainly significant and exacerbated conditions of water insecurity. Evidence for indicators of social dependence and special needs populations was limited, although studies assessing these factors showed significant agreement on their influence on water insecurity. Conceptual framings of social vulnerability and water security determined which indicators were measured, whereas studies of the water-use sectors focused on differing associations of social vulnerability. These findings indicate the importance of recognizing the different contexts posed by water-use sectors and diverse conceptual framings. Further, some determinants such as living conditions remain important but underexplored drivers of a community's experience of water insecurity. Understanding the uncertainty associated with these measures has implications to equitable decision making.

Plain Language Summary Water security ensures sustainable access to adequate quantities of safe water to sustain livelihoods and economic and social well-being. Rapidly growing populations and changing climatic conditions make this a challenging task for the western United States. This study reviews previous academic literature to identify how they measured socioeconomic factors that impact water access, quality, and quantity for the largest water-users - the agricultural and municipal sectors - in the western US. Which social factors were measured depended on which water-use sector was studied, and whether the authors viewed vulnerability and water security as preexisting or emergent conditions. We found most studies measured characteristics of demographics, socioeconomics, or exposure. Characteristics of risk perception or health were studied less often, with less agreement on their relationship to conditions of water security. There are therefore different levels of surety associated with the available measures of social vulnerability to water insecurity. Water resources managers need to be aware of these differing amounts of surety in the measures used to assist their decision making. Our study explores what is known about different indicators of social vulnerability to water security. Further, we provide a framework comparing otherwise disparate research on the complex subject of water insecurity.

1. Introduction

Water insecurity exists where populations cannot maintain access to adequate quantities of water at an acceptable quality in order to sustain livelihoods, development, and human and ecosystem health (Bakker, 2012; Grey & Sadoff, 2007; Scott et al., 2013; United Nations, 2013). The result is a multifaceted social-environmental issue characterized by physical shortages, conflicts of access, and concerns over degrading water quality (Bakker, 2012; Bureau of Reclamation, 2021; Gerlak et al., 2018). Physical shortages occur where there is not enough water to meet water-user demands. Conflicts of access can develop where the legal authority to utilize water

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resources (i.e., water-rights) prioritizes the needs of one water-user group over another, or where costs prohibit some users from adequate access. Water quality issues stem from contamination in water that is unsuitable for its intended use. Protection against water-related hazards, and maintenance of political and social stability further influence water security concerns (Gerlak et al., 2018; Grey & Sadoff, 2007). All these characteristics can be exacerbated by prevailing socio-political conditions, meaning water insecurity is as much a social challenge as a physical one (Brooks & Brandes, 2011; Jepson, Budds, et al., 2017; Jepson, Wutich, et al., 2017).

Water insecurity is a growing challenge in the United States where increasing demands for water resources conflict with a decreasing supply exacerbated by droughts and a warming climate. Specific factors of water insecurity vary from place to place and can change over time; however, locations in the western United States commonly experience some combination of shortage, access, quality, and socio-political issues. Megadrought (Williams et al., 2020), less reliable rain and snowfall patterns (Dettinger et al., 2015; Garfin et al., 2018), increasing number of extreme heat days (Dahl et al., 2019; Vose et al., 2017), and shifts in peak and low-flow timing (Bureau of Reclamation, 2021) all affect the availability of water. Increased water demands to support growing populations and urbanization can compound issues of reduced availability and increase competition with agricultural water demands.

Although concerns of water insecurity are prevalent across the western United States, they do not affect all populations equally (Deitz & Meehan, 2019; Jepson, 2012, 2014; Meehan, Jepson, et al., 2020; Meehan, Jurjevich, et al., 2020; Roller et al., 2019). Social vulnerability frameworks have been used to provide insight into the factors contributing to water insecurity by describing the conditions via which societal factors shape exposure to danger, susceptibility to harm, and the ability to respond to harm (Adger, 2006; Birkmann, 2013; Burton et al., 2018; Cutter et al., 2003). An integrated understanding of how social vulnerability is measured across multiple views of water insecurity and water use would be helpful. This study aims to derive vital information on the societal conditions that contribute to water insecurity across the western United States by summarizing existing evidence on the link between social vulnerability and water insecurity. Specifically, we seek to identify the dimensions of social vulnerability inherent to water insecurity, the relative importance of indicators representing these dimensions, the degree of agreement on their level of importance across literature, and gaps in empirical knowledge on the influence of these indicators of social vulnerability to water insecurity. Findings are summarized by major water-use sectors in the western United States. By identifying relevant dimensions of social vulnerability and appropriate indicators representing them this study can provide two major benefits. First, the results can help direct future scholarship to close knowledge gaps around social vulnerability to water insecurity. Second, the study can guide water-resources decision makers to better understand the limitations associated with using indicator-based tools to define vulnerability as they work to help resolve water insecurity issues.

2. Water and the Western United States

West of the Mississippi River, millions of people suffer water insecure conditions as competing water-uses intensify with population growth and a changing climate in the already water scarce region (Bureau of Reclamation, 2021). This situation is predicted to worsen as increasing drought, floods, heat, and fires are expected to further degrade water quality and availability, affecting some communities more than others (Gartin et al., 2020; Harlan et al., 2006; Hoehne et al., 2018; Jenerette et al., 2011). Water insecurity in this region is exemplified by a 23-year megadrought in the Colorado River Basin. The Colorado River Basin provides water for substantial areas of Arizona, Utah, and Colorado, and partial areas of California, New Mexico, Nevada, Wyoming, and Mexico. The megadrought is the driest period in the basin within the past 100 years, and one of the driest within the past 1,200 years (Bureau of Reclamation, 2021). However, drought is not exclusive to the Colorado River Basin. States in the central and southern areas of the western United States are also enduring water shortages from severe drought (Chen et al., 2012; Janssen et al., 2021).

Other climate trends are predicted to vary regionally. For example, increased average temperatures and decreased precipitation in the West and Southwest are expected to diminish water supply. In the Northwest, flooding from more intense storms may reduce water quality for the Columbia River Basin (Idaho, Oregon, Washington, Wyoming, Montana, and Canada) and Missouri River Basin (Montana, Wyoming, Colorado, Kansas, Nebraska, South Dakota, North Dakota) (Bureau of Reclamation, 2021; Queen et al., 2021). For river basins with headwaters in the Rocky Mountains, annual snowpack substantially contributes to streamflow. Higher temperatures will melt snow earlier, increasing seasonal streamflow from December through March and decreasing streamflow from April through July (Bureau of Reclamation, 2021; Janssen et al., 2021). The outcome is a discrepancy between water availability and time of highest demand for agriculture, one of the largest water-use sectors (Herman-Mercer et al., 2023).

Increasing temperatures, drought, and decreased streamflow combine to create optimal conditions for wildfires by increasing fuel availability and the probability of ignition (Engström et al., 2020; NOAA & NIDIS, 2021). Wildfires threaten water security in several ways. First, fire suppression is extremely water intensive. In 2020, the worst wildfire season in the modern history of California, 10,000 fires burned about 4% (4.2 million acres) of the state's 100 million acres of land (CalFire, 2023). The Department of Forestry and Fire Protection of California used up to 132 aircraft daily, delivering 11 million gallons of retardant and 18 million gallons of water (Cart, 2021). Second, water quality is also threatened post-fire by increased erosion and risk of flash floods. Contaminants, ash, large debris, and sediment can wash into water bodies for years after a fire (Bureau of Reclamation, 2021; Kinoshita et al., 2016).

Flooding can also jeopardize access to and quality of water resources. Huang and Wang (2020) and Hong and Chang (2020) noted the significant economic cost of floods, amounting to billions of dollars in losses over the last decade nationally. Such loss limits the ability to maintain critical water-infrastructure, over time, affecting water quality. Even in areas where precipitation is forecasted to decrease, the frequency and magnitude of flood events are expected to increase as annual precipitation becomes concentrated in fewer, more intense storms, and as flows linger above flood stage longer than usual, stressing water control infrastructure (Blum et al., 2020; Bureau of Reclamation, 2021; Hodgkins et al., 2019).

Reservoirs and dams established to control flooding, serve as sources for irrigation, drinking water, and energy providers are expected to experience reduced flows, intensifying tensions between water-use sectors. The Colorado River Basin megadrought has resulted in Lake Mead's lowest recorded levels. Although 75% of the reservoir's water is used for agricultural irrigation (Bennett, 2022), Lake Mead provides drinking water to 20 million people, and energy to 8 million people (Herman-Mercer et al., 2023). Temperatures are expected to continue increasing in this region, and runoff is predicted to occur earlier in the year, depleting water and energy supplies in the summer when demand is highest (Bureau of Reclamation, 2021). A 0.5 to 2.5% loss of power generation is predicted for the Hoover Dam every year for the next 5 years (Bureau of Reclamation, 2021). The future of this and other similar water bodies is uncertain as climate change affects the efficiency, timing, and magnitude of natural recharge, while growing population leads to increased demands on the resource.

Conflicts of water access have also surfaced during the Colorado River Basin megadrought. The Doctrine of Prior Appropriation is a unique legal structure guiding water-resource use in the western United States (Macdonnell, 2015; Tarlock, 2000). Under this legal system, the first person to divert water for a "beneficial" use has priority over anyone subsequently granted access. "Senior" water-rights holders can use all their legal allocation, even if it disrupts or eliminates water availability for those with "junior" rights. This prioritization can be upheld regardless of the detrimental social or economic impacts for those with reduced access (Macdonnell, 2015; Tarlock, 2000). This results in management decisions that are, at times, misaligned with current or future socio-ecological system needs.

Some municipalities in arid and semiarid regions are actively promoting inter-basin water transfers, and purchasing water rights meant for future agricultural irrigation, repurposing them for municipal and industrial use (Gober et al., 2016). However, water management strategies to secure the resource are often not reflected in community behaviors. Up to 65% of residential water use is directed to outdoor purposes like pools and lawn irrigation (DeOreo et al., 2016). Water demand for lawn maintenance is a human determinant that culturally represents socioeconomic status and is typically reinforced by homeowners' association rules (Herman-Mercer et al., 2023; Robbins, 2012; Vine, 2018). This creates conditions where per capita water use in suburban, higher income, and predominantly White areas is significantly higher than more densely populated urban cores. Greater ability to pay for access to the resource and higher influence on policymakers also incentivizes Community Water Systems to prioritize expansion and service provision in higher income and often suburban areas (Mullin, 2020). The result is that older and inner-city developments where the elderly, poor, and minorities are often overrepresented tend to experience higher instances of interrupted supply and water quality disruptions associated with deteriorating infrastructure (London et al., 2021; Mullin, 2020). These competing uses and increasing land use changes from agriculture to urban areas indicate that reevaluation of current and future water-use priorities in this already water-deficient area would be beneficial.

2.1. The Social Vulnerability-Water Insecurity Nexus

Mullin (2020); Yellow Horse et al. (2020) London et al. (2021); Mendez-Barrientos et al. (2022); and Wutich et al. (2022) all indicate that sociodemographic characteristics are correlated with vulnerability to water insecurity in the western United States. Social vulnerability describes the societal factors that shape the ability of individuals, communities, or populations to resist impacts from external stresses, cope with impacts, or recover from their losses (Adger, 2006; Adger & Kelly, 1999; Blaikie et al., 2003; Cutter et al., 2003). In theory, individuals, households, or communities with higher social vulnerability are more likely to experience harm from a hazard or external threat (e.g., drought) and may be less able to cope with resulting effects. Age, race, income, wealth, and gender are commonly cited determinants of social vulnerability (Cutter et al., 2003; Flanagan et al., 2011; Karaye & Horney, 2020; Rivera & Fothergill, 2021; Wutich et al., 2022). In our theoretical framing, we include exposure as an additional element of social vulnerability because the characteristics of vulnerability associated with marginalization lead some people to be disproportionately exposed to external stressors or hazards (Blaikie et al., 2003; Marino & Faas, 2020; Pulido, 2000; Smith, 2006; Wutich et al., 2022). Exposure represents contact with an external source of harm and has long been associated with the social and structural characteristics which produce inequities in sensitivity and adaptive or coping capacity (Adger, 2006; Cutter, 1996; Turner et al., 2003). Social, political, and economic processes often result in vulnerable populations occupying places which experience higher frequency and intensity of hazards events, making them less desirable to other groups (Best et al., 2023; Wutich et al., 2022). Socially vulnerable groups are therefore more likely to be situated in harm's way. For example, renters are more likely than homeowners to live in places exposed to flash flooding, with lower income and African American renters more likely to reside in locations with higher hazard exposure (Oke et al., 2023; Peacock & Girard, 1997). Similarly, individuals occupying manufactured housing or mobile homes suffer higher exposure to heat and wildfire hazards (Pierce et al., 2022) and are also more overrepresented in flood-prone areas (Tate et al., 2021).

Infrastructure and institutional factors are major determinants of access to and reliability of water delivery in the United States. Native American, Black, and Hispanic households are more likely to lack adequate plumbing, with much of this "plumbing poverty" clustered in the western United States (Deitz & Meehan, 2019; Tanana et al., 2021). As an example, the Navajo Nation, a senior water-rights holder, lacks the financial and infrastructural resources to adequately access the water, reinforcing water insecure conditions (Tanana et al., 2021). The challenge of inadequate infrastructure is not unique to the Navajo, and although this lack of adequate plumbing is often considered a rural problem, a substantial proportion of the population exposed to water insecurity live in urban areas. Meehan, Jepson, et al. (2020); Meehan, Jurjevich, et al. (2020) found 471,000 households or 1.1 million people lacked piped water access between 2013 and 2017, with the majority (73%) of these households located in metropolitan areas, and nearly half (47%) in the 50 largest urban areas. Thus, although water-deserts can be physical features of climate, they are often unintentionally manufactured outcomes of social and institutional features.

Water insecurity places substantial stress on livelihoods and well-being. Social inequities produce conditions where the compound effects of chronic or long-term water stress, and the shorter-term cascading effects of more sudden and extreme events disproportionately fall on those most exposed to, most susceptible to, and/or least able to mitigate the effects of water-insecure conditions. Without sufficient support structures (both physical and institutional), households that lack safe, reliable, sufficient, and affordable water can therefore be pushed into more precarious conditions of water insecurity (Jepson, Budds, et al., 2017; Jepson, Wutich, et al., 2017). However, the lack of such support structures is often characteristic of being socially vulnerable (Blaikie et al., 2003; Rivera, 2022). Without consideration of social equity, programs designed to aid disaster afflicted communities can themselves perpetuate and exacerbate conditions of social vulnerability (Domingue & Emrich, 2019; Drakes et al., 2021; Hooks & Miller, 2006; Howell & Elliott, 2019; Kamel & Loukaitou-Sideris, 2004). Lastly, few programs are designed to support communities facing long-term effects of water insecurity. Existing support programs, such as the Federal Emergency Management Agency's (FEMA's) Building Resilient Infrastructure and Communities (BRIC) Program, do not focus on household needs. Most are designed to alleviate crop and livestock losses (through the U.S. Department of Agriculture e.g., Livestock Forage Disaster Program, Emergency Loan Program (Farm Loans), Noninsured Disaster Assistance Program, and Emergency Watershed Protection Program) or to help institutions with decision-making authority improve infrastructure (through Bureau of Reclamation e.g., WaterSMART Water and Energy Efficiency Grants, and WaterSMART

Drought Response Program) and so have limited capacity to reduce conditions of household vulnerability (NOAA & NIDIS, n.d.).

In effect, many of the factors that contribute to social vulnerability create environments in which those who experience conditions of water insecurity are likely to remain water insecure. Compounding factors such as population growth and changing climate may further exacerbate vulnerability in water-insecure populations while expanding water insecurity to other, previously unaffected, groups (Gleick & Iceland, 2018; O'Keefe et al., 1976; Tate, 2019). Without an understanding of how social vulnerability influences precarious conditions, decision makers cannot adequately combat the water security challenge.

2.2. The Opacity of Indicators

Over the past two decades, researchers and decision makers have increasingly relied on indicators to identify social vulnerability drivers and understand the intensity of their effects. Indicators are measurable variables, such as the size of the average household, representing determinants (concepts known or suspected to be contributing factors e.g., family structure) of vulnerabilities to a particular condition such as water insecurity (Tate, 2012). Composite indices, such as the Social Vulnerability Index (SoVI) of Cutter et al. (2003) and Social Vulnerability Index (SVI) of Flanagan et al. (2011) are combinations of indicators commonly used to represent generic vulnerability. These indices are valuable tools for large scale analyses (e.g., nationally). However, they lack important detail to fully understand hazard-specific exposures or other variations in vulnerability across livelihoods, populations, water-use sectors, or specific locations.

Composite indices of social vulnerability targeted at water insecurity often vary widely in the specific factors examined, the ways those factors are combined to represent common determinants of social vulnerability, or examine distinct types of water insecurity. For example, in determining socioeconomic aspects of vulnerability to drought, Naumann et al. (2014) used 17 indicators and proportional weighting of vulnerability dimensions (thematic groupings of determinants e.g., the "demographic characteristics" dimension includes the determinants "age" and "family structure"), whereas Naumann et al. (2019) used 15 indicators and simple arithmetic aggregation of the individual indicators. Nkiaka (2022) utilized six indicators to discuss access to water resources whereas Rosinger (2022) used four indicators to identify issues of water quality. This variability in indicators and modalities of their use make it challenging to determine true relationships between specific vulnerability indicators and water insecure conditions. Opacity associated with directionality and strength of indicator influence on vulnerability outcomes (such as water insecurity) has led to general criticism of indicator-based research on several grounds including statistical inconsistency (Spielman et al., 2020), failure to acknowledge unequal influence of determinants across different populations (Hinkel, 2011; Saltelli, 2007), and omission of complex interaction effects on vulnerability outcomes (Drakes et al., 2021; Rufat, 2013). Similar uncertainty in causal relationships between indicators of social vulnerability and conditions of water insecurity is a critical barrier to improving decision-support tools for water security.

This paper addresses the above concerns through a systematic review and meta-analysis of empirical research that identifies (a) the dimensions of social vulnerability essential to water insecurity in the western conterminous United States; (b) the relative importance of these social vulnerability dimensions to conditions of water insecurity in the agricultural, municipal, and ecological water-use sectors of this region; (c) the indicators used to measure these dimensions; and (d) the extent of agreement on the direction and importance of indicator influence to water insecurity. The goal for this synthesis is a framework for better understanding the relationship between social vulnerability and water insecurity that is actionable, rather than conceptual. For this reason, we focused on studies measuring aspects of this relationship, and excluded those discussing social vulnerability as a theoretical concept.

3. Data and Methods

3.1. Study Selection

This study is based on the PRISMA guidelines for systematic reviews (Page et al., 2021). To gather relevant studies, we conducted keyword searches of the Web of Science Core Collection, SCOPUS, and Geo Deep Dive databases using the search terms in Figure 1. These were applied to titles, abstracts, and keywords of articles published from 2000 to 2022, a period that saw a boom in water security research (Cook & Bakker, 2012). Use of

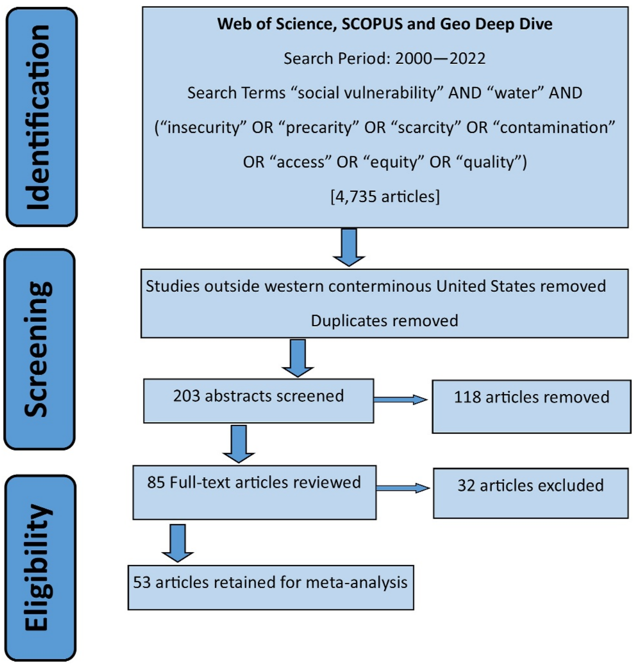

Figure 1. Data collection flowchart.

Boolean operators allowed the return of a broad selection of studies (n = 4,735), across multiple contexts, which were then reviewed by the research team. Results from each database were downloaded in BibTeX format. Because both social vulnerability and water insecurity are highly dynamic phenomena influenced by the interplay of physical conditions and socio-institutional factors (Adger, 2006; Gerlak et al., 2018), the assessment was limited to the conterminous United States west of the Mississippi River. A custom R script (R Core Team, 2022) was used to retain only titles or abstracts with keywords "United States," "USA," or "US," and abstracts were then manually screened to remove studies on areas outside the geographic scope of interest. Duplicate results were removed using BibTeX-tidy V 1.8.5 (West, 2021), a cleaning and formatting utility for bibliographic data. A custom script was then used to exclude reviews and editorials. A total of 203 articles were retained for review.

The article inclusion/exclusion procedure was performed in a multi-step process following Romero-Lankao et al. (2012). In step 1, abstracts were reviewed to identify articles suitable for full-text assessment. Suitable articles had to have been peer reviewed, published on or after 1 January 2000, and must have addressed some factor of water security (resource access, physical shortage, or degraded quality) and social vulnerability (exposure, susceptibility, or coping). During abstract screening, we excluded articles measuring only physical vulnerability, resilience, or adaptation, which we consider separate concepts from social vulnerability, narrowing the included articles to 85. This study seeks to identify how social vulnerability is measured in studies of water insecurity. We therefore excluded 32 additional articles that lacked specific focus measuring elements of social vulnerability. One article contained three distinct water insecurity models and was therefore included as three separate entries. After full article screening, a total of 53 studies containing 55 models remained for review and data extraction. The first three co-authors completed step 1. The co-authors met to define the inclusion/exclusion criteria and conducted a training session to code articles from a test sample. In each case the co-authors agreed on inclusion of the same articles. Each co-author was assigned one third of the data set and independently reviewed those abstracts for inclusion. Any abstracts for which there was uncertainty were reviewed by both remaining co-authors, and the first co-author then reviewed a random sample from the entire data set.

3.2. Meta-Analysis

In step 2, the first three co-authors reviewed the full text of selected articles. Due to time constraints, co-authors independently reviewed one third of the sample. Co-authors coded each article into the same data-collection matrix using a co-developed codebook (Table S1 in Supporting Information S1). The data collection used dropdown menus constructed in a Microsoft Excel spreadsheet to standardize inputs. The dropdown menus coded for elements such as thematic area of water insecurity, study scale, setting, natural hazards, dimension and determinant of social vulnerability, and direction and significance of indicator influence. In addition to the dropdown lists, the exact name/title of each indicator identified was entered for each study. The research team had two training sessions before beginning the process. During Step 2, co-authors were able to flag elements for which there was uncertainty about coding, and in regular team discussions the first three co-authors determined the best action for each point of uncertainty.

Following the approaches of Misselhorn (2005) and Romero-Lankao et al. (2012), we created a data extraction matrix based on our conceptual understanding of social vulnerability and water insecurity. This matrix helped analyze the articles in a systematic and standardized manner. Two training sessions helped to ensure intercoder reliability among the three co-authors completing this step. As previously outlined coding was done in a single spreadsheet and the first three co-authors met regularly to review coding decisions and clarify points of ambiguity. Each article was classified based on both the dominant sector of water use and the component of water insecurity considered. We then coded social vulnerability indicators measured in each paper, and the direction and significance of influence on water insecurity (Figure 2). Significance was coded as "statistically significant" if

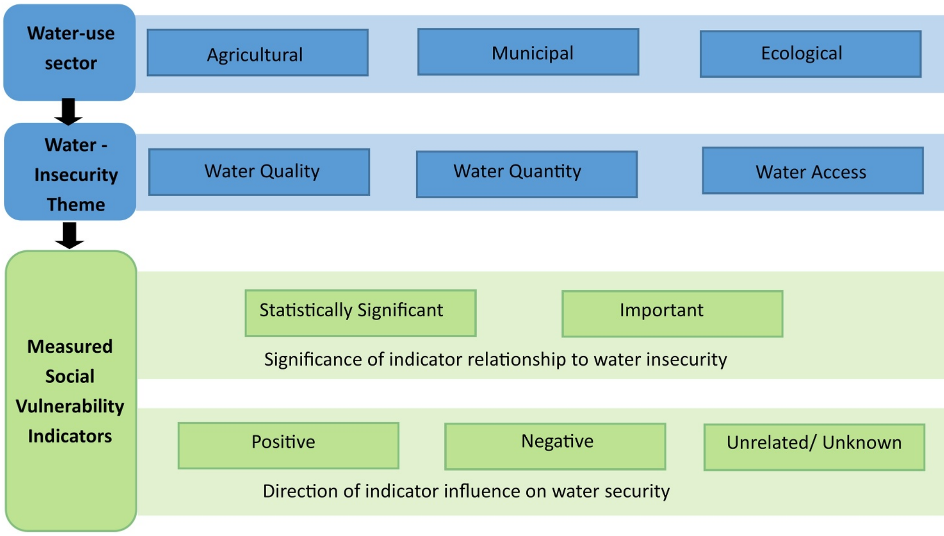

Figure 2. Classification and coding hierarchy of social vulnerability indicators from articles.

identified as such in studies using quantitative methods or "important" for studies using qualitative methods. See Literature Results Summary of Indicators in Hines et al. (2023) for a full list of coded indicators.

For the direction of influence, indicators were labeled as "positive" if they intensified conditions of water insecurity, "negative" if they alleviated conditions of water insecurity, "unrelated" if they showed no influence, and "unknown" in cases where no indication of influence was given. Closely related indicators were aggregated to reflect the broader concept, for example, population >65 years, percentage of population >65 years, and population >75 years were aggregated as "elderly." To further aid analysis, aggregated indicators were grouped into determinants representing related concepts such as "age" or "family structure." This process produced 358 variations of 106 indicators covering 55 determinants of social vulnerability (See Literature Results Summary of Indicators in Hines et al. (2023) for a full list of coded indicators). These determinants were then assigned to one of seven dimensions or themes commonly found in the social vulnerability literature (Bankoff et al., 2006; Birkmann, 2013; Ranci, 2010; Rufat et al., 2015; Thomas et al., 2013). These seven dimensions were demographic characteristics, land tenure, living conditions, socioeconomic status, health, risk perception, and exposure.

An example of the nested structure used in this study is shown in Figure 3.

To identify associations between the indicators measured, we computed co-occurrence matrices and hierarchical clusters using the corroplot R package (Wei & Simko, 2021). Co-occurrence matrices identified how often different dimensions of social vulnerability were measured together, and the statistical strength of these correlations. Clustering identified statistically significant groupings of social vulnerability dimensions based on the frequency at which indicators of different dimensions were measured together. The within cluster sums of squares was used to determine the appropriate number of clusters for each water-use sector.

A vote-counting methodology was used to synthesize results from the 55 models presented across the 53 articles studied. Each study, quantitative or qualitative, was regarded as a model. For each model, the measure of any variation of an indicator was recorded with a value of 1. Each measured variable was therefore given a single "vote" in the overall data set. This simple process facilitated the calculation of the frequency with which specific indicators and determinants were used. Attributes of each aggregated indicator were tallied across all models. This vote-counting approach has found growing application in meta-analyses as a way to assess related attributes across disparate study designs (Misselhorn, 2005; Romero-Lankao

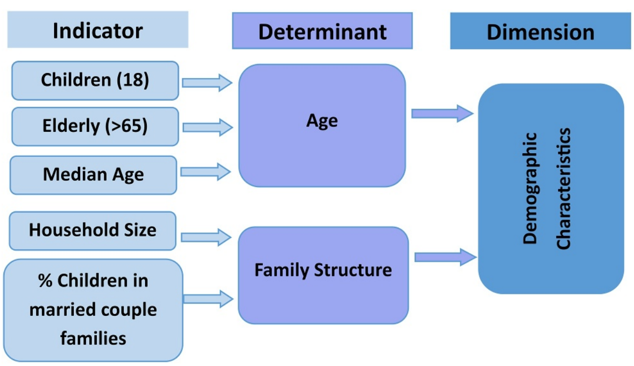

Figure 3. Example of the nested structure of indicators, determinants, and dimensions of vulnerability.

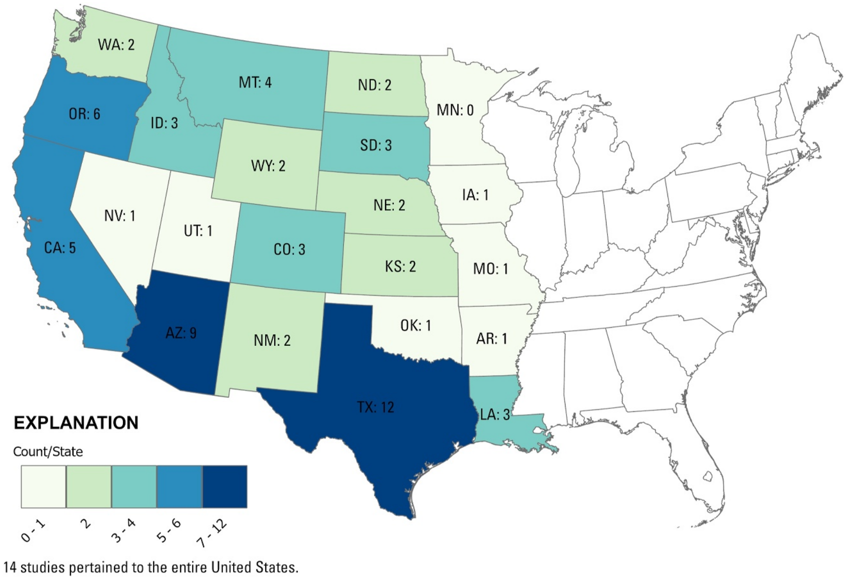

Figure 4. Geographic distribution of studies included in the meta-analysis.

et al., 2012). We assessed uncertainty for each social vulnerability determinant and associated indicators following the Intergovernmental Panel on Climate Change (IPCC) method of summarizing the level of agreement in directional influence across all evidence (refer to Mastrandrea et al. (2011) for greater detail). The level of statistical significance was not considered at this step because the quantitative studies used different thresholds of statistical significance and reliance on this method would exclude qualitative studies from the analysis. An indication of the strength of indicator relationships to water insecurity outcomes is reported in the Uncertainty Summary by Determinant of Water Vulnerability table within Hines et al. (2023) to allow readers insight into statistical significance.

4. Results

The number of studies included in the meta-analysis was greatest in the coastal and southern border states (Figure 4). The studies examined were typically conducted at the local scale, focused on mitigation, and primarily addressed challenges of water quantity (Table 1). Most studies assessed at least one hazard. Floods were most often examined (41% of studies), almost exclusively within the municipal context. Drought and climate variability were more commonly represented across all water-use sectors.

4.1. Typologies of Water Insecurity

Identifying typologies helped to understand the contexts in which social vulnerability and water insecurity were assessed in the literature. The water insecurity themes, and water-use sectors covered (Table 1) constrain how social vulnerability is conceptualized and measured in individual studies, and by extension the understanding of

Table 1
Focal Areas of Studies Addressing Social Vulnerability to Water Insecurity

		Water insecurity theme			Management phase				Spatial scale		
Sector	n[a]	Water quantity	Water quality	Water access	Preparedness	Mitigation	Response	Recovery	Local	Regional	National studies including sites outside study area
Agriculture	13	11	3	6	7	6	3	1	9	7	1
Municipal	43	23	11	13	10	25	6	5	35	6	5
Environmental	5	3	2	1	3	2	2	0	3	3	0

[a]*n* may total more than 55 as some studies covered multiple sectors and issues.

Table 2
Natural Hazard Context of Studies Included in Meta-Analysis

		Hazard						
Sector	*n*[a]	Climate variability	Drought	Flood	Surface water contamination	Groundwater contamination	Heat	Wildfires
Agriculture	13	6	8	1	1	0	2	0
Municipal	43	7	5	22	7	4	6	3
Environmental	5	1	1	0	1	0	0	1

[a]*n* may total more than 55 as some studies covered multiple sectors.

how social vulnerability influences water insecurity. Table 1 shows the frequency at which studies included in the meta-analysis covered specific focal areas. We found social vulnerability to water insecurity in the western United States has been examined mainly through the lens of the municipal water-use sector (78% of included studies; Table 1). These studies focused on mitigation and local scale issues, below county level. Water quantity issues were most often tied to flooding and water quality studies primarily focused on surface water contamination, although groundwater contamination and floods were also highlighted (Table 2). Water access was linked to water contamination, surface water, groundwater, and extreme heat.

Studies in the agricultural water-use sector primarily assessed drought (Table 2). Studies focused on issues of water quantity address preparedness and mitigation management phases, whereas studies examining issues of water quality focused on mitigation only. Studies focused on issues of water access examined climate variability in addition to drought.

The environmental water-use sector received the least attention from studies in our analysis (9%). It had relatively even coverage of water insecurity issues, management phase, and analysis scale. Due to the limited coverage of this water-use sector, we focus on the municipal and agricultural water-use sectors for our analysis.

4.2. Dimensions of Social Vulnerability to Water Insecurity

The studies in our meta-analysis examined water insecurity in the western United States using 106 indicators across 55 determinants. These determinants covered seven dimensions of social vulnerability: demographic characteristics, land tenure, living conditions, socioeconomic status, health, risk perception, and exposure (refer to Hines et al. (2023): Literature Results Summary of Indicators for full list of determinants and their measured indicators). Demographic characteristics, such as age and family structure, describe the structure, size, and dynamics of populations (Clark et al., 1998). These statistics provide information on the population, or specific subset thereof. Land tenure describes the conditions, such as ownership, under which property is occupied. Land tenure is often linked to the ability to cope with and recover from events because conditions of occupancy are tied to legal protections and can affect residents' access to assistance programs (Drakes et al., 2021; Lee & Van Zandt, 2019). Living conditions include determinants such as housing quality and population density, which describe mainly physical circumstances that populations occupy. Socioeconomic status describes the sociocultural and economic interactions (e.g., education and employment) that govern access to physical and political resources (McCoy & Dash, 2013). Health is associated with factors of mortality and morbidity and includes determinants of access to health resources and mortality rates. Risk perception describes how people understand their likelihood to suffer harm in a specific event (Sullivan-Wiley & Short Gianotti, 2017). Risk perception includes determinants such as risk denial/acceptance and prior experience with hazards. Exposure, which includes losses suffered and hazard extent, describes conditions of contact with external stressors (Kelman et al., 2017).

Exposure, demographic characteristics, and socioeconomic status were each evaluated in over 65% of the models included in the review (Table 3 and Hines et al. (2023): Sector Summary of Water Vulnerability). Health (21.8%), risk perception (30.9%) and land tenure (34.5%) were the least studied dimensions. Exposure, the most studied dimension (included in 71% of models), contributed 22% of total indicators measured. Demographic characteristics had the most indicators measured (28% of all indicators). Demographic characteristics and socioeconomic status were studied less frequently in agricultural than municipal water-use studies. Exposure and living conditions were the dominant dimensions of social vulnerability examined in agriculture sector studies.

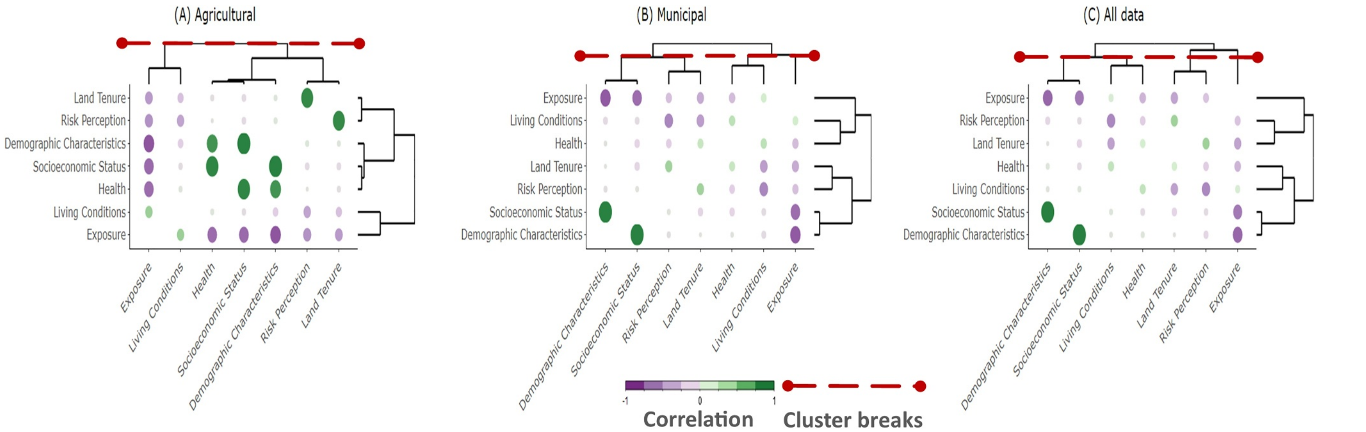

Figure 5. Clustered associations of social vulnerability dimensions in water-use sectors. Note: Colors get darker as correlations increase. Green circles indicate positively correlated dimensions. Negative correlations are represented in purple shades. Correlation represents how often indicators were measured together in the same study. Circle size is proportional to frequency of measurement.

4.3. Relative Importance of Social Vulnerability Dimensions to Water-Use Sectors

Through hierarchical clustering, we examined associations between social vulnerability dimensions determined by the frequency of indicators being measured together in the same study (Figure 5). The agricultural sector had two clusters (Figure 5a). The living conditions and exposure dimensions were positively associated in the first cluster, meaning that when the frequency of indicators measuring one dimension increased, so did the other. The second cluster contained the remaining five dimensions of social vulnerability. All were positively correlated, with demographic characteristics and socioeconomic status almost always measured together.

Amount Of Evidence	Low	Medium	High
Large		Renters Lifelines & infrastructure Land Use Population Education Income Awareness Exposed areas / facilities Other - physical considerations Mitigation	Age Race/Ethnicity Family Structure Gender Language Proficiency Resource Dependence Wealth Hazard Extent
Medium	Migration Potable water	Owners Rurality Urbanization Prior Experience Risk Denial/Acceptance Losses Suffered Preparedness	Social Dependence Vehicular access Employment Occupation Median Rent House Value Access Exposed Population
Small		Citizenship Political Inclination Tenure Length Food insecurity Trust in Officials	Special Needs/ Disabilities Housing Quality Housing Type Literacy social capital # of Events
	Level Of Agreement		

Figure 6. Determinants of social vulnerability to water insecurity; levels of confidence. Note: (1) Amount of Evidence: "small" if indicator measured less than 5 times, "medium" is indicator measured 5–9 times, "large" if indicator measured 10 or more times. (2) Level of Agreement: "low" if direction of influence category with highest tally has <50% of indicator total, "medium" if direction of influence category with highest tally has 51%–74% of indicator total, and "high" if direction of influence category with highest tally has >74% of indicator total. (3) Text color denotes different dimensions of social vulnerability; Green = Demographic Characteristics, Brown = Land Tenure, Blue = Living Conditions, Orange = Socioeconomic status, Purple = Health, Light Blue = Risk Perception, Pink = Exposure. Refer to Hines et al. (2023): Uncertainty Summary by Determinant for full data set on uncertainty.

In the municipal sector we found four clusters: (a) exposure; (b) land tenure-risk perception; (c) socioeconomic status-demographic characteristics; and (d) health-living conditions (Figure 5b). Exposure was typically measured by itself. Measures of demographic characteristics and socioeconomic status were usually co-occurrent.

Across the entire data set, studies examining exposure were less likely to examine other dimensions of social vulnerability, except living conditions, which had a weak positive correlation to exposure (Figure 5c). This likely reflects the weight of studies on the municipal sector. Land tenure and risk perception comprised a second cluster and were positively correlated with each other. This second cluster co-occurred infrequently with socioeconomic status and living conditions with which it was negatively correlated. The third cluster comprised demographic characteristics, socioeconomic status, living conditions and health. These dimensions were all positively associated with each other, and demographic characteristics and socioeconomic status were almost always measured together.

4.4. Areas of Surety and Uncertainty: Agreement on Significance of Indicators

Demographic characteristics (11 determinants, 28 indicators) and living conditions (11 determinants, 26 indicators) were the social vulnerability dimensions with most determinants assessed, and most heavily correlated with water insecurity. However, infrequent measurement meant evidence was limited for many of the individual indicators within every dimension. We identified 106 indicators related to the 55 determinants of social vulnerability. Demographic characteristics had the highest level of certainty among its determinants, 45% of its determinants had a large amount of evidence and high level of agreement on their influence (Figure 6). Eight determinants were measured only once: life expectancy, food insecurity, mortality, and sanitation determinants (health), group facilities (demographic characteristics), private property (land tenure), socially isolated populations (living conditions), and access to basic needs (socioeconomic status). Therefore, we could not estimate agreement level for these determinants. We organize the remainder of this section by social vulnerability dimensions. Because of the limited sample size of most indicators, we present a description of the entire data set. See Uncertainty Summary of Water Vulnerability in Hines et al. (2023) for full data set on uncertainty.

4.4.1. Demographic Characteristics

The measured demographic characteristics appeared mostly aligned to susceptibility, where some populations are more sensitive to shocks, and therefore are more likely to suffer harm. These studies found mostly positive correlations between indicators measured and conditions of water insecurity, for example, indicators “elderly” and “% households receiving social security or public assistance” were always positively associated with water insecure conditions. These relationships were mostly statistically significant/important (Hines et al. (2023): Uncertainty Summary of Water Vulnerability). Indicators of the age determinant were measured 36 times across 24 models. Elderly was most often measured as a sensitive group, with a high amount of agreement on this statistically significant relationship.

Ethnicity & race was the social vulnerability determinant most frequently included as a measurement of water insecurity in the reviewed literature. Measured 58 times across 30 models, ethnicity & race may be considered one of the most important social vulnerability determinants contributing to water insecurity. There was a large amount of evidence for the influence of Hispanic and Black populations, although for Black populations there was only a moderate amount of agreement on the direction and significance of this influence. There was high agreement that measures of Hispanic populations were significant and positively correlated to water insecure conditions. The reviewed studies showed medium amounts of evidence for the influence of Native American populations. However, all studies agreed conditions of water insecurity were more severe in places with higher Native American populations.

We recorded large amounts of evidence and high agreement for both gender and family structure. However, evidence on both determinants was limited at the indicator level, and both were only examined in studies on the municipal sector. The reviewed literature showed indicators of household size, female-headed households, female population, and percentage of females in the labor force were all predominantly positively related and statistically significant/important to water insecurity conditions (Figure 6; Hines et al. (2023): Uncertainty Summary by Determinant).

4.4.2. Land Tenure

Land tenure was one of the least studied dimensions of social vulnerability in both agricultural and municipal sectors. There was a large amount of evidence for the influence of renters, but inconclusive agreement on the direction of this indicator's influence (Figure 6; Hines et al. (2023): Uncertainty Summary by Determinant). Further, the influence of renter status was found to be significant in only half of the cases studied (Hines et al., 2023: Uncertainty Summary of Water Vulnerability).

4.4.3. Living Conditions

The dimension with the most determinants measured in the reviewed literature was living conditions. Specific indicators were infrequently measured by the studies assessed, resulting in a small amount of evidence for most indicators (Figure 6; Hines et al. (2023): Uncertainty Summary by Determinant) within this dimension. However, when measured multiple times, agreement on the direction of influence of these indicators was medium to high. Population density was the only specific indicator for which there was a large amount of evidence and was positively linked to conditions of water insecurity in all cases where the direction of influence was reported. There was a medium amount of evidence where rurality was linked to reduced conditions of water insecurity, mainly in the municipal sector.

4.4.4. Socioeconomic Status

Socioeconomic status was the third most often measured dimension of social vulnerability in the reviewed literature (Figure 6; Hines et al. (2023): Uncertainty Summary by Determinant). The amount of evidence was large for the education, income, and wealth determinants, although only the influence of wealth had a high level of agreement. We found high levels of agreement aligned with medium amounts of evidence for the influence of employment, occupation type, median rent costs, and house value. At the indicator level, there was a large amount of evidence and high level of agreement that populations with less than 12 years of education were more socially vulnerable and more water insecure. However, the statistical significance of this relationship was inconclusive. Higher levels of unemployment were always linked to increased water insecurity. The level of agreement was high that persons working in primary industries and the service sector were more likely to be water insecure, but for half of those studies we could not determine the significance of this relationship (Figure 6; Hines et al. (2023): Uncertainty Summary by Determinant). Median rent and house value were both negatively correlated with water insecurity, probably reflecting greater access to resources for wealthier populations.

4.4.5. Health

Health was the least often measured dimension of social vulnerability in both water-use sectors studied in the reviewed literature. Most indicators in this dimension were measured less than five times, four of them only once. The level of agreement was high that lower access to health care was correlated with conditions of water insecurity.

4.4.6. Risk Perception

Risk perception was the second least often studied social vulnerability dimension in the assessed studies. The amount of evidence for awareness of risk was large, although the amount of agreement was medium for its direction of influence. The amount of evidence was medium for the effect of prior experience, which was found to positively influence water insecurity in about 66% of studies where measured (Figure 6; Hines et al. (2023): Uncertainty Summary by Determinant).

4.4.7. Exposure

Exposure was measured in 70% of the models and was the second highest contributor of indicators measured in the literature. The amount of evidence was large for the influence of exposed facilities, hazard extent, physical considerations, and mitigation measures. However, of these, only hazard extent showed high levels of agreement on the direction of influence on water insecurity.

5. Determinants, Social Vulnerability, and Water Insecurity: What Do We Know?

5.1. A Question of Framing

5.1.1. Social Vulnerability

Academic literature reflects specific research paradigms and their ways of framing the cause of social vulnerability and water insecurity. The water-use sectors covered, and the pathways of influence investigated are tied to these frames, leaving some dimensions of this relationship poorly examined. We found two important ways of framing the causal connection between social vulnerability and water insecurity frequently asserted in the papers studied. The first presents social vulnerability as emergent from events associated with water insecurity. In this more commonly used approach, social vulnerability is but one outcome of events produced by external stressors. Studies taking this approach are more likely to focus on indicators of exposure and socioeconomics (Bixler et al., 2021; Shao et al., 2020). In the second framing, social vulnerability is presented as a preexisting condition from which water insecurity arises as an outcome of inequitable social conditions. As a root cause of unequal societal and environmental burdens, social equity and justice themes are more directly examined. Studies using this framing reduce focus on exposure but more frequently examine indicators related to health, risk perception, and living conditions (Carrão et al., 2016; Derner et al., 2018).

The choice of framing determines how much emphasis is placed on social vulnerability, and which determinants are assessed. Previous research by Romero-Lankao et al. (2012) on temperature related hazards and by Drakes and Tate (2022) on multihazard social vulnerability indicate this dual framing vulnerability is not limited to water insecurity. Multiple framings mean the context for understanding the social factors of water insecurity are different. This context is often shrouded as the underlying framing is not explicitly stated. This dichotomy presents a challenge for comparing results across studies, and for upscaling results from multiple (and more common—Table 1) local studies to understand larger regional patterns useful for designing water-use policy (O'Brien et al., 2007).

5.1.2. Water Insecurity

The water insecurity themes covered also frame which determinants of social vulnerability are studied and which locations are included, therefore influencing how the concept is applied using different metrics and geographic scales (Chang et al., 2013; Gerlak et al., 2018; Janssen et al., 2021). These operational features in turn influence who are considered decision makers, whose interests are addressed, and make some adaptations actionable while precluding others. Thematic framing determines who or which sectors are considered vulnerable. Our findings affirm this vulnerability-defining role of water insecurity themes. The water insecurity studies emphasize water quantity and access—how much water is physically available, and legal and operational hurdles to obtaining it (Table 1). This emphasis likely reflects the unique way water is managed in the West, primarily through the Doctrine of Prior Appropriation and the Bureau of Reclamation. Table 1 also indicates an imbalance in the water insecurity components examined by different water-use sectors. Water quality is mainly reported as a municipal issue. Studies in this metanalysis reported agricultural irrigation is less affected by high levels of nitrates or dissolved organic compounds, which tend to concern household water quality. Therefore, vulnerability in the agricultural sector is focused on water quantity and access for farms, with limited attention given to how irrigation needs limit municipal water use. However, municipal water quality is often affected by upstream activities. Industrial agriculture often has substantial effects on water quality (e.g., Neibergall, 2021) yet this spatial and often causal relationship was infrequently addressed in the sampled literature. Only 6 studies assessed both agricultural and municipal sectors, and these focused on the availability of adequate quantities of the resource.

5.1.3. Geographies of Assessments

This "geography of water insecurity" reveals two issues that received limited attention in the sampled literature: (a) scale of analysis and (b) spatial arrangement of what is being measured. The problem of scale is well known (Fekete et al., 2010; Ivory & Stevenson, 2019). At different spatial resolutions, data aggregation often produces measurably divergent results for the same location (Bisaro et al., 2010; Hinkel, 2011; Machado & Ratick, 2018). Indicator use may also be limited by data availability at the scale associated with individual water insecurity themes, resulting in different indicators representing the same conceptual determinant of vulnerability or ignoring some determinants entirely.

Table 3
Representation of Social Vulnerability Dimensions Across Water-Use Sectors

	Agriculture sector		Municipal sector		Total[a]	
Dimension	Measured Indicators	Models	Measured Indicators	Models	Measured Indicators	Models
Demographic characteristics	9	5	141	34	147	37
Land tenure	3	3	23	15	27	19
Living conditions	25	8	78	27	85	31
Socioeconomic status	11	5	96	33	100	36
Health	7	5	15	11	16	12
Risk perception	7	6	26	12	32	17
Exposure	54	11	97	31	115	39

[a]Totals may be less than sum of indicators or models in agricultural and municipal sectors as some studies covered multiple sectors.

Further dissonance exists with conceptualizing areas of measurement as political units versus drainage-basin boundaries. Although decision-making for water quality criteria occurs at municipal and institutional levels, water dynamics are watershed dependent. Political and drainage basin units seldom align, meaning decision-making and the social-ecological processes addressed are often spatially misaligned (Barham, 2001). Recent efforts in western states to consider downstream effects in addition to established water-rights reflect attempts at amending this incongruity (Bureau of Reclamation, 2023). Operational definitions of water insecurity are likely spatially diverse and based on locally salient issues (Cook & Bakker, 2012). Social vulnerability as an outcome appears to be more easily measured at larger geographic units, but the aggregation needed to achieve this may dilute important local context (Cook & Bakker, 2012; Hinkel, 2011; Saltelli, 2007). Similarly, water quantity and access appear most studied at municipal or higher aggregations. Integrated watershed management using nested scales approaches is a functional approach that would balance these competing scalar needs. Watershed based approaches complemented by analyses at municipal, regional, and other political/administrative based scales (Bakker, 2012) would facilitate integration with “soft path” approaches. “Soft paths” consider social and cultural dimensions of water use in decision-making, and have been proposed as an additional component to future western water policy (Brooks & Brandes, 2011). Ensuring equitable and just access to sufficient quantities of high-quality water is helped by understanding inequities at household and community level in addition to municipal, county, and irrigation districts.

The spatial arrangement of measurement units is also important for understanding water insecurity. Upstream activities exert considerable influence on water quality and quantity downstream. Doeffinger and Hall (2021) and Flores et al. (2020) illustrate this downstream effect. Climate variability and drought contribute to reduced water quantity and quality at locations downstream (Upton & Nielsen-Pincus, 2021; Vasquez-Leon et al., 2003). Industrial agriculture and large urban populations have similar negative effects on downstream areas (Chang et al., 2013; Harlan et al., 2006) but may also affect upstream locations as their water uses result in more of the resource being removed from the system (Herman-Mercer, Bair, Restrepo-Osorio et al., 2023; Hong & Chang, 2020). This patchwork of interrelated water insecurity issues further indicates the usefulness of an integrated, multiscale approach to address them.

5.2. What Is Important in the Context of the Western US?

The water-use sectors present distinct patterns in the dimensions of social vulnerability studied (Figure 5). Exposure (included in 85% of models) and living conditions (62% of models) were the dominant dimensions measured in the agricultural water-use sector (Hines et al. (2023): Sector Summary). Studies of the municipal sector focused on demographic characteristics (79% of models), socioeconomic status (77% of models), and exposure (72% of models) (Table 3). These differences are likely due to the distinct concerns for water insecurity themes across the two sectors and indicates an understanding of western water insecurity would benefit from an approach combining the different sectors.

Studies in the agricultural water-use sector were event centric and associated with water quantity. Measures of living conditions and exposure were dominant in this sector (Table 3, Figure 5) probably because they allow exploration of the physical conditions people occupy, and the extent to which people interact with the water insecurity condition (mainly water quantity). The frequency of indicators for poor living conditions increased along with those of exposure. As living conditions and exposure worsened, water insecure circumstances were more likely in the agricultural sector. This relationship was constant in all three water insecurity themes.

The municipal sector had greater disaggregation of social vulnerability dimensions with four clusters (Figure 5) indicating a broader, yet fractured approach to understanding water insecurity. The single dimension exposure cluster indicates many studies focused on determinants of exposure almost exclusively. The exposure heavy focus identifies where water insecurity conditions exist. Ignoring other determinants of social vulnerability produces a limited view of who disproportionately suffers conditions of water insecurity. Where other social vulnerability dimensions were measured, demographic characteristics and socioeconomic status were most often assessed. This combination provides a more balanced view of which populations suffer disproportionate burdens of water insecurity.

Within each dimension, most determinants measured were linked to the susceptibility and exposure components of social vulnerability. Framing social vulnerability as the likelihood to suffer harm and extent of contact with dangerous conditions is common in the natural hazards literature (e.g., Cutter et al., 2003; Emrich et al., 2020; Flanagan et al., 2011; Frazier et al., 2014). Its use here indicates a hazard centric view being applied to water insecurity. The hazard centric view is commonly applied to study single events in isolation. Such an approach may have limited utility for water insecurity, which exists in a compound context, where the interplay of prolonged and/or multiple overlapping events produces the unique conditions faced (Balch et al., 2020; Drakes & Tate, 2022; Zscheischler et al., 2018). Further, reliance on event centric indicators can obscure underlying social conditions producing vulnerability (Chmutina et al., 2021). This event focus may underlie the preference for vulnerability as an outcome frame over vulnerability as an underlying factor.

5.2.1. Gaps in Western Context

There was limited consideration of the coping capacity element of social vulnerability, which addresses the ability to withstand the effects of harm suffered. This limited utilization of short-term coping capacities indicates the understanding of water insecurity in the western United States is unbalanced and incomplete. This underbounding of vulnerability is common in the empirical literature which overwhelmingly relies on available census-derived variables associated with susceptibility (for examples see Cutter et al., 2003; Flanagan et al., 2011; Frazier et al., 2014; Kuhlicke et al., 2023; Shah et al., 2023; Tee Lewis et al., 2023). Communities experiencing conditions of heightened susceptibility and repeated exposures to hazards can develop extensive means of coping with these conditions (van der Geest & Warner, 2015; Venkataramanan et al., 2020). Reliance on the body of knowledge studied, with its limited consideration of the ability to cope, risks misrepresenting the true nature of relationships between social vulnerability and water insecurity. Such a mischaracterization can result in misalignment of policies and resource allocation with community needs. Communities with greater access to resources, particularly social and political capital, are likely to also have increased opportunity and ability to respond to the physical implications of their exposure. They are also more likely to have capacities (e.g., senior water-rights, purchasing, or storage) for coping with harm suffered due to their conditions of water insecurity (Venkataramanan et al., 2020). Facets of this concern may be captured in the long-term adaptation of resilience literature, which is outside the scope the current study, but the understanding of short-term coping remains underexamined. Without consideration of coping capacities, such communities may be portrayed as being more water insecure than they actually are. Workman and Shah (2023) have demonstrated how affluent communities can rely on these enhanced capacities to remain segregated from municipal water systems, maintaining conditions of higher susceptibility, as a tradeoff to sustaining political and social homogeneity and power. Conversely, communities with fewer resources to cope may exist in more precarious conditions than a susceptibility focused water policy may identify. The result can be inequity and compounding of water insecure conditions on already burdened populations (i.e., unjust, and unequitable water security outcomes). See Arcaya et al. (2020); Collins (2010); and Jerolleman et al. (2024) for a deeper discussion on how policy interventions can compound conditions of vulnerability. Policy approaches that combine the physical, economic, and social aspects of water insecurity are more likely to address these imbalances.

Demographic characteristics are a key dimension of social vulnerability, but unevenly applied in studies of water insecurity. Half of determinants associated with demographic characteristics were only applied in studies of the municipal sector. Studies of the agricultural sector did not consider family structure, gender, special needs/disabilities, or dependence on social services. Each of these is an important contributor to social vulnerability (Birkmann, 2013; Clark et al., 1998; Cutter et al., 2003). Although corporate-run, industrialized agriculture may be the dominant form in the western United States, small holder, family, and community operated farms are still an important part of the vulnerability picture in this region. By not considering these factors, water insecurity research in this part of the country may be missing key elements of social vulnerability.

With the possible exception of floods, it remains unclear how land tenure affects access to resources designed to reduce water insecurity. Land tenure is often linked to the ability to cope with and recover from events. Long-term coping and adaption are particularly important in repeat, or slow onset/long duration stressors such as water insecurity. Resource and recovery programs are often tied or heavily skewed to property ownership (Burby et al., 2003; Peacock et al., 2015; Rodriguez-Dod & Duhart, 2007). Such programs are important factors bolstering the ability to withstand, recover from, and adapt to the stressors inherent in water insecurity. Domingue and Emrich (2019), Drakes et al. (2021), and Peacock et al. (2015) have shown disaster recovery programs place renters at a disadvantage versus homeowners. Do similar inequities exist in programs targeting water insecurity? The limited research on the effects to renters (Table 3 $n = 19$; Hines et al. (2023): Sector Summary) indicates a critical knowledge gap between land tenure and water insecurity.

5.3. Uncertainty

Determinants with large amounts of evidence and high levels of agreement are ideal for assessing relationships between social factors and conditions of water insecurity. In theory, researchers could be assured of the scientific consensus on the use of these determinants (Figure 6) and incorporating them into decision-support tools only requires following norms established in the literature. Substantially more care is warranted when using determinants associated with lower levels of confidence. Empirical evidence remains limited for determinants with small amounts of evidence and lower levels of agreement (Figure 6). Before using the determinants in the lower third of Figure 6, more work could be done to validate the effects on water insecurity conditions, and to communicate the uncertainty associated with their use. This need for validating vulnerability measures at the index and indicator levels has been underscored by Painter et al. (2024), and Tate (2013). Further areas of uncertainty stemming from underlying data quality and accuracy are beyond the scope of this review but have been addressed elsewhere by Folch et al. (2016); Spielman et al. (2020); Spielman and Singleton (2015); and Tuccillo (2023). Decision makers are encouraged to understand the limitations of tools incorporating determinants with moderate to low levels of confidence, and to account for the associated higher levels of uncertainty in their policymaking processes.

Several social dimensions have limited evidence of measurement in the literature. Though renters in urban areas more likely to lack piped water (Meehan, Jepson, et al., 2020; Meehan, Jurjevich, et al., 2020) or be served by community water systems delivering water with unsafe lead content (Cade et al., 2023), land tenure was infrequently studied in the articles sampled by this meta-analysis. Where measured, land tenure showed mostly significant effects on water insecurity conditions. Given the importance of tenure for resource access (Burby et al., 2003; Lee & Van Zandt, 2019), further study on the relationship to water insecurity is vital. Likewise, limited research hinders understanding the relationship between health factors and water insecurity. Although health factors are known to be associated with water insecure conditions (see Karaye & Horney, 2020; Tippin, 2021; Yellow Horse et al., 2020), more research would be beneficial to understand the form of this relationship, and to build evidence for the utility of these indicators. Risk perception was among the least measured dimensions. This is unexpected given its importance in understanding and mounting a response to danger. For example, understanding indicators of social vulnerability to water insecurity associated with the prolonged and slow onset effects of droughts or burdens of increased costs of water access could be improved by understanding perceived risk.

The agricultural water-use sector lacks coverage of important social vulnerability determinants. This gap extends across all dimensions of social vulnerability but was most pronounced in demographic characteristics and socioeconomic status. Studies of this sector may be focused on effects surrounding industrial agriculture, with limited attention given to smaller family-owned farms or household level impacts of agricultural water use. The limited attention to demographics and socioeconomic status is also a plausible result of the sector's reduced focus on water quality. There is certainly a need for water quality related studies of social vulnerability as disadvantaged communities in agricultural settings are more likely to be served by unmonitored wells or out-of-compliance community water systems (Doeffinger & Hall, 2021; London et al., 2021; Wutich et al., 2022) and are at higher risk of interrupted water supplies (Mullin, 2020). The higher levels of uncertainty in indicators associated with the agricultural water-use sector may result from the small number of studies covering this sector.

Across all sectors, demographic characteristics were the most studied and understood dimension of social vulnerability. We found indicator use in this dimension had highest levels of confidence, with good evidence for, and agreement on use. The emphasis on susceptibility may be the reason for this dominance as the commonly employed social vulnerability models, SoVI (Cutter et al., 2003) and SVI (Flanagan et al., 2011) both assess the susceptibility component as does the water security index (Nkiaka, 2022). Demographic characteristics are a traditional focus for identifying susceptibility factors of vulnerability. However, attention to social dependence and special needs populations was limited in these studies, yet the factors represented by these indicators can substantially inhibit individuals' ability to withstand events. Limited research on their relationship to water insecurity may also mean limited consideration is being given to the requirements of these populations. This example highlights the uneven attention given to, and corresponding levels of uncertainty associated with indicators measuring different determinants of social vulnerability in the water insecurity literature. The significant variation that exists in the level of agreement and amount of evidence for indicators, even within commonly studied vulnerability dimensions, means analysis and decision-makers cannot treat all indicators with equal levels of trust.

6. Conclusion

We are not the first to review water insecurity research (refer to Romero-Lankao et al. (2012) on temperature related hazards and Gerlak et al. (2018) on global water security). The contribution of this study is to look across water-use sectors and thematic areas of water insecurity to provide a framework comparing otherwise disparate research on the complex subject of water insecurity in the geographic area of the western United States. Understanding vulnerability comes back to context. "Vulnerability to what?"—in our case, distinct thematic areas of water insecurity. "Vulnerability of what?"—agricultural and municipal water-use sectors. "Vulnerability of whom?"—populations with different needs and concerns and that are affected by different arrangements of vulnerability producing conditions. Reductionist approaches focusing on a single thematic area create a myopic picture of water insecurity. A holistic understanding of this problem would benefit from contributions from multiple views of water insecurity.

What is measured matters for determining how vulnerability is understood (Chmutina et al., 2021; Gerlak et al., 2018; Kappes et al., 2012; Machado & Ratick, 2018). Different conceptualizations of social vulnerability and water insecurity lead to diverging emphasis on vulnerability dimensions. Which determinants and specific indicators are used is therefore dependent on an author's focus on water quality, quantity, or access. Our findings affirm this bounding (and limiting) role of framing. This meta-analysis illustrates the benefits of intentionally assessing these divergent frames of water insecurity to ensure social vulnerability to water insecurity is adequately understood. Consolidative approaches such as integrated watershed management may provide practical ways of including these multiple frames in water-related planning. A nested spatial and temporal scale approach may help bind the socially driven decision-making elements of political/administrative units with watershed dependent physical elements. Socio-hydrology is another promising approach proposed for weaving together multiple framings of vulnerability and water insecurity (Bakker, 2012).

Several of the assessed studies recommend soft paths to redress conditions of water insecurity. Soft paths, however, warrant a critical look at decision-making, attention to who can participate in water management and planning, and what type of participation they are allowed to have (Brooks & Brandes, 2011). Studies that utilized the participatory process demonstrated success in understanding the interplay of vulnerability producing conditions, and therefore which indicators of vulnerability are relevant to a particular context. Participatory process can build paths toward equitable provision of water resources for all stakeholders. Although this review identifies social vulnerability indicators deemed important to water insecurity in the academic literature, validating these findings with communities experiencing social vulnerability would provide additional insight toward understanding how decision-makers might manage water resources to support all. Given the high levels of uncertainty associated with many indicators and the demonstrated role the framing of vulnerability and water insecurity plays in determining what is measured in the literature, stakeholder engaged research may be beneficial to address existing gaps left by limitations of the current literature. Participatory assessments can help determine how the relative importance of interacting social vulnerability indicators changes across communities. Likewise, community driven studies would build understanding of how decision-making processes intensify or attenuate the influence social vulnerability determinants, and ultimately water-insecurity outcomes.

Concepts of equity and justice remain poorly explored in the literature contributing to this meta-analysis. Water security is a highly contested topic in the western United States (Pahl-Wostl et al., 2016; Sheikh et al., 2015; Stern & Pervaze, 2023). Varady et al. (2016) note the water insecurity discourse remains fraught with resistance to address these topics, difficulty with defining and implementing measures for them, and limited in exploring them as potential paths toward achieving water security. Though recent studies have addressed these issues (see Arcaya et al., 2020; Collins, 2010; Méndez-Barrientos et al., 2023; Tippin, 2021; Workman & Shah, 2023), the lack of explicit attention given to equity and justice related drivers of marginalization and vulnerability in studies reviewed this meta-analysis suggests a continued need for research in this area. However, the limited framing of vulnerability as an underlying factor may also contribute to the infrequent exploration of equity and justice as root causes of water insecurity in the meta-analysis.

The amount of uncertainly associated with several dimensions of social vulnerability to water insecurity is large. The limited evidence for land tenure, health, and risk perception stretches beyond individual indicators, encompassing entire determinants and broader themes of social vulnerability. Given the importance of these dimensions of vulnerability, there is a large gap in understanding, and empirical evidence for or against the effects of these indicators would be beneficial to fully understand social vulnerability to water insecurity. The reviewed literature shows stronger evidence for the role of demographic characteristics, living conditions, socioeconomic status, and exposure in defining conditions of water insecurity. Uncertainty still fluctuates widely at the indicator level even within these determinants. Until empirical evidence for or against the effects of these indicators can be obtained, understanding of social vulnerability to water insecurity remains shrouded.

Data Availability Statement

Data for this research, including a full list of assessed articles, coded data entry tables, and analysis outputs, are available in the ScienceBase catalogue as Hines et al. (2023). *Literature Summary of Indicators of Water Vulnerability in the Western US 2000–2022*. U.S. Geological Survey data release, https://doi.org/10.5066/P93IDTUZ.

Software Availability: Co-occurrence matrices and hierarchical clusters were calculated using the corroplot R package version 0.92 (Wei & Simko, 2021), available under the MIT License at https://cran.r-project.org/package=corrplot.

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