Exploration of groundwater knowledge and private well programs across the United States

by

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Abstract

Groundwater serves one third of the United States (US) population as their main source of drinking water. Groundwater accessed from private wells serves about 15% of the population. Private well water is not regulated by the federal government, and less than half of states regulate private well water quality. Thus, the responsibility of management falls on the private well owner. Management involves many facets such as knowledge about well type, well depth, local hydrogeology, local landcover and land use, and how and when to test water quality. These factors contribute to water quality and may be difficult to find information about, furthermore implementing management may be arduous. Well stewardship, a form of management, is a way for well owners to learn about their wells and well water. Well stewardship includes annual testing of water quality and can be facilitated in many ways. One way stewardship is encouraged is through outreach, like private well programs (PWPs). PWPs utilize educational materials like online resources and handbooks as well as educational events like workshops and webinars lead by well water professionals to aid well owners in making management decisions. Previous researchers have evaluated barriers to well stewardship and effective methods for outreach PWPs to promote stewardship. However, there is no central resource about PWPs across the US. Therefore, the first objective of this study was to create an inventory and webmap of PWPs and resources across the US, and to identify areas that may need resources. Methods similar to a literature review were utilized, and search terms were generated and conducted on all 50 states and data was collected about programs and resources. In addition, few studies have used a mixed methods approach to understand how PWPs affect knowledge about groundwater. Without knowledge about groundwater and stewardship, well owners may not be aware of potential risks and ways to prevent them. Thus, the second objective of this study was to deploy the Groundwater

Concept Inventory (GWCI) to a well owner population to explore the differences in knowledge between well owners who participated in PWPs and those who did not. Statistical analysis revealed a significant difference between respondent's groundwater knowledge. Then, program coordinators of PWPs were interviewed to elucidate how programs engage with well owners using thematic coding.

Our results show that 64% of states had an established PWP and that 72% of PWPs are housed in Cooperative Extension. Results also found that 18% of states had no programs or resources (https://aub.ie/pwpinventory). This could be due to a small well owner population in the state or regulation in the state. The second objective results shows that private well owners that participated with a PWP had more groundwater knowledge than well owners that had not participated (*t*-Test = 2.18; p = 0.038), leading us to deduce that PWPs do result in more knowledge. Results from thematic analysis of interviews found four themes: Program Establishment, Program Purpose, Engagement, and Testing. The most common advice from interviewees was for well owners to test their well water, which PWPs can help with. The findings from these studies can be useful to program coordinators to connect with other states and develop programs in states without PWP. In addition, we encourage funding, access, and awareness of PWPs.

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I would like to dedicate my thesis to my Dad, Robert Foust. His faith, wisdom, and devotion to his family is unforgettable. Although he is no longer with us, I know he would have been proud. I would also like to dedicate this work to my Mom, Nathan, and Celeste. Without their unconditional love and support I would not be the person I am today. Thank you all.

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List of Abbreviations

CDC	Center for Disease Control and Prevention
E. coli	*Escherichia coli*
EPA	Environmental Protection Agency
GWCI	Groundwater Concept Inventory
PWP	Private well program
SDWA	Safe Drinking Water Act
SI	Survey Interview
US	United States
USGS	United States Geological Survey
WBDOSS	Waterborne Disease and Outbreak Surveillance System

Chapter 1

Literature Review

1.1 Introduction

There are two main sources of drinking water in the United States (US): surface water and groundwater (Center for Disease Control, 2022). Over one third of the nation's population relies on groundwater for drinking water, and 15% of the US population gets their water from a private well located on their property (DeSimone, 2009; US Geological Survey, 2015). Private wells are predominantly used in rural areas due to the lack of access to public water utility via expense or location (Murray et al., 2021). The Environmental Protection Agency (EPA) regulates public water supply under the Safe Drinking Water Act (SDWA) but does not regulate private well water quality (US EPA, 2015a). All states have policies involving drilling and construction of private wells, but less than half of states regulate water quality and maintenance (Bowen et al., 2019). Therefore, it is largely the private well owners' responsibility to manage and maintain their well and water quality.

Management is imperative to ensuring safe and reliable drinking water, like testing well water annually (US EPA, 2015a). Without proper management, well water may become contaminated with geogenic or anthropogenic contaminates and may lead to serious health issues like gastrointestinal problems or cancer (Fewtrell, 2004; Lee & Murphy, 2020; Wallender et al., 2014). However, managing a drinking water source may be difficult without adequate knowledge, access to resources, and awareness of potential risks. One solution to these difficulties is through outreach, like private well programs (PWPs). PWPs are non-regulatory programs established in some states to provide education and resources to private well owners about their private wells, water, and management strategies (Clemens et al., 2007; Fox et al., 2016; Morris et al., 2015). PWPs are essential educational opportunities to learn about wells and well water, however their existence, establishment, and engagement with private well owners have not been quantified. Thus, the main goal of this research is to explore the relationship between PWPs participation and well owners' knowledge about groundwater (here on referred to as groundwater knowledge), which may contribute to well owner's management behavior. The first objective was to create an inventory of PWPs across the US to identify where resources and programs exist, provide information to well users, and

highlight geographic areas that may lack resources with the overall goal of increasing access and awareness to PWPs. The second objective was to compare groundwater knowledge between private well owners who participated in PWPs to private well owners who have not participated to understand how PWPs participation affects groundwater knowledge and management behavior.

1.2 Private Well Water Management and Well Stewardship

Private well owners are solely responsible for the maintenance and management of their well and water quality (US EPA, 2015a), which may be a dauting task. Understanding groundwater and related processes are integral to making informed decisions and awareness of potential risks of contamination. Groundwater is water that has been absorbed by soil that travels in all directions through pores and cracks of sand, gravel, and rock until it hits an impermeable rock barrier (Brooks et al., 2012). Groundwater can then be accessed using private wells that are constructed deep enough to reach the water table and pull water up to the surface. The three types of wells are dug, driven, and drilled (US EPA, 2015b). Dug wells are typically shallow (e.g., 10 to 30 feet deep, and constructed using a shovel and casing with rocks (US EPA, 2015b). Driven wells are constructed using a pipe inserted into the ground and are around 30 to 50 feet deep (US EPA, 2015b). Drilled wells are drilled using machinery and are the deepest type of well (e.g., hundreds of feet deep) (US EPA, 2015b). The depth of a well in proximity to the surface of the ground can affect the likelihood of groundwater contamination, as shallow wells are more likely to face contaminants (US EPA, 2015d). Information about the type and depth of a well can be important to know when making management decisions as these variables can dictate the type and propensity of contamination (US EPA, 2015b).

The EPA defines a contaminant as any "physical, chemical, biological or radiological substances or matter in water", (US EPA, 2015d). Examples of each type of contaminant are sediment, pesticides, *Escherichia coil (E. coli),* and uranium (US EPA, 2015d). The location of a well in proximity to septic tank systems, livestock, fuel tanks, agriculture, and landfills can introduce contaminants (CDC, 2022). The type of soil and geology can also dictate the type of contaminants in groundwater (CDC, 2022). Microbiological contaminants including pathogens, bacteria, parasites, and viruses can come from underlying hydrogeology, improper

well construction, surface runoff from livestock, or nearby septic tank systems (Lee & Murphy, 2020; Swistock & Sharpe, 2005). Chemical contaminants such as nitrates, lead, polyfluoroalkyl substances (PFAS), arsenic, and manganese can be a result of improper construction, fertilizers, human and animal waste, industrial waste, and the surrounding environment (Arnade, 1999; Fewtrell, 2004; Lee & Murphy, 2020; Wheeler et al., 2015). Most of these contaminants can be hard to detect due to their colorless, tasteless, and odorless nature (Jones et al., 2006). The effects drinking contaminated well water can be serious health problems like gastrointestinal illnesses, kidney and liver issues, blue baby syndrome, and cancer (Fewtrell, 2004; Wallender et al., 2014). Health issues from contaminated drinking water make up about 30% of waterborne disease outbreaks reported to the Center for Disease Control (CDC) (Wallender et al., 2014). Therefore, it is important to reduce the risk of health problems via contaminated drinking water through proper management.

Private well water is also at risk of water quantity issues. Flooding and drought can result in private well owners not having a dependable water supply. Groundwater levels fluctuate, and monitoring weather and climate in the regional area can help determine if private well owners should test water quality after heavy rain events of conserve water during times of drought (Swistok & Sharpe, 2022; US EPA, 2015c). It is important for private well owners to understand risks and sources of water quantity issues to ensure adequate drinking water, especially with climate change multiplying these issues.

Well stewardship is a form of private well water management and well maintenance that includes regular testing and treatment of wells and well water (Malecki et al., 2017). Stewardship can also involve talking to neighbors who may also use a private well to raise awareness of local risks like a nearby landfill or being involved in an outreach program. Well stewardship can be paramount in detecting issues early and preventing contamination. PWPs aim to increase well stewardship behavior, specifically regular testing.

1.3 Barriers to Well Stewardship: Knowledge, Perceptions, and Inconvenience

There are three main barriers to well stewardship: lack of knowledge (Hooks et al., 2019; Imgrund et al., 2011; Morris et al., 2015; Schuitema et al., 2020), lack of perceived risk (Hooks

et al., 2019; Schuitema et al., 2020), and inconvenience (Flanagan et al., 2020; Imgrund et al., 2011; Morris et al., 2015; Seliga et al., 2021). Lack of knowledge includes knowledge about well management or about groundwater processes (Imgrund et al., 2011). If well owners' do not know that they need to test their water to detect contaminants, or do not know how to, they are less likely to conduct testing. Increasing knowledge could be conducted via outreach education about groundwater or emphasizing groundwater within the water cycle in K-12 education. Information about how groundwater may become contaminated and how to preventatively manage through well stewardship may increase awareness about well management. Additionally, when working with well owners their perceptions are an integral part of understanding their management behavior (Hooks et al., 2019; Schuitema et al., 2020). Compared to public water utility users, whose water is regulated by the government, well owners feel in control of their water (Hooks et al., 2019). This may be from the lack of regulatory interference. Well owners also like that their water is "natural" and comes straight from the ground (Hooks et al., 2019). These feelings of control and perception of naturalness may suppress feelings of risk, and lead to a lack of management action (Schuitema et al., 2020). Thus, accurately informing well owners of potential risks to their water and offering solutions may help inform their perceptions without causing them to feel overwhelmed. Lastly, inconvenience is another barrier to testing and well stewardship. This encompasses long drives to and from health departments to pick up and drop off testing materials, limited hours the health department is open that may conflict with working hours of well owners, or issues interpreting test results once they do arrive (Imgrund et al., 2011; Morris et al., 2015; Seliga et al., 2021). Each of these barriers may hinder well owners from engaging in well stewardship. Well stewardship is the first step in detecting and preventing serious well and well water issues.

1.4 Private Well Programs

Private well programs are a pertinent way to target well stewardship barriers by increasing knowledge, informing perceptions, and increasing convenience to testing and guidance (Morris et al., 2015). PWPs are free educational outreach programs that empower well owners to make their own management decisions by providing resources. PWPs serve well owners statewide, and exist in some states, but not in all states. PWPs are housed in Cooperative Extension, non-profits, or state agencies like department of health. Different methods for program delivery

include workshops, webinars, and contact with well water professionals, like program coordinators. PWPs address a multitude of topics from well drilling and construction, well head integrity, local hydrogeology, potential contamination and risk, and water quality testing and results guidance. PWPs have been the subject of previous studies (Fox et al., 2016; Imgrund et al., 2011; Morris et al., 2015) and efforts to promote well stewardship. Qualities that make PWPs successful in promoting stewardship are understanding their audience, targeting barriers, trust and credibility, and continued support for well owners (Morris et al., 2015). PWPs are a key part in increasing well stewardship, however there is often a lack of awareness and access to PWPs.

1.5 Groundwater Surveys, Interviews, and Inventories

Methods to understand private well owner's perceptions and knowledge about groundwater are integral in understanding their management behavior. If private well owners do not know they are at risk of contamination, they are less likely to preventatively manage or engage in well stewardship (Hooks et al., 2019). To measure private well owner's beliefs, perceptions, and knowledge researchers have turned to social science methods for collecting data (McDowell et al., 2020). Survey instruments allow researchers to ask curated questions to a specific audience and retrieve data quickly. Traditional methods for collecting survey data in a private well owner population include mail surveys (Hu & Morton, 2011) and online survey platforms (Huff & Tingley, 2015; Ojeda et al., 2023). When working with human subjects, utilizing multiple data collection approaches can be pertinent to understanding variables like knowledge and behavior. Qualitative data analysis has also been utilized and may include interviews with well owners (Hooks et al., 2019; Imgrund et al., 2011; McDowell et al., 2021; Schuitema et al., 2020) or focus groups with experts (Fox et al., 2016). A mixed methods approach, utilizing quantitative and qualitative data, can lead to a deeper understand of results especially when working with human subjects. In addition to understanding well owner's behaviors, beliefs, and perceptions, researchers need to understand the infrastructure that exists for well stewardship. Being able to access PWPs and understand differences in policies may help decision making when allocating resources and funding. An inventory of policy concerning wells has been created (Bowen et al., 2019), however, there is a lack of resources about PWP across the US.

1.6 Conclusions

Private well water serves roughly 43 million people in the US, or 15% of the population (DeSimone, 2009; Maupin et al., 2014). Proper management is critical to ensuring that this portion of the population has safe, clean, and reliable drinking water. Barriers to well stewardship like lack of knowledge, misperceptions, and inconvenience can be targeted by outreach PWPs to decrease barriers and promote stewardship. PWPs provide education about wells, well water, and continued support for well owners, which is important especially when interpreting test results. Despite the plethora of studies that exists on effective outreach to encourage well stewardship (Clemens et al., 2007; Fox et al., 2016; Imgrund et al., 2011; Kreutzwiser et al., 2011; Morris et al., 2015; Seliga et al., 2021), there are few studies about how PWPs affect groundwater knowledge among well owners. Understanding where PWPs exists, places that need more resources for private well owners, and how PWPs influence groundwater knowledge may yield new insights into management behavior change and increase in well stewardship.

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Chapter 2

An Inventory of Private Well Programs across the United States

2.1 Abstract

Private well owners comprise ~15% of the United States (US) population and are responsible for managing their well water. Management of domestic wells can be burdensome, requires knowledge, and is critical for maintaining clean drinking water. Management resources vary by state and the resource landscape across the US is unclear. Thus, our objective was to inventory where resources exist, while also highlighting geographic areas that may need improved resources to ensure that people have the ability to safely manage their drinking water. Results of this inventory showed that 64% of states have programs; 72% of which were Cooperative Extension programs.

2.2 Introduction

About 15% of the United States (US) population relies on private well water as their main source of drinking water (DeSimone, 2009; Maupin et al., 2014), and private well water quality is not regulated by the federal government under the Safe Drinking Water Act (US EPA, 2015a). Each state has policies concerning the drilling and construction of wells, but less than half regulate well maintenance or management of water quality (Bowen et al., 2019). Thus, roughly 43 million people are responsible for managing their drinking water source, which if left untreated, can contribute to health impacts such as disease outbreaks (Wallender et al., 2014). Barriers such as cost, time, and lack of access to information may hinder private well owners from managing their wells properly, which could result in contaminated drinking water and lead to illness (Flanagan et al., 2020; Swistock et al., 2013; Wallender et al., 2014). Consumption of contaminated drinking water has been correlated to adverse health effects like gastrointestinal issues or cancer (Fewtrell, 2004; Lee & Murphy, 2020; Wallender et al., 2014), thus it is critical to ensure that well owners are aware of these risks and provided with adequate resources to support their decision making and management behavior.

Management behavior (e.g., testing water quality, treating water, protecting well integrity) is a voluntary responsibility of well owners and may be overlooked due to a lack of access to resources and education. Therefore, well owners may be uninformed about how to properly manage their wells, water, and potential risks to contaminants (Clemens et al., 2007). Well water comes from groundwater, which is defined as, "water in saturated zones lying beneath the soil surface" by Brooks et al. (2012). A common misconception about groundwater is that it forms underground rivers, when in fact, groundwater exists around cracks of sand, gravel, and rock (Brooks et al., 2012; US Geological Survey, 2024b). When asked about groundwater storage with the Groundwater Knowledge Concept Inventory (Ojeda et al., 2023), a third (33%) of respondents chose, "underground rivers and streams", indicating that a large portion of the surveyed population holds misconceptions about the physical nature of groundwater. This notion has been observed in previous studies (Dickerson & Dawkins, 2004; Pan & Liu, 2018), and may have been perpetuated due to a lack of emphasis on groundwater in the water cycle in US National Science Standards (Dickerson et al., 2007). Another misconception is that soil acts as a natural groundwater filter therefore well water does not need to be filtered and is not contaminated (Hooks et al., 2019). However, soil does not filter out all contaminants and groundwater may contain unwanted substances that are naturally occurring (geogenic) or man-made (anthropogenic) (US Geological Survey, 2024a; Wallender et al., 2014). Often, contaminants go undetected due to the lack of color, odor, taste, or smell of the water (Jones et al., 2006). If well owners are not aware of fundamental groundwater concepts, and potential risks, and are relying on human senses (taste, smell, appearance) to detect issues, preventative testing of well water may be neglected, and contaminants may go unnoticed (Kreutzwiser et al., 2011; Malecki et al., 2017).

Barriers to effective management behavior may also be attributed to a lack of knowledge about management options, lack of perceived risk of contamination, and inconvenience (Gitter et al., 2023; Morris et al., 2015). Management behavior, like testing well water annually, is encouraged by the Environmental Protection Agency (EPA) (US EPA, 2015b), however well owners may be unaware of this guideline. Furthermore, well owners may be unaware how and where to have their water tested (Hooks et al., 2019; Morris et al., 2015). Past research has explored private well owners' management behavior from influences of their beliefs and perceptions (Hooks et al., 2019; Hu & Morton, 2011; Schuitema et al., 2020). Compared to public water utility users

whose water is regulated by the government, private well owners felt more in control of their water quality. Strong feelings of control may be from a lack in government interference and the sole responsibility of management falling on the well owner (Hooks et al., 2019). Well owners' feelings of control over their water may suppress feelings of risk of contaminated drinking water (Schuitema et al., 2020). These feelings of control and lack of risk may result in well owners being reluctant to test their water and engage in management behavior (Hooks et al., 2019; Jones et al., 2006; Kreutzwiser et al., 2011). It has been observed that well owners participated in testing when it was free to them, or when there was a person who was vulnerable to illness relying on well water (Hooks et al., 2019; Kreutzwiser et al., 2011). Thus, it is important to minimize barriers and to increase awareness of proper management behavior. Promoting well stewardship is an integrative way to target well owner's misperceptions about their well water, increase knowledge about management, and make management convenient to well owners (Fox et al., 2016; Gitter et al., 2023; Morris et al., 2015; Schuitema et al., 2020). Fox et al. (2016) defined stewardship as, "maintenance to prevent contamination and periodic water testing to detect contamination and prevent exposure." Encouraging well stewardship can be facilitated through outreach, workshops, collaboration, research, and policy to create a community and infrastructure to help well owners manage their water preventatively, instead of ad hoc or not at all (Charrois, 2010; Fox et al., 2016; Morris et al., 2015). Awareness of barriers to management may help in targeting effective solutions, like access to resources and support for well owners.

Educational programs have been shown to be key to ensuring private well owners have the tools and knowledge to adequately manage their well water (Morris et al., 2015). Private well programs (PWPs) were created to provide statewide education to private well owners and users about managing their home water systems and can be housed in various agencies like Cooperative Extension or state health departments (Clemens et al., 2007). PWPs offer resources about a plethora of topics from how to test well water and how to interpret test results, to treatment and filtering options. PWP materials are disseminated through workshops, webinars, online instructional materials, and communication with groundwater experts. Outreach PWPs develop relationships with well owners to offer continued support. By working with well owners and designing programming to meet the needs of the audience, PWPs can reduce barriers and foster new management behavior (Morris et al., 2015). PWPs are a way to encourage preventative and

routine management of wells and well water to people statewide, which can be a key piece in advancing well stewardship. Previous research has inventoried polices about private wells across the US (Bowen et al., 2019), however, there are no existing studies that locate non-regulatory, educational PWPs. This study aims to fill that gap in knowledge by creating an inventory to identify where resources and programs exist, provide information to well users, and highlight geographic areas that may lack resources with the overall goal of helping people safely manage their drinking water. Ultimately, the data and resources gathered in this study are essential for education about management of drinking water. Management of private well water may be perceived as overwhelming, but it is crucial for maintaining safe drinking water.

2.3 Methods

Data for this inventory were collected using internet search methods and specified search terms (Figure 1). The search focused on educational programs that were intended for private well owners about private well water. Common names of programs were "well owner network" and "private well program." Each phase was performed three times for every state, once on a personal laptop, once on an on-campus desktop computer, and once in an incognito browser to ensure that data collection was unbiased. We searched for preliminary data on programs in all 50 states using the EPA's "Drinking Water Well Programs in Your State" website (Figure 1, Phase 1) (US EPA, 2015c). For Phase two, search terms were generated using a combination of the state name and private well water terms (*i.e., [state] + private well program; [state] + well owner network; [state] + private well water*) and input into Google Search Engine (Figure 1, Phase 2). For example, "Alabama Private Well Program", "Alabama Private Well Owner Network", and "Alabama Private Well Water" were the search terms input for the state of Alabama. Lastly, we searched for PWPs through the Cooperative Extension Service that exists to educate and provide resources to citizens and are housed at land-grant universities (*Cooperative Extension History | NIFA*, 2024). After searching for each state's land-grant university, the predetermined search terms were used in each states' Cooperative Extension's website (Figure 1, Phase 3).

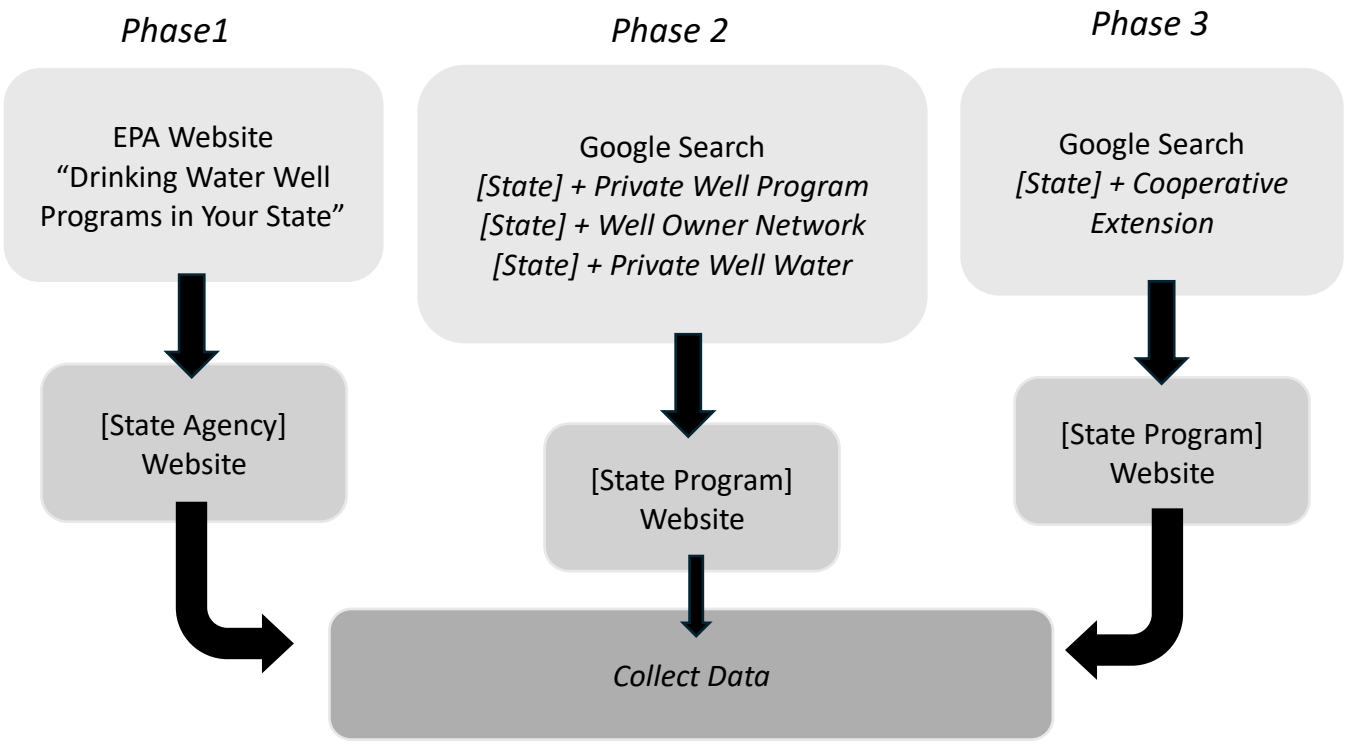

Figure 1. Process diagram for Internet search methods. Phase 1 used the Environmental Protection Agency's website, "Drinking Water Well Programs in Your State" to identify any state agency websites that provide resources, education, or testing for well owners. Phase 2 used Google Search Engine and a combination of search terms in all 50 states to locate state websites that may be through Cooperative Extensions, Non-Profits, or non-state agency websites. Phase 3 focused on Cooperative Extension programs. For each state and phase, relevant program data were collected on each state and recorded.

Data collected during the search included: program name, entity (where the program was hosted i.e., a state agency, University, or non-profit, etc.), department (what section of the entity, like state Department of Health or Cooperative Extension), year established, percent of the state population on private well water, website address, contact information, and any ancillary information like program materials if available. Based on the collected data each state was classified as having a private well program, resources, or none identified through internet search. If a state had a website with a named program, contact information, and any kind of educational materials, it was classified as a "program". States that did not have a named program or contact information, but had resources and materials were classified as "resources". Searches that found no informational websites or found regulatory websites were labeled "none identified through internet search."

To display results and share with stakeholders, a webmap was created using Esri's ArcGIS Pro (Version 3.2) to show PWPs by state with the information about each program displayed in the attribute table. A state shapefile was downloaded from Esri Data and Maps and joined with the program Excel file (US Census Bureau, 2022). The map shows the three classification levels and allows users to click on states and view what resources are available. Webmaps are an accessible way for people to view information spatially and use this layer as data in future studies.

2.4 Results

We found that 64% of states had a PWP (n = 32), 18% had resources (n = 9), and in 18% of states, no resources were found (n = 9) (Figure 2). Of the states that did have PWPs, Cooperative Extension housed the most across the nation (n = 23, 72% of total) (Figure 3). Four other agencies were found and included the state Department of Health (or Public Health), Department of Environmental Quality, Department of Health and Environment, and Non-Profits. The PWP name varied by state, with the most common names including "program", "well owner network", "project". Information in Figures 2 and 3 are examples of data included in the webmap (https://aub.ie/pwpinventory).

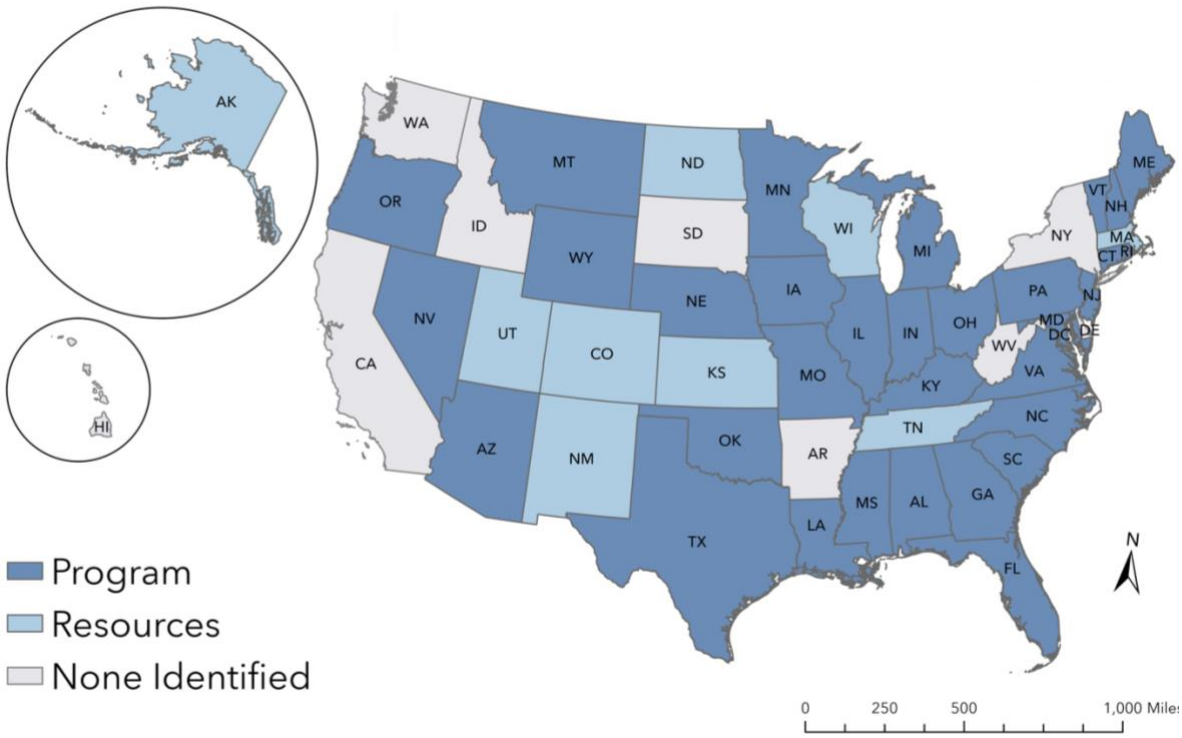

Figure 2. Private well program inventory of the US results with 64% of states (n = 32), shown in dark blue, have established programs that provide resources, education, or testing. States shown in light blue had online resources available (18% of total, n = 9) and states shown in white have no program or resources (18% of total, n = 9).

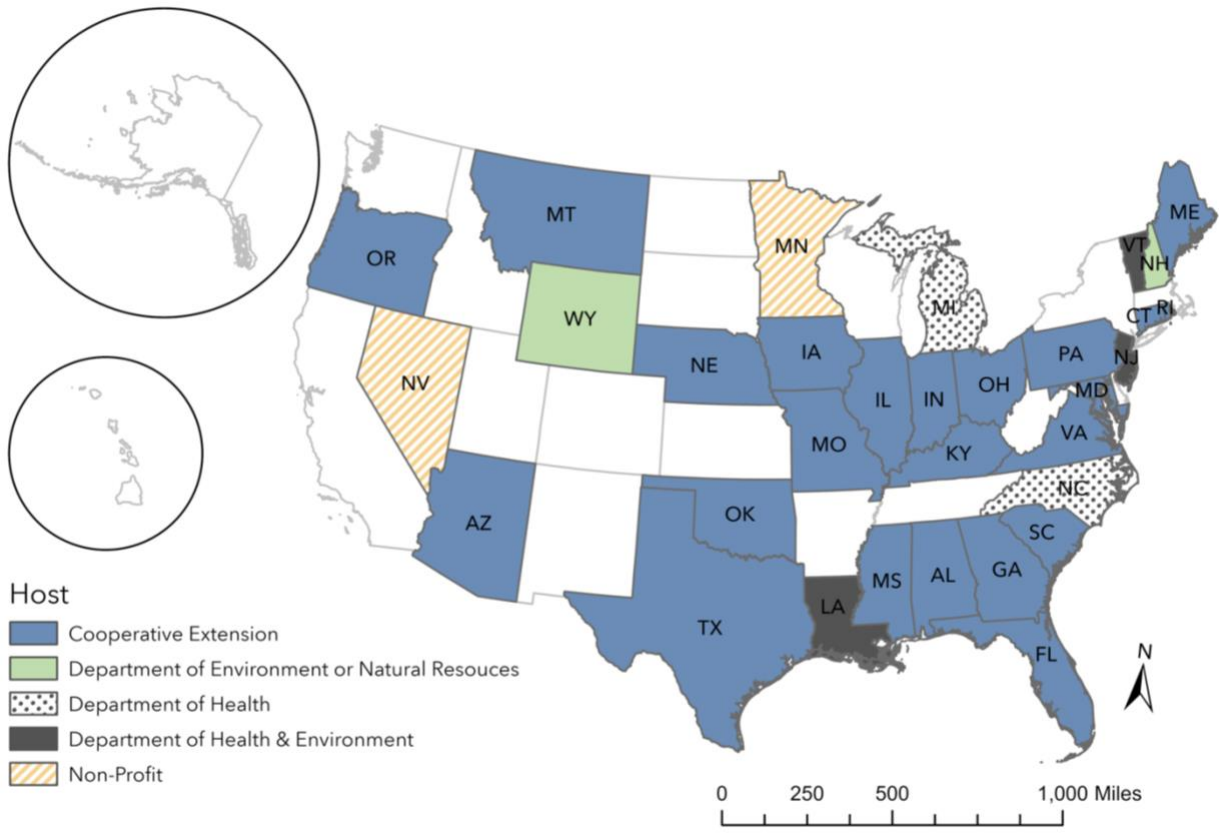

Figure 3. Map showing states that have private well programs and the respective agency or entity. Cooperative Extension has the most programs across the US (72% or n = 23). State Department of Health and Environment (shown in gray, n = 3) housed the second most, and state Department of Environment or Natural Resources (shown in green, n = 2), Department of Health (shown in dots, n = 2), and Non-Profits (shown in orange hatch, n = 2) all housed the same amount.

2.5 Discussion

Proper management of private well water quality may be a difficult task, especially without access to resources and educational events. This study aimed to increase awareness about effective management of private wells using internet search methods to build a dataset of programs and resources available to private well owners. Results indicated that more than half of states have programs, and Cooperative Extension housed the majority of PWPs. These findings help highlight established programs, and identify areas that may benefit from resources, such as the nine states where no resources were found (i.e., Arkansas, West Virginia, New York, South Dakota, Idaho, Washington, Hawaii, Delaware, and California). Identifying and consolidating data about PWPs into an inventory will increase awareness about PWPs and ease of access to educational materials,

which may lead to an increase in management like water testing, and in turn a decrease in water-related illness.

By mapping where programs and resources exist, it was observed that each state has different resources available. States where nothing was found could be due to a small percent of the states' population relying on well water. For example, no programs or resources were found in Arkansas, New York, or Utah, and in these states less than five percent of the population relies on private well water (Arkansas Department of Health, 2022; New York State Department of Health, 2023; Utah State University Extension, 2024). Despite a small percentage of a states' population utilizing well water, there may still be a need for program development and for well owners to gain information and assistance if needed, or connections to neighboring state programs where information is available. States like Pennsylvania, Virginia, Texas, Mississippi, Alabama, and Oregon all have established Extension programs that should be recognized as leaders in PWP development. These programs have websites, outreach events, online educational materials, and contact information to connect with an expert either at the state or county level. Resources like these are paramount when forming relationships with well owners and continuing support in well stewardship. Sharing of program delivery materials across states could lead to PWP formation in other states, PWP effectiveness evaluation (i.e., sharing of experience about what methods work best), and, thus, an increase in stewardship. In fact, several PWPs contribute the genesis of their program to Pennsylvania State University's Master Well Owner Network (Benham et al., 2016; Clemens et al., 2007). Findings from this study can be used to increase awareness of Extension PWPs for well owners, encourage program development for new PWPs, and advocate for funding opportunities to support PWPs.

The methodological framework used in this study could also be used for inventory creation of other educational programs like septic systems or household air quality programs (e.g., radon screening and testing). Once again, we stress the importance of access to education and programs to aid and empower homeowners in strategies of preventative maintenance that could ultimately prevent health issues.

Limitations lie within the online nature of this study. First, demographics of well owners are often older populations residing in rural areas (Malecki et al., 2017) where broadband internet may be sparse, therefore online resources may not be effective for that audience. However, many PWPs host in-person workshops which may connect well users to information that is housed online. Secondly, results found through internet search may not be up-to-date, or lack information about when the site was last updated. Similarly, programs that are funding-dependent could have existed but are no longer functioning due to grant completion. This study could be further verified by phone surveys, particularly in states where no resources were found, but that again proves difficult because no contact information is readily available online.

2.6 Conclusions

This study builds a PWP inventory by identifying and classifying programs, resources, and lack thereof, throughout the US. Consolidated information provides accessibility and awareness of states that are on the forefront of program development, and states that may have an opportunity for growth. Engaging with PWPs may be a pertinent beginning to understanding risks and management resources, encouraging preventative maintenance of wells, and empowering well owners to make their own decisions. The findings gathered by this study enforce the importance of well stewardship and program development so that people can confidently use their household water.

Applications of the inventory can be for personal use of well owners to find recommendations about management plans of their private well and well water. Whether a state has a PWP or not, well owners are encouraged to learn what different resources states provide in efforts to gain a greater understanding of groundwater. This inventory is also intended for program coordinators of PWPs to connect, share ideas and lessons learned. Disseminating information from this study could be most useful to states with no existing PWP or states wanting to develop a PWP. Inventory methods could be used in further studies to bring attention to other needs and potential programs. These findings promote the accomplishments and importance of Cooperative Extension programs, and we encourage program funding, engagement, and development.

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Chapter 3

Groundwater Concept Inventory reveals higher groundwater knowledge among outreach program participants

3.1 Abstract

Groundwater, specifically private well water, serves an estimated 15% of the United States population. Private well water is not federally regulated, and regulation may vary by state, thus it is the responsibility of the private well owner to manage and maintain their drinking water source. Management of a water resource may be difficult, and barriers of lack of knowledge, lack of perceived risk, and inconvenience can all deter private well owners from well stewardship. Outreach private well programs may help well owners with education and well stewardship to ensure their water is safe and reliable for consumption by targeting barriers. We used a mixed methods approach to explore if private well owners who participated in private well programs had more knowledge about groundwater than private well owners who did not participate. Deploying the Groundwater Concept Inventory (GWCI) in a well owner population (n = 142) and statistically analyzing groundwater knowledge measure, we found the private well owners engaged in private well programs did have a higher groundwater knowledge measure than well owners who did not engage with programs (*t*-Test Statistic = 2.18; p = 0.0383). We then interviewed private well program coordinators to understand how programs engage with well owners. Thematic analysis revealed four themes: Program Establishment, Program Purpose, Engagement, and Testing (κ = 0.74). Unanimously, all interviewees filled in the blank, "If I could leave one thing with well owners it would be," with, "To test your water". Ultimately, findings from this study could be used to deploy the GWCI in different populations and advocate for funding for programs.

3.2 Introduction

Groundwater accessed from private wells serves as the main source of drinking water for roughly 15% of the United States (US) population, however, private well water is not federally regulated like public water utility systems (DeSimone, 2009; Maupin et al., 2014; US EPA, 2015). Therefore, private well owners are solely responsible for undertaking the maintenance and

management of their well and well water. Without management, well water may become contaminated and may lead to serious health issues like gastrointestinal problems or cancer (Fewtrell, 2004; Lee & Murphy, 2020; Wallender et al., 2014). A United States Geological Survey (USGS) found that 23% of wells sampled (n = 2,167) from across the country had at least one contaminant present at concentrations surpassing recommended thresholds for safe consumption (DeSimone, 2009). Common contaminants affecting well water include nitrates, heavy metals, pesticides, and pathogenic bacteria (Simpson, 2004). Thus, awareness of potential contaminants associated risks, and preventative management options are imperative information to well owners. In addition to awareness, access to management behavior like testing well water and guidance interpreting test results, are integral steps in making informed management decisions and ensuring private well water is safe for consumption. Outreach programs for well owners may be a useful resource to learn about well water and implement well stewardship behavior (Flanagan et al., 2020). Well stewardship is the voluntary behavior well owners take to preventatively manage their well water and can involve many facets, the most important of which is regular testing of their well water to detect contamination.

Management of well water includes testing water quality, treating water (e.g., filters or softeners), and protecting well integrity. These actions may be overlooked due to a lack of access to information which may result in well owners being uninformed of potential risks and how to prevent these risks through stewardship (Clemens et al., 2007). Annual testing of well water is encouraged by the Environmental Protection Agency (US EPA, 2015), however considering the rural nature of wells and lack of research on where people rely on well water (Murray et al., 2021), disseminating this information can be difficult (Clemens et al., 2007). Even if well owners are aware that testing is recommended, they may not have access or information about how to test and what the results mean. Of disease outbreaks from groundwater contamination reported to the Center for Disease Control and Prevention's (CDC) Waterborne Disease and Outbreak Surveillance System (WBDOSS) (1971 – 2008), 67% were from onsite waste water systems, pathogen transport from hydrogeology (26%), and flooding or heavy rainfall (21%) (Wallender et al., 2014). Factors like well location, construction, depth, and hydrogeology all affect water quality and potential contaminants (Lee & Murphy, 2020; Wallender et al., 2014). Contaminants may also be present in water without altering the color, taste, or smell and detection by human senses is

unlikely (Jones et al., 2006). These concepts convey the complexity of well water quality and without knowledge about potential risks and only relying on the appearance of their water, stewardship may be neglected, and contaminants may go unnoticed, resulting in human sickness (Kreutzwiser et al., 2011; Malecki et al., 2017).

Barriers to implement well stewardship behavior include lack of knowledge, lack of perceived risk, and inconvenience (Fox et al., 2016; Imgrund et al., 2011; Kreutzwiser et al., 2011; Morris et al., 2015). Previous studies have identified that there may be a general lack of knowledge about groundwater across the US, not only among well owners (Ojeda et al., 2023). Groundwater is defined as, "water in saturated zones lying beneath the soil surface" in a watershed management textbook by Brooks *et al.* (2012). A common misconception is that groundwater pools underground and forms rivers, when in fact, groundwater exists around cracks of sand, rock, and gravel underground (Brooks et al., 2012; US Geological Survey, 2024). When asked about the storage of groundwater with the Groundwater Concept Inventory (GWCI) (Ojeda et al., 2023), a third (33%) of respondents chose "underground rivers and streams", suggesting that a large portion of respondents hold misconceptions about the physical properties of groundwater. This idea has been found in previous studies (Dickerson & Dawkins, 2004; Pan & Liu, 2018) and may have been perpetuated from the lack of importance placed on groundwater in the water cycle in US National Science Standards (Dickerson et al., 2007). Another common misconception is that well water does not need to be filtered or house contaminants because the soil naturally filters groundwater (Hooks et al., 2019). Soil can filter out large matter like leaves, however soil does not filter out all contaminants and groundwater may contain contaminants that are geogenic or anthropogenic (U.S. Geological Survey, 2024a; Wallender et al., 2014). In addition, a lack of knowledge about groundwater processes and management may hinder motivations to enact well stewardship behavior. Imgrund *et al.* (2011) explained that knowledge about the environment and management may influence attitudes and values towards behavior. Things like values, attitudes, knowledge, beliefs and perceptions have all shown to contribute to well owner's management behavior (Hooks et al., 2019; Imgrund et al., 2011; Schuitema et al., 2020). When comparing public water utility users and private well owners, well owners felt more in control of their water, which may be from the lack of government regulation (Hooks et al., 2019). Feelings of control may suppress feelings of risk of contaminants in well water (Schuitema et al., 2020). These feelings of control may result

in well owners being hesitant to test their water and engage in well stewardship (Hooks et al., 2019; Jones et al., 2006; Schuitema et al., 2020). Previous studies found that well owners were likely to engage in well stewardship when testing was free or when there was a person who was vulnerable or sick relying on well water (Hooks et al., 2019; Kreutzwiser et al., 2011). The third barrier to well stewardship is inconvenience like travelling to and from health departments for testing, and limited availability for testing (Imgrund et al., 2011). Studies that have utilized outreach programs to increase well stewardship suggest offering free testing, guidance when interpreting results, and encouraging the sharing of results with neighbors who may also be on well water and face similar conditions (Seliga et al., 2021).

Private well programs (PWPs) are an outreach mechanism that aid in education about well and well water management and maintenance and have been studied to understand and encourage well stewardship (Flanagan et al., 2020; Fox et al., 2016; Imgrund et al., 2011; Malecki et al., 2017; Morris et al., 2015; Seliga et al., 2021). PWPs offer an "infrastructure" for well stewardship by understanding their audiences, decreasing barriers to stewardship, and offering continued support for well owners (Fox et al., 2016; Imgrund et al., 2011). PWPs were created to provide education to private well owners about managing their private water systems. PWPs typically serve private well owners statewide and can be housed in the Cooperative Extension Service or state agencies like departments of public health (Foust et al. *under review*; Clemens et al., 2007). PWPs offer resources about water and well systems like drilling and construction systems, maintenance, water quality, and education about potential contaminants and local geology. Resources are distributed through events like workshops, webinars, websites, handbooks, and contact with well experts (Foust et al. *under review*). Participating in PWPs allows well owners to form relationships and trust with program coordinators that can provide continued support. These functions of PWPs are essential to reducing barriers and encouraging well stewardship (Morris et al., 2015). Several studies have explored motivations and barriers to well stewardship (Flanagan et al., 2020; Fox et al., 2016; Imgrund et al., 2011; Malecki et al., 2017; Morris et al., 2015; Seliga et al., 2021).

However, no studies have used a mixed methods approach to explore how PWPs influence well owners' knowledge, specifically about groundwater. Thus, we have formulated the following research question: Do well owners involved in PWPs have higher groundwater knowledge

measures than well owners who do not participate in PWPs? We hypothesize that people involved with a PWP have a higher measure of groundwater knowledge on the GWCI than well owners that are not. The results from the work by Hooks *et al.* (2019) found that beliefs, perceptions, and knowledge may influence private well owners' management behavior, like regularly testing their well water for contaminants. Therefore, we expect to find that well owners that participate in programming will have a higher groundwater knowledge measure because they have experiences with programs, whose goal is to provide resources and education about groundwater to make management decisions (Fig. 1). An example that supports this hypothesis would be if a well owner knows that well water can become contaminated without an obvious change in taste, color, or smell and that a way to detect is to test their well water, they are more like to take the steps to do this management behavior. Knowledge can come from different sources; however, this study focuses on groundwater knowledge from participation and education from outreach like PWPs. Imgrund *et al.* (2011) also assumes that well owners who participated in programs would have a higher likelihood to test their water regulating and engage in well stewardship behavior, thus PWPs may contribute to knowledge. To test this hypothesis, we employed a mixed methods approach of the GWCI (Ojeda et al., 2023) and semi-structured interviews with PWP coordinators. Mixed methods allow for a quantitative and qualitative understanding of relationships, specifically about experiences. Ultimately results gleaned from this study may promote PWPs and well stewardship, specifically regular testing. These actions may be a first step in preventing contamination, detecting contaminants early, that may also decrease the risk of health issues from contaminated drinking water.

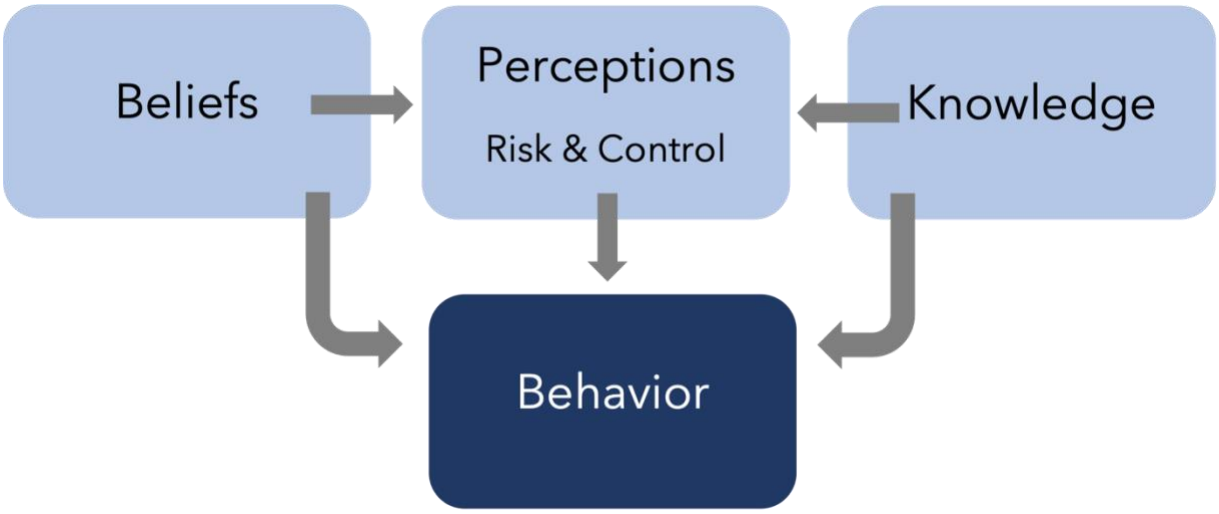

Figure 1. Theoretical framework showing that beliefs, perceptions, and knowledge of well owners can all contribute to their behavior. This diagram expands on the theoretical framework proposed by Hooks *et al*. (2019) that proposed beliefs about water sources, contamination sources, social context, and external interference feed into well owners perceived control over their well water, and into their perceived risk of contaminated water.

3.3 Methods

This study used a mixed methods approach to explore the relationship between participation in a PWP and groundwater knowledge, to understand how these variables may be related to management of private wells and well water. Mixed methods are a research approach that incorporates quantitative and qualitative data to provide a deeper exploration of the relationships than simply employing a single data type (Bryman 2006). The GWCI Survey Instrument (SI) was used in a well owner population (n = 167) to measure groundwater knowledge (quantitative metric). The groundwater knowledge measure was then used as the response variable in statistical analysis with demographics and program participation to elucidate how programs may contribute to groundwater knowledge. Then, program coordinators (n = 6) of PWPs were interviewed to gain a deeper understanding of how PWPs engaged with private well owners and contributed to their knowledge about groundwater and well management.

Survey Data Collection

When working with human subjects, like well owners, surveys are a common way to ask curated questions and retrieve data quickly (Hu & Morton, 2011; McDowell et al., 2020; Schuitema et al., 2020). A concept inventory (CI) is a research grade instrument that measures an individual's knowledge about a specified topic and is deployed in the form of a survey (Jorion et al., 2015). After CI evaluation, a quantitative measure of knowledge of the specific topic is produced and can then be used in further analyses. The GWCI SI with additional questions about private well owners' participation in outreach PWP (see 4.7 Appendix) was administered through an online survey platform, Qualtrics, with Internal Review Board (IRB) approval (Protocol 22-196 EX 2204, Auburn University). The intended audience for this study was private well owners and users; participants were recruited through existing outreach PWPs. The GWCI SI was distributed via email to PWP coordinators, agents, and professionals affiliated with well water. The recruitment email contained information about the SI and a request to forward the SI link to private well owners that had participated in their respective state's PWP. States with PWP were contacted to aid in distribution of the SI, with a focus on eastern states, who have more private well water users than other regions of the US (Murray et al., 2021). Auburn University's Cooperative Extension specialists contacted states without PWPs through their respective Extension or Department of Health. The GWCI SI was distributed to Alabama (AL), Arkansas (AK), Florida (FL), Georgia (GA), Mississippi (MS), North Carolina (NC), Oregon (OR), Pennsylvania (PA), South Carolina (SC), Texas (TX), Virginia (VA), Washington (WA), and West Virginia (WV). We also contacted people in Oklahoma (OK), Kentucky (KY), Maryland (MD), Ohio (OH), Louisiana (LA), Tennessee (TN), Connecticut (CT), Iowa (IA), Missouri (MO), and Montana (MT) (Fig. 2), however we did not obtain survey responses from these states (i.e., responses from 13 of 23 states contacted). States where the SI was sent but collected no responses may be due to outdated contact information found on program websites, a need to keep well owners' information private, a small population on well water, or another unspecified reason from the person contacted. Through this distribution method 167 participants were recruited from May to October 2023.

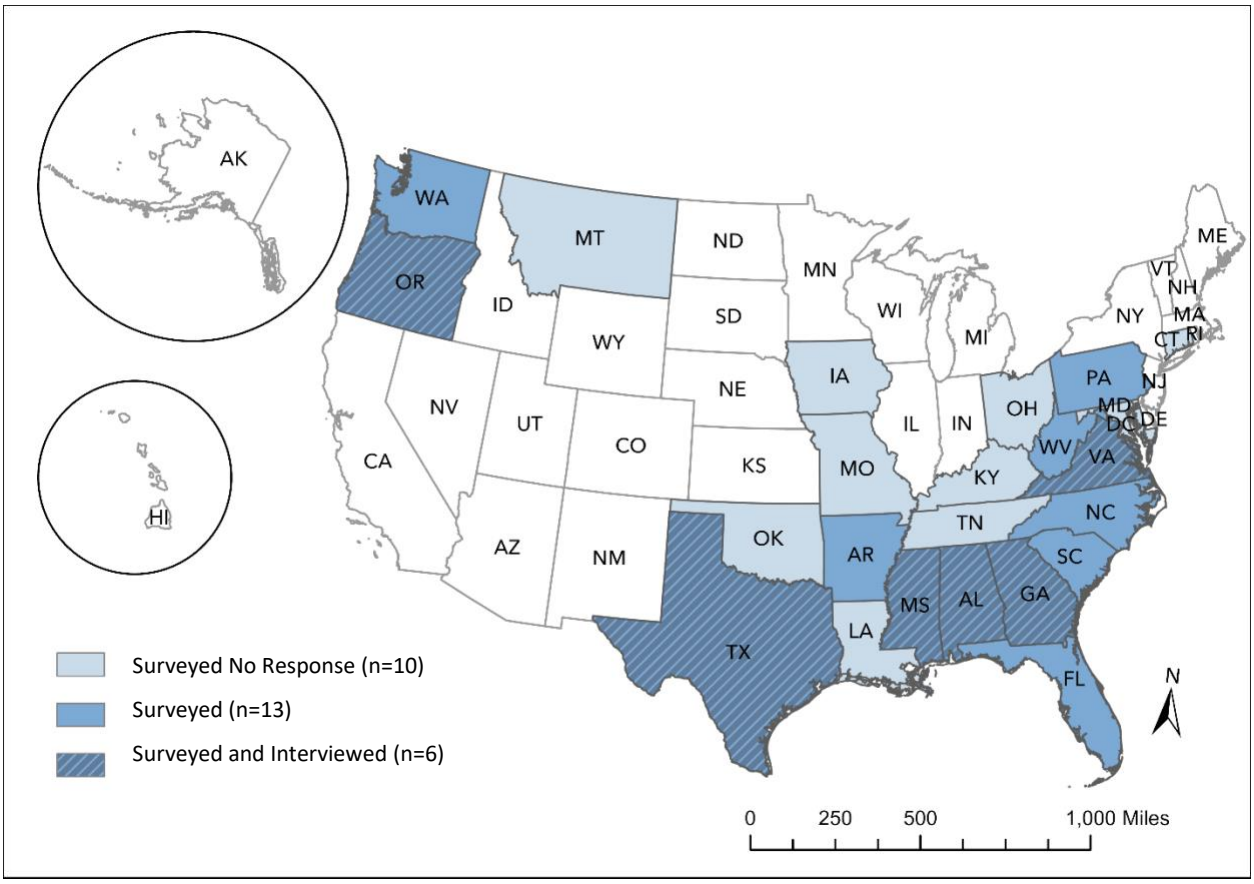

Figure 2. Map of study area. States in light blue were sent the survey, however no respondents were recruited (n = 10). States in dark blue were sent the survey and collected responses (n = 7, a total of 13 states surveyed), and states in blue hatch were surveyed responded, and interview (n = 6). States in white were not surveyed or interviewed.

Survey Analysis

The original GWCI (Ojeda et al., 2023) was developed into 14 items or questions, and all 14 questions were deployed in the SI, which can be found in Appendix (4.7). The GWCI used the Rasch model, which explained by Ojeda et al. (2023), "configures the relationship between person ability on the unobserved construct and the probability of selecting the correct answer." A respondent with low ability may have a low probability of selecting the correct answer, and a respondent with a high ability may have a high probability of selecting the correct answer. After collecting survey responses, and assessing Rasch model fit, four questions were removed because they did not fit the unidimensionality, that all items measure a singular latent construct, of the Rasch model (Ojeda et al., 2023). Exploratory factor analysis was used to confirm dimensionality

of items using PROC FACTOR command in SAS OnDemand for Academics (Release 3.1.0). In addition to unidimensionality, the measure must be aligned to the target population. Therefore, nine of the questions were used in the Rasch model to quantify groundwater knowledge (Fig. 3). The responses were analyzed using Rasch models in WinSteps software (Version 5.3.2.0). Statistically extreme responses (scoring too low or high) identified as model misfits were not included in reported score, which resulted in 142 useable responses. Demographic data were collected from respondents and used in summary statistics (Fig. 4). Student's test (*t*-Test) with equal variances was used to evaluate program participation and GWCI measure between private well owners who participated in programs and those who did not, as well as between private well owners and public water utility users. All assumptions of parametric tests were satisfied.

Interview Data Collection

After survey responses were collected, six PWPs coordinators from states with the most survey responses (AL, VA, MS, TX, OR, and GA) were recruited to be interviewed about their programs and experiences engaging with private well owners (Fig. 2). Semi-structured interviews provide a deeper understanding of findings and allow respondents to share their beliefs, experiences, and constructs that are needed to understand the relationships between programs and well owners. Semi-structured interviews were conducted via Zoom, recorded, and automatically transcribed in October and November 2023 (Table 1). According to the principle of saturation, this was a sufficient sample size to continue analysis (Guest et al., 2006). Because of the county-level nature of one of the programs (GA), the interviewee did not feel their responses were usable, so five out of the six interview transcripts were used in analysis.

Table 1. Interview questions and respective categories.

Interview Section	Interview Question
About the Program	Why did this program start, was there a specific need or event that led to its creation? When did this program start (year)? How is the program funded? What is the main goal or mission of this program? Who does the program Serve? What resources and education do you provide for private well owner? What is the primary function of the program (i.e., workshops, online resources, etc.)? How do well owner's contact or interact with the program? What are common issues in [state], or what do you hear about the most from private well owners? How do you receive feedback from well owners after you have interacted with them?
Well Owners	What is your main goal when interacting with well owners? (i.e., increase knowledge about well testing or contaminants) OR fill in the blank: *If I could leave one thing with well owners it would be…* What are common themes that you have observed when working with well owners? How would you describe the demographics of well owners? (Age, gender, income, education, type of residence) Do well owners like being on private water supply or have opinions about public versus private water supply?

	What are barriers or reasons why people would opt to be on private well water instead of public water supply?
Working with well owners, researchers, and programs	How many people in [state] rely on private well water as their main drinking water source? Do you or have you ever worked with programs in other states? Have you worked with other agencies within your state? Is there any type of research that you feel would be helpful for programs and well owners in your state, regionally, or nationally? Is there anything that we have not discussed today that you would like for me to know about your program?

Interview Analysis

Thematic analysis was used to code the interview responses into categorical themes for interpretation. Dedoose software (v. 9.0.17) (SocioCultural Research Consultants, LLC, 2021) was used to thematically code transcripts and elucidate themes that emerged from the data. A Co-coder was enlisted to quality control themes, and for the generation of Cohen's Kappa, which is a statistic that measures the agreement of themes identified in qualitative data (McHugh, 2012).

3.4 Results and Discussion

Survey Results and Discussion

Statistical analysis was used to investigate relationships between GWCI measure, participation in PWPs, and demographic variables. Compared to the Mechanical Turks (MTurks) population that the 14-item and 10-item GWCI was developed with by Ojeda *et al.* (2023), a 9-item GWCI was used for analysis of our data because it aligned better with an unidimensional

internal structure required of a Rasch model (Fig. 3). Of the nine questions answered, 50% or more of respondents answered correctly. This is notable increase in correct responses compared to the responses found in Ojeda *et al.* (2023) where only two of the nine overlapping items had above a 50% correct response rate (items 1 and 3). Assessing the Rasch model fit for the audience is important for instrument validity and targeting misconceptions about groundwater.

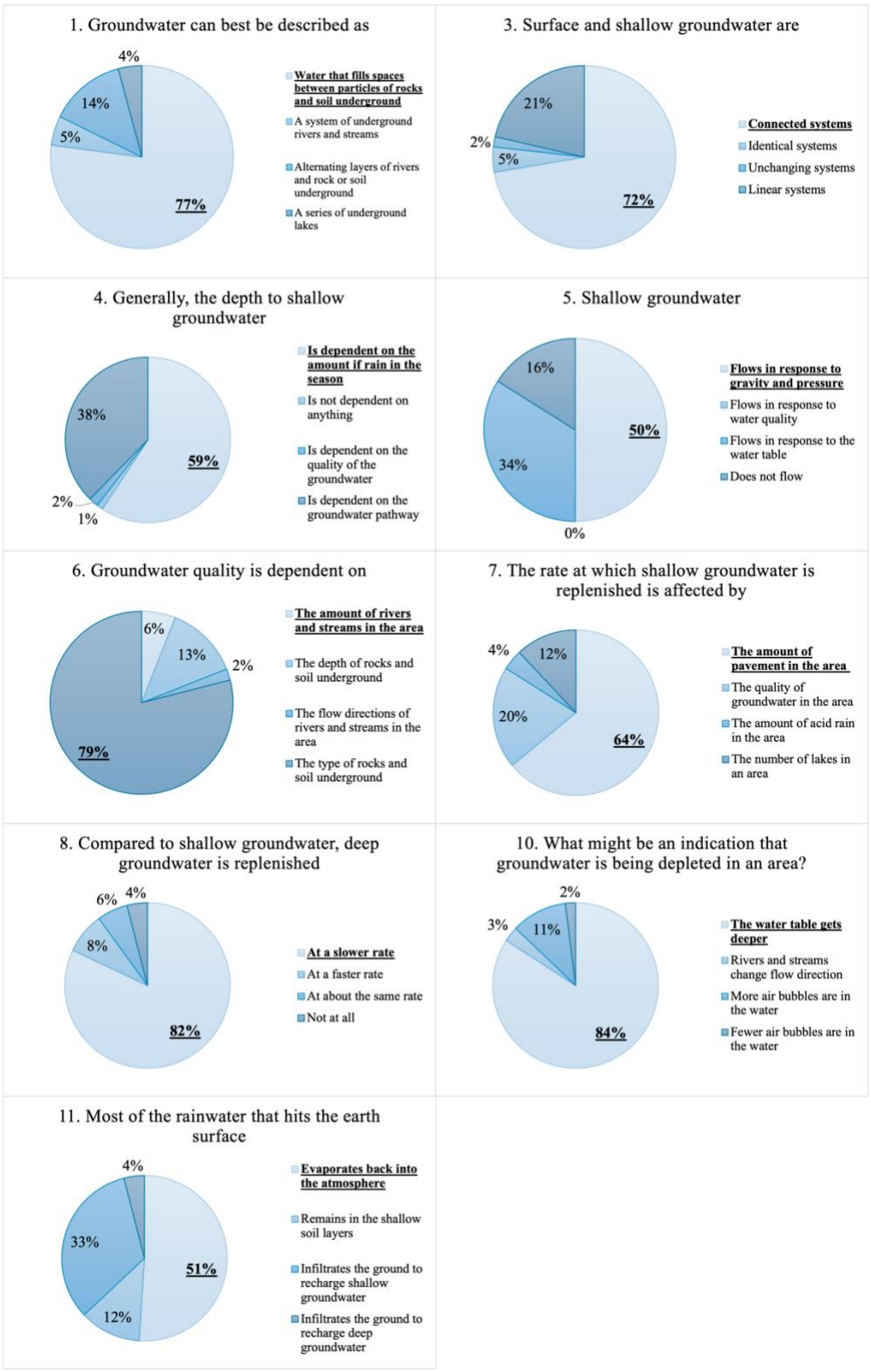

Figure 3. Pie charts showing 9 of 14 GWCI items used in Rasch Model. Items 2, 9, 12, 13, 14 were removed because they did not meet the unidemsionality of the Rasch model (See 4.7 Appendix for 14-item GWCI). Correct Answers in bold.

When working with well owners, it is important to understand the intended audience (Morris et al., 2015). Demographics of survey respondents were mainly older, white, college educated, high income earners, and rural residents (Fig. 4), which are echoed in previous studies (Flanagan et al., 2020; Fox et al., 2016; Jones et al., 2005, 2006; Kreutzwiser et al., 2011; Murti et al., 2016; Ternes, 2019). Because the method to recruit survey respondents relied heavily on Cooperative Extension, the demographics of this study overlap with the demographics of Cooperative Extension, which was confirmed by the interview responses. Thus, it is imperative to explore different avenues of survey distribution and program delivery for diverse and underserved communities. Efforts like targeting K-12 schools, social media, and flexible workshop hours may make PWPs more accessible. Spearman's correlations were run between GWCI measure and age, education, political affiliation, and income, however all correlation coefficients were low and the only variable that was statistically significant and positive was education ($p < 0.05$), meaning that the higher education the respondents had, the higher their measure of groundwater knowledge was (Table 2). Political affiliation and GWCI measure were negatively correlated and significant ($p = 0.03$), meaning that respondents that identified as democratic had higher GWCI measure (Table 2). These findings are similar with correlations by Ojeda *et al.* (2023) that there were no clear relationship between demographic variables and GWCI measure, however education and political affiliation were significant instead of age in our findings. This difference is interesting because Ojeda *et al.* (2023) hypothesized that education would have a positive relationship with GWCI measure, and that there would be a relationship between political affiliation and GWCI measure. We did not ask respondents to specify their fields of study or professions, and therefore cannot definitively explain the relationship between education and GWCI measure, however one explanation could be that program coordinators and agents, who typically possess multiple degrees (MS and/or PhD) and are professionals in the field, responded to the survey. As hypothesized by Ojeda *et al.* (2023), one might assume a politically democratic respondent that was pro-environmental would have a higher groundwater knowledge that may be associated with a pro-ecological worldview.

Figure 4. Bar charts showing demographics of survey respondents. Respondents were mainly older, white, highly educated, high-income earners, rural residents, and private well users.

Table. 2 GWCI measure and demographic variables Spearman's correlations. *Statistically significant at $\alpha = 0.05$.

Parameter	**Sample size *(n)***	**Correlation Coefficient**	***P* Value**
Age (continuous)	141	0.07	0.38
Education (categorical)	141	0.39	<0.001*
Income (categorical)	120	0.06	0.51
Political Affiliation (categorical)	120	-0.2	0.03*

Responses classified as "Other", or "N/A" were not included.

It was also hypothesized by Ojeda *et al.* (2023) that private well owners would have higher GWCI measure than pubic water utility users, however there was no difference found between the two groups. A Student's Test *(t*-Test) with equal variances in R was used to test this hypothesis with our data and results concur with this finding. We observed that public water utility users had 0.3604 point (± 0.3603944; ± 95% C.I.) higher groundwater knowledge measure than private well owners (p = 0.3144), however this was not a statistically significant finding and shows no difference in GWCI measure between the two groups. A *t*-Test with equal variances was also used to determine if private well owners who participated in PWPs showed a difference in groundwater knowledge measure than private well owners who had not participated in a PWP. We observed that private well owners that engaged with a program had 0.6387 point (± 0.6037133; ± 95% C.I.) greater groundwater knowledge measure than private well owners that did not engage with a program (p = 0.0383) (Fig. 5). We accept our hypothesis and suggest that PWP have shown a significantly higher amount of groundwater knowledge compared to populations that have not participated in PWPs indicating that PWPs are instrumental in conveying concepts to well owners that may be useful in management behavior.

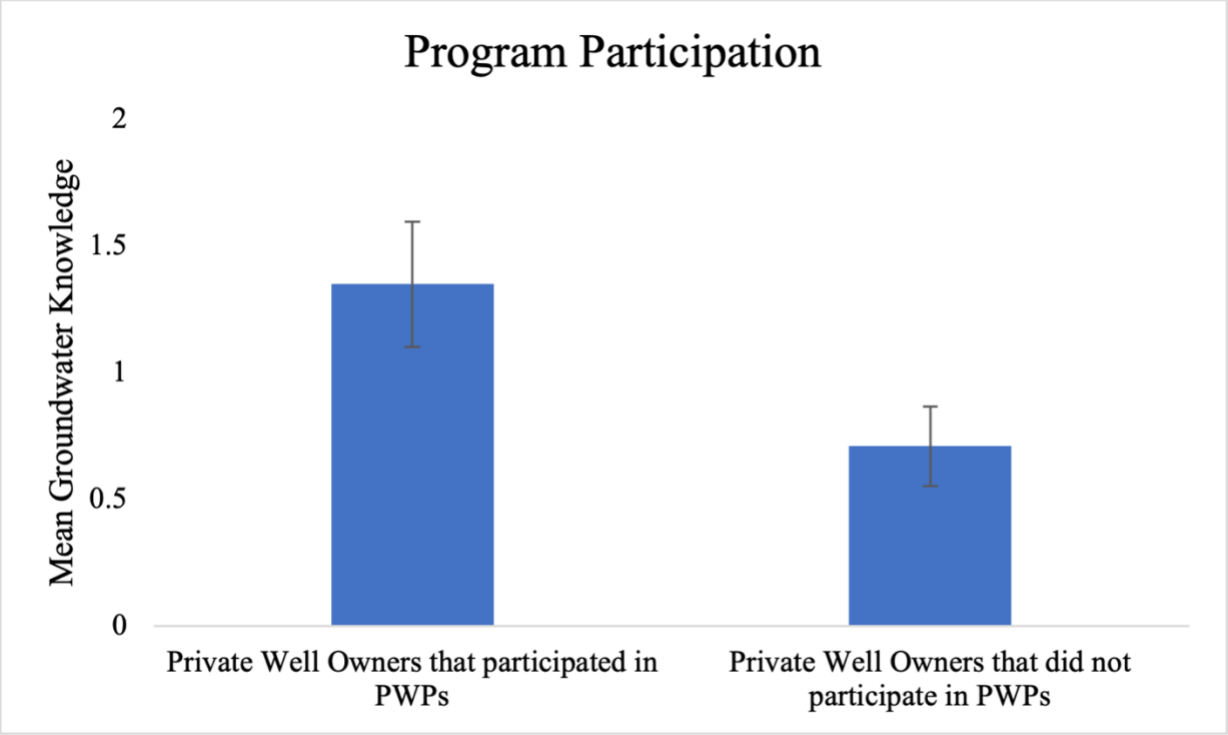

Figure 5. Bar chart of Mean Groundwater Knowledge Measure of well owners that engaged with a program (mean = 1.35; n = 31) and well owners that did not engage with a program (mean = 0.71; n= 91; *t*-Test Statistic = 2.18; p = 0.0383). Error bars do not overlap with one another and represent there is a difference between the two groups.

Interview Themes

Thematic analysis of interview transcripts indicated four main themes that described experiences of program coordinators working with well owners: PWP Establishment, PWP Purpose, Engagement, and Testing (Table 3). Each theme is important to support to results of the statistical findings of this study and emphasize how programs target barriers to increase knowledge, convenience, and encourage well stewardship. After initial coding, a co-coder was enlisted to test interrater reliability, that the data collected was a correct representation of the themes found (McHugh, 2012). A Cohen's kappa ($\kappa = 0.74$) was generated and found substantial agreement among the coder and co-coder.

Table 3. Results of four themes found from interviews. Table shows a description of the theme and frequency of mentions in the code.

Theme	**Definition**	**Frequency of code**
Program Establishment	When the program was established, and why the program was established	12
Program Purpose	Main goal of program	24
Engagement	Information about how program coordinators interact with private well owners and understand the audience through their perceptions and demographics	75
Testing	When asked to fill in the blank, "If I could leave one thing with well owners…"	11

Theme 1. Program Establishment

Interviewing program coordinators provided insight about the history and need of programs to encourage well stewardship. Previous literature underlines that effective PWPs include continued support for well owners, collaboration with other agencies, and decreasing barriers to well stewardship (Imgrund et al., 2011; Morris et al., 2015). Thus, it is important to understand how and why programs began, ways to develop programs, and indicators that a state may need to start a program. Program establishment refers to when the program began and what events led to the program's creation. Results found two programs began in the 1980s – 1990s, two programs

were established in the 2010s, and one program was created in 2020. When asked about the reason a program started, or if there was a specific event or need, the main finding was a need across the state for well water resources and an overall lack of resources for well owners statewide. For example, interviewees shared:

> *"I think that it was accumulation of need. It wasn't one event, but more so just a lot of need identified in our counties across the state over a really long period of time, so decades of getting well owner questions and needing help, responding to those, and just having a formal program established."*
> *(Interviewee 2)*

And:

> *"Once we started determining where the well owners were, … did a couple of workshops together. And once we started seeing just an interest and then really a need for the program" (Interviewee 5)*

And:

> *"…no one checking water quality and water quality across our state is a very big issue. We've got a wide range variety of waters. So, it was just a need that needed to be met to look at those water quality issues."*
> *(Interviewee 4)*

As well as:

> *"I think it was a function of there being a need for water testing for people with Wells."*
> *(Interviewee 3)*

These results show that programs are relatively new and increasing in need. States without PWPs may have a need for resources that has not been met yet, and established programs can serve as

blueprints for newer and developing programs. Morris *et al.* (2015) identifies one of the best practices in outreach PWPs are partnerships with other agencies. Interviewees also unanimously agreed that working with other PWPs and agencies (e.g., state department of health and conservation districts) advanced the program's effectiveness and helped program growth.

Theme 2. Program Purpose

The theme program purpose describes the purpose or goal of a program when working with private well owners. Morris *et al.* (2015) stressed the importance of outreach educators being aware of program goals and responsibilities and providing continual support for well owners. Excerpts from interview transcripts show that the main purpose of a PWP are resources for well owners, defined in two ways: providing resources via educational material and the program itself being a resource, like consulting with well owners about their test results and filtering options. Examples of the program being a resource include:

> *"So, if they have questions, they want to do screening, or they need somebody to look at it. You know, they can always give us a call. So just letting private well owners know that they are not alone."*
> *(Interviewee 5)*

And:

> *"…help kind of guide them to any questions that they may have, or answers to questions that they may have. The main goal of our program is to be a resource for well owners across our state."*
> *(Interviewee 2)*

And:

> *"When hosting these workshops, we're interacting with well owners in general is to just let them know that we do have a program that is available specifically to help them."*

(Interviewee 3)

And:

"But you know, having done it, for you know, a decade now, I would say the goal really is more education for well owners. But if they don't understand what the sample results mean, the results are fairly useless to them, and if they don't understand how their actions or inactions are causing these results."
(Interviewee 5)

And:

"…unbiased information that's specific to their water supply in their hands so that they're able to make better decisions about managing those systems."
(Interviewee 3)

As well as:

"Aquifers and wells and pieces and parts of a well. So that's we're trying to do that in the water quality to just make them aware that there are water quality issues across the areas across the State, and we want to make sure that they are not drinking something that is just totally bad for them. So that's it's just trying to open some eyes and make some awareness."
(Interviewee 4)

Interviewee excerpts show clear evidence that PWP's goals are to create awareness of the program to well owners, so that well owners know they have access to resources and are not alone when making management decisions. Continued support from PWPs and program coordinators leads to empowerment of well owners and agency to make informed decisions. Thus, it is integral to increase awareness about outreach programs for well owners.

Theme 3. Engagement

Engagement involves how program coordinators interact with well owners. As mentioned, Morris *et al.* (2015) explains that effective outreach programs need to engage with audiences and overcome barriers to observe a change in management behavior. Barriers include lack of knowledge, lack of perceived risk, and inconvenience (Flanagan et al., 2020; Fox et al., 2016; Imgrund et al., 2011; Morris et al., 2015). Methods to engage and decrease these barriers are understanding your audience, and developing trust and credibility with your audience, especially when communicating knowledge and risk. The excerpts highlighted in this theme show that program coordinators utilize these methods in many facets. Three main ways well owners engage with PWPs are through one-on-one contact with the program coordinator or agent, at events like workshops or webinars, and using materials like educational websites or handbooks provided by the PWP. These approaches are conducive for varying audiences. Interviewees also shared that they collect feedback surveys from well owners, annually and after events. This is pertinent when understanding the audience and adjusting materials for well owners. Understanding the audience also involves their demographics. Interviewees shared the demographics of well owners that they had worked with were usually older, white, and highly educated:

"*bachelor's degree or higher"*
(Interviewee 5)

And:

"better educated than the average person"
(Interviewee 3)

And:

"*whereas the folks that are a little bit higher income. Well, they may be more environmentally aware."*
(Interviewee 1)

And:

“wealthier”
(Interviewee 3)

And:

“older”
(Interviewees 1, 2, 4, and 5)

And:

“*say 85 to 92% will be white”*
(Interviewee 5)

Interviewees highlighted efforts to increase diversity among participants reached and underserved communities. Thus, it is imperative that outreach efforts increase in awareness, accessibility, and diversity to include all demographics of well owners and users. Many program coordinators expressed these sentiments in their interviews. Efforts detailed by interviewees included increased funding for more workshops and events across the state of differing types and at different times and including groundwater and well water education and involvement in K-12 schools:

“*Not typically people of color. We're gonna try to improve on that*”
(Interviewee 2)

And:

“*and the common theme is that those lower income folks like know they should be testing a lot, but they don't wanna test, because if they test and they find out there's an issue, then they know that they need to treat it.*”
(*Interviewee 1)*

And:

"We started a high school program. So, we know because of the way our drinking water clinics work. You know, it requires you to go pick up a sample kit, collect it and drop it off, and then sometimes go back for a meeting to get your results. And we know that's those are barriers, you know, to busy families. But we also know that water testing for families with kids is really important. So, we started a program where we reached out to science and agriculture teachers and more rural counties. And we would get donations funding to provide free water testing and we would incorporate a field trip to campus and tie it to whatever they were learning in their classes. So, they would come and get a lab tour, they would get to see what happened with the samples. We would get permission from the parents, and the kids would actually collect and bring the samples with them. So, we would run the program similarly to how we do for the public. But through the high school and when it worked best. The high school students would actually help deliver the results meeting, so they would learn pieces of it and then communicate it back to the parents and guardians."
(Interviewee 3)

A key part of outreach is understanding the audience, specifically their perceptions and how to correctly inform any misperceptions that may be a barrier to well stewardship (Hooks et al., 2019; Morris et al., 2015). Targeting misperceptions may inform well owners and help program coordinators develop effective communication methods to meet the needs of their participants. Interviewees recounted that well owners typically had positive perceptions of their well water and that they liked being in control, liked the taste, and were proud of their water:

"*a lot of them really like the fact that they're in charge.*"
(Interviewee 3)

And:

"*They love to have their own private wells; to be on their own supply that nobody's regulating, nobody's telling them how to use, what to use, when to use. So, they really like to be independent."*
(Interviewee 4)

And:

"*Folks come to well workshops and their well water is the best water they've ever had, and they want nothing to do with the public water supply*"
(Interviewee 5)

And:

"they're proud of their wells."
(Interviewee 2)

Thus, effectively and safely communicating to well owners' potential risks of contaminated water and how to prevent associated risks can accurately inform well owners' perceptions and encourage well stewardship. Negative perceptions were observed when there was an associated sickness with consuming contaminated well water. Understanding that well owners like their water is important when communicating with them and empowering them to make their own decisions. Two interviewees shared about well owner's negative perceptions:

"But then, when things go wrong that can swing in the other direction and be kind of overwhelming for people."
(Interviewee 3)

And:

"Persistent bacteria problems, or if their water has a smell or taste or odor that they haven't had success addressing that can be really frustrating for people."

(Interviewee 3)

One interviewee shared their mindset of credibility and trust when engaging with well owners:

> "*I feel very committed to do the best job possible to translate what we learned so that it can go back to help the people that it most impacts. So, I'm really aware of that balance between, you know, doing this more academic research and making sure that we're actually, we have a commitment to explain what we find clearly, and that does not mean dumb it down. It means think a lot of people just once they have the information they need. They just feel a thousand times better, you know. So just understanding kind of what people are looking for and helping them along the way just goes a long way."*
> *(Interviewee 3)*

Theme 4. Testing

Well stewardship is an approach to managing and maintaining to prevent contamination of well water. The main takeaway when encouraging stewardship is routine testing of well water. We asked interviewees to fill in the blank, "If I could leave one thing with a well owner it would be…" all interviewees replied to test your water:

> *"If I could leave one thing with well, owners, it would be to test your well water, because there's so many things that we just can't detect with our human senses. So, it's so important recommend testing for bacteria at least once a year to make sure nothing's changed with the system. Emphasizing how important well water quality testing is and giving them connections to testing entities in our state."*
> *(Interviewee 2)*

And:

> *"Understand the importance of water testing and then help them access water testing and understand the results to be able to solve problems."*

(Interviewee 3)

And:

"Test your water every month. And if you notice a difference in smell, appearance, or taste, stop using it until you get it tested, to make sure that it's safe to drink."
(Interviewee 5)

And:

"Well, the main thing we want to leave with them is, think about water quality. the message that I really preach, and my team preaches is if you see a change in color, odor tastes of your water coming out of your well, it's time to get it tested again the question we asked, when was the last time you got your well tested? The most common question is never. So, we're trying to make sure people understand and realize they need to get those wells tested annually for bacteria issues."
(Interviewee 4)

And:

"*You really don't know what's in your water unless you are treating or you're testing for it… testing to understand your water like the water you're consuming. … Because, like that testing will lead you to understand, like, what are the health risks to you and your family? So testing is kind of that. It's the gateway drug into understanding a lot more about your water. I hate hearing the phrase. Well, it hasn't killed me yet, and I linger with the yet, because yeah, something like arsenic or nitrate may not have short-term health effects."*
(*Interviewee 1)*

The data shows the importance of well stewardship behavior, especially testing. The most common issues interviewees had heard from well owners included water quality and contaminants, water quantity and mechanical issues, testing, results, and interpreting results, sickness, and

questions about buying real estate with a well on the property. Previous outreach found that providing free private well testing encouraged stewardship, increased the number of wells tested, and raised awareness of the potential risks associated with contaminated well water (Malecki et al., 2017; Seliga et al., 2021). Advocacy for funding for PWPs could make free testing available to well owners and help reduce barriers to stewardship. However, one interviewee shared that their program had a better testing rate when they charged a fee for testing because participants "you get what you pay for" mentality (Interviewee 4). Thus, if testing was free, it may not be credible. This experience shows the importance of understanding your audience and their beliefs and perceptions. Overall, both findings advise regular testing and making it available to well owners.

Developing and delivering effective outreach is encapsulated by these three areas: (1) understanding your audience (Fox et al., 2016; Morris et al., 2015), (2) decreasing barriers of inconvenience, lack of perceived risk, and knowledge and awareness (Flanagan et al., 2020; Imgrund et al., 2011; Morris et al., 2015), and (3) trust and continued support for well owners (Fox et al., 2016; Kreutzwiser et al., 2011; Morris et al., 2015; Seliga et al., 2021). Using the GWCI as a metric and information from the interviews, we deduce that programs do contribute to well owners' knowledge, which in turn may help well owners make informed and preventative management decisions which may reduce risk of health issues from contaminated drinking water. Future studies could deploy the GWCI SI to different audiences like in K-12 educational settings or at well water workshops to measure different audience's knowledge about groundwater and raise awareness about the importance of this water resource. Further work could also use a mixed methods approach of the GWCI and interviews with well owners about their responses and experiences with PWPs. Findings may be compelling for implementing groundwater curriculum in K-12 education, and to advocate for funding for PWPs if an increase in groundwater knowledge is observed after participation in specific workshop or event. Methods from this study could also be used to develop concept inventories and outreach programs for other household systems that remain unregulated like air quality and onsite wastewater systems to raise awareness from potential risks, responsibilities, and contaminants that harm human health.

Science Communication and Climate Change

An integral part of working with communities, specifically well owners, during research is ensuring there is a trusted messenger, typically a program coordinator (Morris et al., 2015). This messenger can provide lasting support and communicate risk to well owners in a safe way. PWPs and program coordinators are essential in communicating climate change impacts that may affect well water and proposing mitigation efforts for well owners.

Limitations

The limitations of this study lie within the recruitment methods. This study relied heavily on the support of Alabama Cooperative Extension, and without the guidance from Extension, this study would not be possible. With help from Extension specialists and agents the GWCI SI was distributed primarily through the vast Extension service in almost half the US. Thus, the demographics of respondents of the SI overlap with the demographics of Cooperative Extension. This sampling bias may not allow results to be generalized to different populations, however previous studies affirm that demographics of well owners align with the demographics of this study's respondents. As mentioned, there are efforts by PWPs to reach diverse and underserved populations. This bias does not threaten the validity of the GWCI SI, because it is assessed to fit the audience. The sampling method may have also resulted in the positive correlation between education and GWCI, because it was distributed through well water experts who are typically college educator or higher and who would have knowledge about groundwater via their careers and experiences. Thus, future studies should emphasize the intended audience during distribution and allow for experts aiding in distribution to see the survey beforehand.

3.5 Conclusions

This study used a mixed methods approach to determine that participation in outreach programs resulted in more knowledge about groundwater among well owners. Our results revealed that there was no significant difference in groundwater knowledge between public water utility

users and private well owners, thus leading us to conclude that PWPs and other outreach are beneficial for a higher level of knowledge about groundwater. PWPs are relatively new and increasing in need. Program coordinators use collaborative efforts across other PWPs and agencies to communicate education about groundwater, wells, and well water to their audiences. PWPs not only provide resources like websites, workshops, and handbooks about management, they also provide consultation resources like test results interpretation. To serve a more diverse audience, efforts to involve K-12 age participants and families are being developed. Unanimously, program coordinators advise well owners to test their water annually, and if there are any changes in color, taste, or smell of their drinking water, which PWPs can help with. PWPs are needed to decrease barriers to well stewardship by increasing knowledge, increasing informed perceptions of risks, increasing convenience, and increasing audiences' breadth. Findings from this study promote the importance of private well programs, and we encourage funding, awareness, and access of programs.

3.6 References

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4.7 Appendix Groundwater Knowledge Concept Inventory Survey Questions *asterisk shows 9 of 14 items used. Answers in bold.

Section	Item	Question	Answer Choices	Percent Response
Groundwater Knowledge	1*	Groundwater can best be described as	**Water that fills spaces between particles of rocks and soil underground**	**74**
			A system of underground rivers and streams	15
			Alternating layers of rivers and rock or soil underground	13
			A series of underground lakes	4
	2	The water table is	**The depth below which the ground is saturated with water**	**93**
			The slope on which groundwater flows	1
			The water that is contained in the soil	4
			The total amount of water available to pump from a well	3
	3*	Surface and shallow groundwater are	**Connected systems**	**81**
			Identical systems	5
			Unchanging systems	2
			Linear systems	24
	4*	Generally, the depth to shallow groundwater	**Is dependent on the amount if rain in the season**	**96**
			Is not dependent on anything	2
			Is dependent on the quality of the groundwater	3
			Is dependent on the groundwater pathway	61
	5*	Shallow groundwater	**Flows in response to gravity and pressure**	**81**
			Flows in response to water quality	0
			Flows in response to the water table	55
			Does not flow	26
	6*	Groundwater quality is dependent on	The amount of rivers and streams in the area	6
			The depth of rocks and soil underground	13
			The flow directions of rivers and streams in the area	2
			The type of rocks and soil underground	**79**

	7*	The rate at which shallow groundwater is replenished is affected by	**The amount of pavement in the area**	**64**
			The quality of groundwater in the area	20
			The amount of acid rain in the area	4
			The number of lakes in an area	12
	8*	Compared to shallow groundwater, deep groundwater is replenished	**At a slower rate**	**82**
			At a faster rate	8
			At about the same rate	6
			Not at all	4
	9	What percent of water near the earth's surface is available to drink?	More than 60%	8
			Between 40 -60%	8
			Between 10 -12%	37
			Less than 1%	**47**
	10*	What might be an indication that groundwater is being depleted in an area?	**The water table gets deeper**	**85**
			Rivers and streams change flow direction	3
			More air bubbles are in the water	11
			Fewer air bubbles are in the water	2
	11*	Most of the rainwater that hits the earth surface	**Evaporates back into the atmosphere**	**51**
			Remains in the shallow soil layers	12
			Infiltrates the ground to recharge shallow groundwater	33
			Infiltrates the ground to recharge deep groundwater	4
	12	Compared to river water, groundwater	Flows much faster than river water	3
			Flows at about the same rate as river water	3
			Flows much slower than river water	**75**
			Does not flow	19
	13	If a person drilled a well to get groundwater, from where could this water come?	Underground pool	12
			Public water supply	1
			Underground river	21
			Rock, gravel, or sand layer	**66**
	14	Deep groundwater is considered to be a	Non-renewable resource	37
			Renewable resource	**54**
			Biological resource	8
			Man-made resource	1
Drinking Water Source		*What is your main drinking water supply?	Public water supply	14
			Private well water	85

			Other	1
Engagement	ENG	*Have you ever participated in a community, network, or organization of private well owners? Examples include Cooperative Extension led programming, city or state government led programming, or grassroots community organizations.	No Yes	75 25
	ENG_1	How often do you engage with well programs?	Every 1 – 3 months Twice per year Once per year Less than once per year	9 3 30 58
	ENG_2	How do you engage with well programs? - Selected Choice	By phone Through a website Email with program contact In-person workshops or meetings Other	3 21 21 42 12
	ENG_3	How do you engage with well programs?	Text entry	
	ENG_4	What has the program assisted you with?	Text entry	