GEOSPATIAL TRENDS OF PER- AND POLYFLUOROALKYL SUBSTANCES (PFAS) INCIDENCE IN PRIVATE DRINKING WATER IN VIRGINIA

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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are a class of synthetic organic compounds that are hydrophobic, thermally stable, and resistant to environmental degradation. Widespread industrial and household use has resulted in frequent environmental and drinking water detection, raising concerns about adverse human health effects associated with PFAS exposure. In response, the United States Environmental Protection Agency (USEPA) has established mandatory monitoring campaigns and future maximum contaminant levels (MCLs) for two PFAS compounds (PFOA and PFOS) in public water systems under the Safe Drinking Water Act. However, the 20-40 million Americans who rely on private drinking water supplies remain unregulated and comparatively understudied.

This study investigates the incidence of PFAS in private drinking water under 'baseline' conditions and assesses the impacts of contributing land cover types, point sources, household characteristics, and traditional water quality parameters on PFAS incidence across Virginia. Point-of-use samples (n=382) were collected from private wells across 10 counties and analyzed for 30 PFAS compounds using USEPA Methods 533 and 537.1. Geospatial variables, household characteristics, and traditional water quality parameters (e.g., lead and bacteria) were analyzed using GIS and RStudio.

At least one PFAS compound was detectable in all samples, with 90% exceeding method reporting limits, although median total sum PFAS concentrations were low (1.50 ppt). Short-chain PFAS compounds were more prevalent than long-chain legacy compounds in both total concentration and unique compound detection rates. The USEPA MCL of 4 ppt was exceeded in 2.4% and 5.2% of samples for PFOA and PFOS, respectively. While most samples had generally low total sum PFAS concentrations, 10% of samples exceeded 10.03 ppt with a maximum total sum PFAS concentration of 303 ppt. High PFAS sampled homes were associated with increased urban land cover, closer proximity to point sources, higher frequency of nearby point sources, older well age, elevated lead, and indicators of corrosive water chemistry, including low pH, and higher conductivity/total dissolved solids. These findings suggest PFAS concentrations in private drinking water are associated with more anthropogenic activity as well as potential mobilization of PFAS from in-home sources such as plumbing networks.

Traditional water quality concerns remain prevalent, with exceedance of public water standards observed for lead (5.01% > 0.01 mg/L health-action-limit), *E. coli* (4.19% > absence), and total coliform bacteria (34.8% > absence). While 70% of homes employed some form of treatment, only 22% of homes used health based treatment types (e.g., reverse osmosis and activated carbon) which are capable of removing heavy metals, bacteria, or PFAS. These findings highlight the continued vulnerability of private drinking water users to both emerging and established contaminants and underscore the need for improved monitoring, targeted treatment adoption, and enhanced support for private drinking water supply stewardship.

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GENERAL AUDIENCE ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are often referred to as “forever chemicals” which are long-lasting human-made chemicals commonly used in everyday products such as non-stick cookware, water-resistant clothing, and firefighting foams. Because these chemicals do not break down easily, they are now widely found in the environment and in drinking water, raising concerns about their negative human health effects. While PFAS are being regulated in public drinking water systems, private drinking water supplies, used by 20-40 million Americans, are not regulated and understudied.

This study examines how PFAS incidence in private water supplies across Virginia and explores how land cover and point sources influence PFAS presence. Drinking water samples were collected from private water supplies (typically wells) in 10 counties and tested for 30 PFAS compounds, traditional water quality (e.g., lead and bacteria) and participants sociodemographic and household characteristics were collected. Geospatial and statistical analysis on nearby land cover, point sources, household characteristics, and traditional water quality parameters were evaluated for their relationships with PFAS incidence.

At least one PFAS compound was detectable in all sampled homes, although most concentrations were low with a median of 1.50 ppt and few exceeded public water standards. While most samples had generally low total sum PFAS concentrations, 10% of samples exceeded 10.03 ppt with a maximum total sum PFAS concentration of 303 ppt. High PFAS homes were associated with more urban land cover, more point sources, homes with older wells, and in homes with more corrosive water chemistry. These findings suggest that more human activity as well as potential PFAS exposure from in-home sources such as plumbing networks.

Traditional water quality concerns remain prevalent, with exceedance of public water standards observed for lead (5.01%), E. coli (4.19%), and total coliform bacteria (34.8%). Although many households reported using water treatment devices, few homes use treatment types designed to remove contaminants that pose health risks including such as heavy metals, bacteria, and PFAS. Overall, this study highlights ongoing challenges faced by those reliant on private water supplies and emphasizes the need for increased testing, public awareness, and access to effective water treatment to reduce exposure to both emerging and long-standing drinking water contaminants.

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possible. Their contributions to this study are deeply valued and help support continued scientific research studying private drinking water.

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1. Introduction

Per- and polyfluoroalkyl substances (PFAS) are a class of synthetic organic compounds that are hydrophobic, thermally stable, and resistant to environmental degradation. Because of these unique properties, PFAS are widely used as additives in various industrial and household applications, including rain protective clothing, fire retardants, food packaging, and pharmaceuticals (Bell et al., 2021). PFAS have been integral to modern life since their development in the 1940s; over 4000 unique PFAS compounds are currently in use (Sunderland et al., 2019). New analytical strategies able to quantify PFAS levels at the part per trillion level have revealed that these anthropogenic chemicals are now widely detectable in environmental samples, prompting concerns regarding ecological and human health effects associated with unintended exposures (Sunderland et al., 2019; Teymourian et al., 2021). For example, reports suggest PFAS are detectable in drinking water, groundwater, and in as many as 98% of human blood samples collected in the United States during epidemiological studies (Shearer et al., 2020; Sunderland et al., 2019). At present, PFAS are considered emergent contaminants that pose significant challenges due to their versatile pathways of entering and remaining in the environment ("EPA's PFAS Strategic Roadmap: Second Annual Progress Report," 2023).

The health impacts of PFAS exposure are significant and multifaceted, though these impacts are still under considerable investigation. Associations between PFAS exposure and negative health outcomes, particularly related to human development and endocrine systems, have been documented. PFAS exposures in pregnant mothers and children are linked to impairments to fetal growth and early childhood development (Y. J. Lee et al., 2021). In adults, PFAS exposure is associated with an increased rate of endocrine disruption, lowered immune response to stressors, kidney deterioration, and certain cancers (Sunderland et al., 2019).

Repeated demonstration of quantifiable risks linking PFAS and human health underscores the need for further research on not only health effects, but also potential sources of environmental contamination and human exposure pathways.

Research identifying primary environmental pathways for PFAS exposure are evolving rapidly, though water resources are frequently cited as a primary concern. For example, a 2023 study on the extent of PFAS incidence in Pennsylvania surface waters reported that at least one PFAS compound was detectable in 76% of the 161 streams sampled, with streams located near industrial sites, agricultural lands, water treatment facilities, and urban areas most likely to yield PFAS-positive samples (Breitmeyer et al., 2023). Nationally, 87% of the U.S. population relies on public water supplies, with 74% of this water sourced from surface waters like those sampled in Pennsylvania (Dieter et al., 2018). Although community water systems treat source waters prior to distribution to customers, conventional water treatment processes may be insufficient in the removal of these PFAS-chemicals to safe levels (Appleman et al., 2014). A national study conducted by the US Geological Survey (USGS) exploring PFAS incidence in municipal water supplies across 35 states reported that at least one PFAS chemical was detectable in 40% of the 447 point-of-use (POU) samples collected; it is worth noting that this study partly relied on a quantification method with higher minimum detection limits than present recommended standards, and so may represent an underestimate (Smalling et al., 2023).

Although the USEPA proposed primary drinking water standards under the Safe Drinking Water Act (SDWA) for a limited selection of PFAS chemicals, these have recently come under review and will not become statutory until at least 2031 (US EPA, 2025). Regardless, SDWA standards for PFAS in municipal waters will not apply to the estimated 13.7-15.1 million Americans (11% - 15%) reliant on private water supplies (Hernandez & Pierce, 2023; Murray et al., 2021). Private water supplies are defined by the U.S. Environmental Protection Agency (USEPA) as water systems serving less than 25 people (US EPA, 2015). Previous work has stressed that private drinking water supplies may pose unique risks to consumers (D. Lee & Murphy, 2020). For example, Wallender et al. (2014) reported that 30.3% of the 818 waterborne disease outbreaks in the US between 1971-2008 were associated with untreated groundwater from private wells. Both community and non-community groundwater supplies contribute to an estimated 6.5 million annual cases of waterborne illness in the US, including gastrointestinal illnesses and other health effects resulting from pathogen exposure in drinking water (Reynolds et al., 2008).

Because private drinking supplies are outside the purview of the Safe Drinking Water Act (SDWA), data describing the occurrence of contaminants, including PFAS, in private wells are quite limited. The previously described USGS study of PFAS incidence in drinking water collected 269 samples from private wells from across the nation, and 20% of those samples contained at least one detectable PFAS compound (Smalling et al., 2023). Similarly, an examination of 254 groundwater sources in the eastern region of the US reported that 20% of private well and 60% of public well samples contained at least one detectable PFAS compound (McMahon et al., 2022). However, region-specific studies have at times observed much higher rates of detection. For example, a smaller study focused on two counties in southwest Virginia reported detectable PFAS in 95% of point of use (POU) samples (n=60) (Hohweiler et al., 2024); higher detection rates may reflect rapidly advancing analytical capabilities and/or unique localized risk factors. Without knowledge of the full scope of PFAS incidence in all water supplies, proper regulations and targeted remediation strategies cannot be developed.

1.1 Study Goal and Research Questions

This effort examines potential links between the incidence of an array of PFAS compounds detected in samples collected from the point of use (POU) of private drinking water supplies and surrounding land cover, point sources, household characteristics, and traditional measures of water quality. This study represents a partnership with the Virginia Household Water Quality Program (VAHWQP), a Cooperative Extension program that offers affordable water quality testing and education on private water supplies to all of Virginia's 95 counties (Benham et al., 2016). Centering this work in Virginia is of direct use to the citizens of the Commonwealth, as private water supplies are used to meet the in-home water needs of an estimated 1.7 million citizens (~20% of the population) (Benham et al., 2016). Understanding the risks posed by any emerging waterborne contaminant in these systems is critical to maintaining the public health, and will potentially provide insights into local groundwater quality, well water stewardship, and community perceptions of emerging contaminants. Through collaboration with VAHWQP on sample collection and messaging, this work will explore the following questions:

- Is there a difference in detection rates between short chain and long chain (legacy) PFAS compounds?
- Are surrounding land cover types or point sources associated with total sum PFAS concentration in samples collected from private drinking water supplies?
- Are system characteristics or traditional water quality markers (e.g., the presence of treatment, well age, lead, bacteria) associated with total sum PFAS concentrations trends?

2. Literature Review

2.1 PFAS and the Environment

Per- and Polyfluoroalkyl substances (PFAS) are a class of synthetic organic compounds that have been integral to modern life since their original design and production in the 1940s (Sunderland et al., 2019). At present, over 4000 unique PFAS compounds have been created to support a wide range of applications including consumer-care products, rain protective clothing, pharmaceuticals, firefighting foams, food packaging, and non-stick cookware (Bell et al., 2021; Sunderland et al., 2019). Although products containing PFAS have added safety and convenience to multiple aspects of everyday life, there is growing awareness that their increasing usage is associated with multiple unintended human and environmental health concerns.

All PFAS compounds are comprised of carbon atoms attached to fluorine atoms, which create an exceptionally strong chemical bond that is hydrophobic, thermally stable, and resistant to environmental degradation (Bell et al., 2021). While this unique stability is responsible for its usefulness in a wide range of applications, this resilience also renders PFAS compounds persistent and often bioaccumulative within the environment following release via point and non-point sources. Accordingly, past studies report that PFAS are detectable within biosolids (Sepulvado et al., 2011; Venkatesan & Halden, 2013), wastewater treatment plant discharges (Washington et al., 2010), marine and fresh water organisms (Berger et al., 2009; Kelly et al., 2009; Stahl et al., 2014), livestock, crops, and soil (Simones et al., 2024).

PFAS are widely detectable in surface water, groundwater, soil, air, animal tissues, and plant tissue, even in relatively pristine locations far from known industrial point sources, including the arctic atmosphere (Shoeib et al., 2006; Teymourian et al., 2021). Because of the strength of the carbon-fluorine bond, bioaccumulation within ecosystems is common, particularly for longer chain “legacy” compounds (Teymourian et al., 2021). PFAS readily binds to fatty tissue in organisms and can be passed to offspring, and observed concentrations generally increase with the age of the animal (Ahrens & Bundschuh, 2014; Shi et al., 2012).

Research has linked higher concentrations of PFAS to widespread toxicity across multiple species, including humans, as well as broader negative impacts to ecological systems. Studies have documented harmful effects in aquatic organisms, including toxicity to green-blue algae and zooplankton (Latała et al., 2009; Sanderson et al., 2004), and genotoxicity in hamster lung cells through increased membrane permeability (Jernbro et al., 2007). In commonly consumed farmed fish such as tilapia and carp, PFAS exposure causes damage to vital organs including the brain and liver (Shi et al., 2012). Toxicity studies in rodents have reported increased tumor rates, neonatal fatalities, and compromised immune system responses (Steenland et al., 2010). Research on zebrafish has demonstrated major endocrine disruption leading to decreased reproduction rates (Liu et al., 2010).

Though highly persistent, over time longer chain legacy PFAS compounds such as Perfluorooctanoic acid (PFOA) and/or Perfluorooctanesulfonic acid (PFOS) do begin to decompose. However, they degrade into short chain PFAS compounds such as Perfluoroalkyl Sulphonates (PFSA) and Perfluoroalkyl Carboxylic acids (PFCA) which still pose significant ecological health risks. Short-chain PFAS are associated with transportation across farther distances via atmospheric deposition, similar toxicological effects to their long chain counterparts, and longer half-lives (Butt et al., 2014; Gomis et al., 2018; Sunderland et al., 2019; Young & Mabury, 2010). Damage to local ecosystems results in immediate and direct downstream consequences for humans as the consumption of animals and fish can result in further PFAS bioaccumulation within the human body (Berger et al., 2009). Accordingly, USEPA has recently developed recommendations to guide the issuance of PFAS fish advisories by local states, tribes, and territories (US EPA, 2024).

2.2 PFAS and Health

Rising concerns related to PFAS compounds stem not only from widespread environmental prevalence but also a mounting number of demonstrated associated human health and ecological risks associated with exposure. Exposure appears nearly inescapable in modern communities: a nested case-control study of 324 US adults aged 55 and over determined that 98% of participants' blood serum had detectable levels (limit of detection LOD=0.1 μg/L) of PFAS (Shearer et al., 2020). Although for the majority of the population blood levels of PFAS may be due to chronic low level exposure from drinking water, common household items, and bioaccumulation through the food chain, the majority of human-specific epidemiological examinations of PFAS effects have focused on communities exposed to large doses from nearby industrial areas or significant industrial spills. For example, examinations of individuals living in six communities (n=32,524) in Ohio and West Virginia exposed to PFOA releases from a nearby chemical DuPont plant revealed a positive association between PFOA exposure and higher rates of kidney and testicular cancer (Barry et al., 2013; Vieira et al., 2013). It is important to note that because of the persistence of these compounds, the impacts of industrial spills and associated risks may continue for significant quantities of time. For example, demonstrated elevated PFAS concentrations remained present in the surrounding soil 15 years after a fire fighting foam spill at a Michigan military base (Bell et al., 2021). While cancer is of particular concern in high exposure settings (e.g. postindustrial spill or repeated occupational exposure), the risk of cancer does not appear significant in lower exposure dosages (Sunderland et al., 2019).

Currently identified risks associated with lower, chronic PFAS exposure are endocrine disruption, lowered immune function, liver disease, impaired neurodevelopment, childhood and fetal development, thyroid disease, and metabolic disruption (Bassler et al., 2019; Bell et al., 2021; Y. J. Lee et al., 2021; G. Liu et al., 2018; Rafiei & Nejadhashemi, 2023; Sunderland et al., 2019). Childhood development is a major concern given lower body mass and rapid growth and development, with one study reporting that PFAS exposure at age five led to a 49% decline in antibody concentrations by age seven (Grandjean et al., 2012). Metabolic and fertility issues in adults are tied to hormone irregularities in producing estrogen. Investigations during a dietary weight loss study linked resting metabolic rate in women to bloodstream PFAS levels, i.e. fluctuations in weight were more extreme in women with higher bloodstream PFAS (Liu et al., 2018). PFAS exposure also impacts the caspase-3 enzyme which is important in liver function and can decrease anti-inflammatory responses in the body, thereby reducing the body's ability to appropriately process various environmental stressors and exposures (Bassler et al., 2019). Other metabolic issues associated with PFAS exposure include changes in glucose, lipids, and thyroid hormones (Bell et al., 2021; G. Liu et al., 2018; Sunderland et al., 2019).

2.3 PFAS and Drinking Water

Along with diet, drinking water is believed to be a primary driver of chronic low dose PFAS exposure in humans (Sunderland et al., 2019). An early statewide study in New Jersey reported that PFOA was detectable in 65% of public drinking water supplies (n=23) (Post et al., 2009); more recent national estimates reliant on more sensitive analytical techniques suggest that over 200 million Americans are exposed to PFOS and PFOA through their household water (Andrews & Naidenko, 2020).

As the majority (87%) of the US population is reliant on centralized public water supplies, which are subject to Safe Drinking Water Act (SDWA) contamination limits and monitoring requirements (Bradley et al., 2021), increasingly restrictive regulation is a potentially significant intervention to reduce PFAS exposure. Accordingly, PFAS regulations have undergone rapid and repeated revisions in recent years (Teymourian et al., 2021). As of May 2025, USEPA has established maximum contaminant levels (MCL) of 4 ppt for both PFOA and PFOS with maximum contamination level goals (MCLG) of 0 ppt, i.e. not detectable (US EPA, 2025). Community water systems are required to begin monitoring regimes for these chemicals, but full compliance is not required until 2031 (US EPA, 2025). Although these limits will potentially protect a significant number of Americans, they are not applicable to private drinking supplies such as household wells, which operate outside the SDWA and serve between 13.7-15.1 million Americans (Hernandez & Pierce, 2023; Murray et al., 2021).

Because the monitoring of private water supplies relies on the homeowner rather than any government regulatory agency, datasets describing water quality are relatively limited (Bradley et al., 2021). Numerous studies do suggest these systems can be highly vulnerable to contamination due to limited treatment prior to consumption and inconsistent awareness of and/or adherence to maintenance recommendations (Lee & Murphy, 2020). Past examinations of private water supplies have reported elevated concentrations of established contaminants of health concern, including fecal indicator bacteria (Allevi et al., 2013; Wallender et al., 2014), arsenic (Ayotte et al. 2017), radon (Law et al., 2017), and lead (Pieper et al., 2015). An examination of 3000 POU samples from private water systems collected through a Virginia Cooperative Extension program determined that over half (55%) exceeded at least one health-based drinking water standard (Benham et al., 2016).

While datasets describing PFAS detection in public water supplies (PWS) are growing rapidly, data specifically reporting on PFAS and other emerging contaminants in private water systems are relatively limited. A recent national study of PFAS in drinking water conducted by the USGS examined 269 POU samples from private water wells collected from across the United States and detected PFAS compounds in 20% of samples (Smalling et al., 2023). Work examining differences in detection across eastern American aquifers reported that PFAS were detectable in 54% of point of extraction (POE) groundwater samples (n=254) before any treatment, blending, or pressure tanks (McMahon et al., 2022). Interestingly, PFAS were detectable from 60% of public drinking wells (n=163) while only 20% were detectable in private wells (n=50) (McMahon et al., 2022). More localized studies have reported much higher rates of detection. For example, Babayev et al., 2022 detected PFAS contaminants in all private wells sampled (n=25) in rural Alaska, as well as in blood samples collected from every household participant (n=60), which may be due to influences from a nearby airport. In a rural Virginia study, 95% of samples (n=60) contained at least one detectable PFAS compound, with PFOA and PFOS detectable in 13% and 22% of the samples respectfully (Hohweiler et al., 2024).

2.4 Land Cover and PFAS

A substantial number of drinking, ground, and surface water monitoring studies targeting PFAS emphasize risks and pathways from known point sources to water supplies. Airports and military bases are often of particular concern due to the high prevalence of aqueous firefighting foam used for training and real fire emergencies, and industrial sites rely on PFAS in a wide range of products including non-stick cookware and electronics manufacturing (Hu et al., 2016; Rafiei & Nejadhashemi, 2023). An examination by Hu et al. (2016) of eight-digit hydrologic unit code (HUC-8) watersheds across the US demonstrated a 35% increase in PFOS in public drinking water for each military fire training area in a watershed (Hu et al., 2016). Recent studies examining the Huron River watershed (Rafiei & Nejadhashemi, 2023) and 161 Pennsylvania streams (Breitmeyer et al., 2023) reported high levels of detection (79% and 76% of samples positive for PFAS). Notably, both studies suggested that the presence of PFAS in water may be linked to prominent point sources in the respective watersheds, including industrial sites, airports, military bases, and wastewater treatment plants (Breitmeyer et al., 2023; Rafiei & Nejadhashemi, 2023). Wastewater treatment outflows can be a major source of PFAS; estimates suggest that wastewater contributes to 85% of PFOS releases to surface water in the United States (Sunderland et al. 2019). Many of these treatment facilities do not have the capability to remove PFAS, and so these chemicals pass directly from household drains through the entire treatment system (Herkert et al., 2020).

Non-point source pollution, such as biosolids application, proximity to urbanized areas, and atmospheric deposition can result in PFAS contamination of receiving waters via runoff, leaching to groundwater, and even aerosolization of volatile PFAS, although the relative influences of these sources is complex (Rafiei & Nejadhashemi, 2023; Siegel et al., 2023; Sunderland et al., 2019). Early work by Sepulvado et al., 2011 examining the soil of thirteen agricultural fields receiving biosolid applications demonstrated a linear increase between PFAS soil concentrations and biosolid loading rates. Although agriculture is frequently cited as a concern related to PFAS in environmental waters, an analysis of surface water samples (n=160) by Breitmeyer et al (2023) determined concentrations were most significantly associated with developed land cover areas (i.e., USGS NLCD defined open space and low to high intensity development).

Direct examinations of the impact of surrounding land cover on drinking water supplies, i.e., water provided to consumers through a public distribution system or through private wells, are limited. An analysis of over 40,000 samples from 18 state-wide PWS indicated that proximity to PFAS point sources such as industrial zones, airports, and military bases significantly increased risk of elevated PFAS concentrations (Liddie et al., 2023). Liddie et al., 2023 also determined that PFAS risk in rural communities with median incomes below the federal poverty line is equivalent to that of more urban or affluent areas close to the previously mentioned point sources. A recent study examining PFAS concentrations in domestic groundwater wells in the Central Appalachian region of the US indicated that there were no significant relationships between local oil and gas extraction activities and well water concentrations; in the absence of other point sources the authors hypothesized that atmospheric deposition may be responsible (Siegel et al., 2023). In Wisconsin, researchers analyzed 450 point-of-use (POU) samples from shallow private wells (≤40 feet deep) to examine the relationship between land cover and PFAS contamination (Silver et al., 2023). The study found that 71% of sampled wells (n=450) contained detectable PFAS levels. However, detection rates varied significantly by land cover type: wells in developed areas showed the highest detection frequency at 89%, compared to lower rates in forested (70%), agricultural (65%), and grassland (69%) areas. Interestingly, while developed areas had the highest detection frequency, the highest PFAS concentrations were observed in agricultural areas, possibly due to biosolids application practices, despite having a lower overall detection rate than developed areas (Silver et al., 2023).

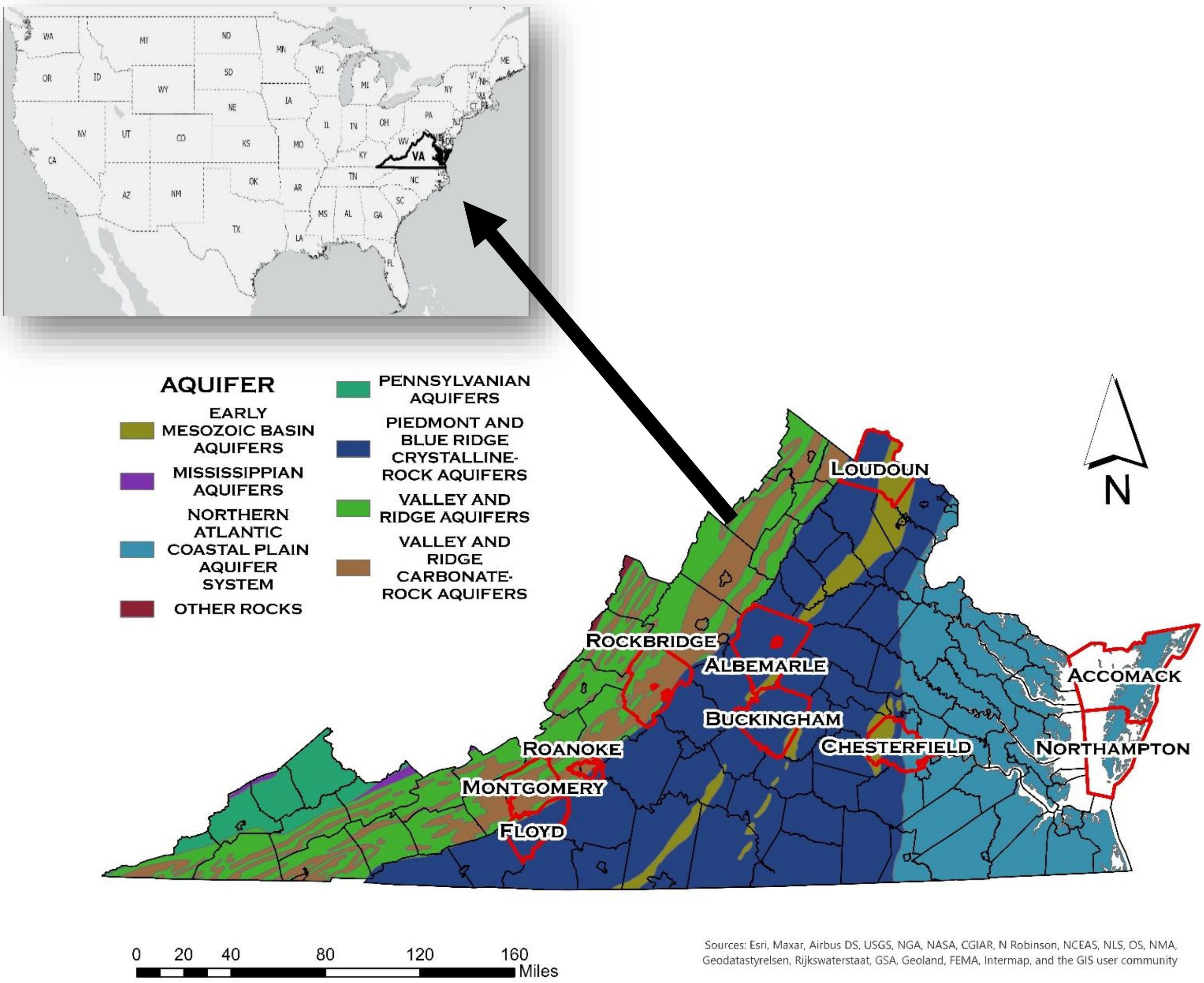
2.5 Motivation for research

Relationships between the incidence of PFAS in environmental waters and land cover are comparatively well-studied compared to examinations of the influence of land cover on drinking waters (Breitmeyer et al., 2023; Liddie et al., 2023; Smalling et al., 2023). In particular, private water supplies are understudied due to the difficulty in accessing samples and/or a perception of rural areas as a lower priority. However, rural communities are already prone to more water quality hardships than urban areas (Bradley et al., 2021), and private systems may be more vulnerable to environmental contamination due to limited treatment prior to consumption and monitoring (Lee and Murphy, 2020). Understanding potential risk factors for PFAS incidence, including surrounding land cover and well construction, is therefore necessary to support the development of proper regulations and targeted remediation strategies.

3. Methods

3.1 Study Area, Participant Recruitment, and Sample Collection

Drinking water clinics were held in ten counties in the state of Virginia: Accomack, Albemarle, Buckingham, Chesterfield, Floyd, Loudoun, Montgomery, Northampton, Roanoke, and Rockbridge (Figure 3.1). Counties were selected based on interest and participation in past Virginia Household Water Quality Program (VAHWQP) programming, and to represent a wide variety of underlying geologies, sociodemographic characteristics, and land covers (Table 3.1 and Appendix C; Table C1)



Sources: Esri, Maxar, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap, and the GIS user community

Figure 3.1: Participant counties and underlying major aquifers (US State Boundaries, 2025.)

Table 3.1: Key sociodemographic characteristics for participant counties compared to characteristics for the entire state of Virginia (Census Bureau Search, 2025.)

County	Accomack	Albermarle	Buckingham	Chesterfield	Floyd	Loudoun	Montgomery	Northampton	Roanoke	Rockbridge	Virginia
Total Population	33,413	112,395	16,824	364,548	15,476	420,959	99,721	12,282	96,929	22,650	8,631,393
Persons per Land Sq. Mile	74	156	29	862	41	816	258	58	387	38	219
Median Household Income	$57,500	$103,413	$59,199	$101,543	$61,401	$174,148	$68,079	$55,933	$80,809	$63,975	$89,931
Bachelor's Degree or Higher	22%	62%	14%	46%	23%	65%	49%	33%	36%	32%	42%
Median Age	47.5	42.1	43.7	39.2	48.0	38.3	29.8	51.6	42.9	49.7	39.3
White	59%	71%	61%	0.1%	91%	52%	78%	56%	82%	94%	59%
Hispanic or Latino	10%	7.5%	2.5%	11%	3.1%	14%	4.7%	8.7%	3.6%	2.3%	11%

Black or African American	26%	9%	32%	23%	1.5%	7.1%	4.1%	31%	5.8%	2.5%	18%
Other	5%	12.3%	4.2%	66%	4.1%	27%	13%	4.3%	8.1%	1.3%	13%

3.1.1 Participant Recruitment

Residents were eligible for participation if they had participated in previous VAHWQP drinking water clinics between 2020 to 2024 in the target counties. Recruitment emails and/or letters (mechanism dependent on prior preference during drinking water clinics) were sent to eligible participants directly from Cooperative Extension (VAHWQP) advertising the study. Participants who expressed interest were registered for a drinking water clinic on a pre-arranged date. Each household received free point of use (POU) water testing for metal ions, fecal indicator bacteria, and PFAS in exchange for participation. All recruitment, data collection, and communication strategies were pre-approved by the Virginia Tech Institutional Review Board (VT IRB #23-839). Drinking water clinics were conducted between 2023 and 2025 and resulted in a total of 382 participants.

3.1.2 Point of Use Well Water Sample Collection

Registered participants picked up a pre-prepared drinking water sampling kit at a central location (often the county Extension office) a day or two before the specified sample kit drop off date. Each kit contained the following items: one acid-washed polypropylene 125 mL bottle for pH, conductivity/total dissolved solids analyses; one acid-washed polypropylene 250 mL bottle for first draw metals, one pre-packaged IDEXX 125 mL bottle for fecal indicator bacteria testing; one 250 mL PFAS-free polypropylene bottle for PFAS analysis; nitrile gloves to prevent field contamination; laminated step-by-step sample collection instructions; and two surveys. To prevent cross contamination of the PFAS samples, the PFAS-free bottles were double bagged and separated from the other bottles. Post sample collection, participants returned their samples to the pre-arranged drop off point, typically the same county Extension office used for kit pick-up. Samples were then transferred to coolers and stored on ice during their return to Virginia Tech laboratories on the Blacksburg, VA main campus to begin sample analysis within 12 hours of collection.

3.1.3 Water Quality Analysis

Samples were analyzed for the following water quality parameters: first draw metals, pH, conductivity, total dissolved solids (TDS), fecal indicator bacteria (total coliforms and *E. coli*), and 30 PFAS compounds. Total coliform bacteria and *E. coli* were analyzed using the Colilert define substrate method (IDEXX, Westbrook, MN; Standard Method 9223B), pH and conductivity using the Oakton benchtop pH/conductivity/TDS meter (Cole Parmer, Vernon Hills, IL, USA), metallic cations (Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Fe, Mn, Co, Ni, Cu, Zn, As, Se, Sr, Mo, Ag, Cd, Sn, Ba, Pb, U) using ICP-IMS described by Standard Methods 303D and 3125B (APHA/AWWA/WED, 1998). However, due to laboratory errors only first draw lead, manganese, and iron were fully analyzed across all samples. A suite of 30 PFAS compounds were quantified using an Agilent LCMS 6490 Triple Quad system following USEPA Standard method 533 and 537.1 with solid phase extraction (SPE) to clean samples and LCMS (liquid chromatography mass spectrometry). Public water regulations on PFAS are regularly updated with the this study following the most recent May 2025 regulatory changes aimed solely at PFOA and PFOS MCL/MCLG guidelines (US EPA, 2025). Detection limits for metallic cations and PFAS compounds are provided in Appendix B; Table B1.

3.1.4 Participant surveys

Every drinking water sample kit provided to participants came with two household surveys: an 18 multiple choice and short answer VAHWQP survey (IRB #20-616) on perceived water quality, water use, and water system characteristics; and a PFAS supplemental survey (IRB #23-839) consisting of 24 multiple choice and short answer questions requesting additional water treatment information, household sociodemographic characteristics, consumer product use, nearby potential PFAS sources, land cover, and prior PFAS awareness (Appendix A; Figures A1, A2). Survey responses were entered manually into Microsoft Excel and matched to the drinking water sample results via an alphanumeric lab code used both on bottle and survey labels.

3.1.5 Participant Communication

Participants received individual summaries of their water quality results directly to their home or email address as preferred. Standard water quality measures (such as lead and coliform) were compared to existing EPA regulatory guidelines for municipal systems. Due to the rapidly evolving regulations surrounding PFAS, participants received separate letters outlining their PFAS results compared to the regulations at the time of sample collection (Appendix A; Figures A3, A4). Participants with further questions were provided with both VAHWQP and researcher contact information for follow up as needed.

3.2 Geospatial Trends and Statistical Analysis

3.2.1 Geospatial Attributes

Geospatial trends were examined via ESRI ArcGIS Pro geographic information system (*Desktop GIS Software | Mapping Analytics | ArcGIS Pro*, 2024.) software version 3.4.0 to explore potential relationships between water quality data, landcover as delineated by the National Land Cover Database (NLCD) (*National Land Cover Database | U.S. Geological Survey*, 2023.), and a variety of point sources (*Virginia Environmental Data Hub*, 2025.) (US EPA, 2013). The NLCD identifies the following land covers: Unclassified, Open Water, Perennial Snow/Ice, Developed, Open Space, Developed, Low Intensity, Developed, Medium Intensity, Developed, High Intensity, Barren Land, Deciduous Forest, Evergreen Forest, Mixed Forest, Shrub/Scrub, Herbaceous, Hay/Pasture, Cultivated Crops, Woody Wetlands, Emergent Herbaceous Wetlands. These land cover types were simplified into the following categories: Water (contains Open Water and Perennial Snow/Ice), Urban (contains all Developed classifications), Barren, Forest (contains Deciduous, Evergreen, and Mixed forests), Vegetation (contains shrub/scrub and herbaceous, woody wetlands, and Emergent wetlands), and Agriculture (contains Hay/pasture and cultivated crops) which is in line with other studies using land cover data categories (Breitmeyer et al., 2023; Seyam et al., 2023). The following point sources from VA DEQ and USEPA were identified and attributed to an overarching point source group based on similar characteristics to better establish statistical relationships in Table 3.2. Importantly these point sources are not necessarily specifically PFAS point sources nor differentiated based on air or water pollution. Rather, these point source grouping are looking at general human activity and if certain human activities are more important than others. For example, stormwater outfalls themselves are not point sources, but act as a funnel for human activity in the surrounding area concentrating at the stormwater outfall.

Table 3.2: Point Source groups with data associated with the overarching group

Point Source Group	**Specific Point Source Data**
Manufacturing and Materials	Cement Mfg., Glass Products, Paper Mills and Products, Textiles and Leather, Furniture and Carpet, Metal Machinery Mfg., Electronics Industry
Chemical, Coating, Plastic Industries	Chemical Mfg., Paints and Coatings, Metal Coating, Printing, Plastics and Resins, Cleaning Product Mfg.

Oil and Gas	Oil and Gas, Petroleum, Industrial Gas
Consumer Products	Consumer Products
Fire Facilities	Fire Protection, Fire Training Sites
Airports	Airports, Airports (Part 139)
Defense	National Defense, Formerly Used Defense Sites (FUDS)
Waste Management	Waste Management Facilities
Biosolids	Permitted Biosolids Applied Field
Stormwater	Permitted Stormwater Outlets
TRI	Toxic Release Site

3.2.2 Geospatial Analysis

All GIS analyses relied on the projected coordinate system UTM zone 17N. In brief, 5 km buffers around each sample address were used to delineate adjacent landcover for each sample. Despite the best efforts for clinics to be run within specific counties, some participants homes fell over the planned county line; for the purposes of county-level analyses these samples were assigned to the county clinic attended. Additionally, the county-lines are arbitrary with regard to the geospatial variables analyzed in this study making these samples outside of the county a non-factor. The key geospatial attributes calculated in ArcGIS Pro were land cover percentage areas within the 5 km buffer, distances to the nearest point source group from sample site, and the number of point sources within 5 km of a sampled site. A brief summary of key geospatial analysis tools used is modeled in Figure 3.2.

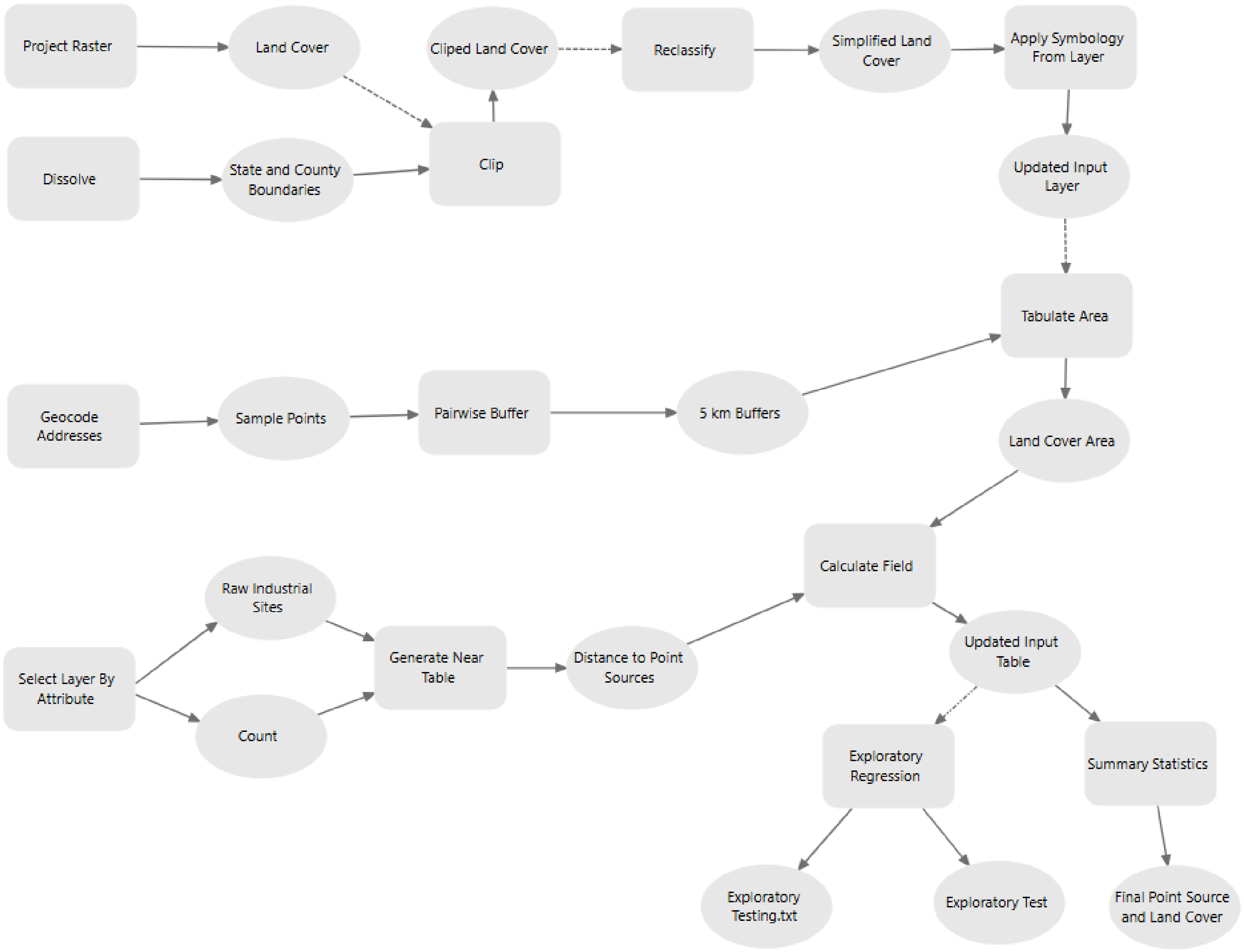


Figure 3.2: Project ArcGIS pro workflow

3.2.3 Statistical Analysis

All statistical analyses were completed using RStudio version 4.1. When calculating descriptive statistics (e.g., median, mean, minimum, maximum), samples for which a PFAS compound was reported as the method reporting limit (MRL) were assigned as half the MRL value for that compound; non-detectable (ND) samples were assigned zero. When calculating PFAS detection rates, samples reported as MRL were assumed detectable; for calculating quantifiable PFAS concentration rates, MRL were assumed to be zero. Additionally, survey results and traditional water quality markers were grouped by county as well as total over the entire data set.

The Shapiro-Wilks normality test demonstrated that the total sum PFAS concentrations of this study are strongly-non-normal (W=0.228, $p=2.2 \times 10^{-16}$). RStudio was used to explore statistically significant relationships between household characteristics (well systems, septic systems, pipes, and treatment), traditional water quality markers (metals, fecal indicator bacteria, pH, conductivity, total dissolved solids), and geospatial variables (land cover, number of point sources within 5 km, distance to point sources) to total sum PFAS concentration incidence via the nonparametric statistical analyses described in Table 3.3.

Table 3.3: Summary of Statistical Methods

Research Question	Statistical method	Variable Type	Purpose
Does total sum PFAS concentration vary with household characteristics, traditional water quality, or geospatial variables?	Spearman rank correlation	Continuous variables (distance to point sources, land cover %, lead concentration, well depth)	Measures the direction and strength of relationships between with household characteristics, traditional water quality, or geospatial variables with PFAS concentrations
Are the characteristics of high total sum PFAS households (e.g., number of point sources and water quality) different than those of low total sum PFAS households?	Wilcoxon test	Binary (High total sum PFAS = top 10% vs. Low total sum PFAS = bottom 90%) and continuous variables (e.g., number of point sources with 5 km, TDS concentration, and fecal indicator bacteria)	Determines whether high total sum PFAS households are associated with more point sources or cooccurrence with traditional water quality parameters
Are the characteristics of high total sum PFAS households (e.g., bacteria, pipe material, or treatment type) different than	Chi-square test/Fisher's test	Binary (High total sum PFAS = top 10% vs. Low total sum PFAS = bottom 90%) and True/False of variable	Determines whether high total sum PFAS households are disproportionately represented with household characteristics, traditional

those of low total sum PFAS households?		(e.g., treatment present/absent, coliform present/absent)	water quality. When the distribution of a variable between the bottom 90% and top 10% of households is below 5 in a bin Chi-square assumption fails (n>5 per bin) and Fisher’s test was ran

4. Results and Discussion

4.1 Sociodemographic and Household Characteristics

4.1.1 Sociodemographic Information

Overall participant demographics are provided in Table 4.1. As is clear when comparing to the US Census data for the target counties (Table 3.1), the demographics of participating homes were not broadly representative of Virginia. For example, participating households are overwhelmingly self-identified as white (93%) although across the state only 59% of the population identifies as white. The median age of participating head of households was 49 years old, which is 10 years older than the 39 year median age across Virginia. Finally, although only 42% of Virginians have obtained a bachelor’s degree, 48% of participating head of households had completed a graduate degree. For a more detailed breakdown of participant demographics by county of demographics refer to Appendix C; Tables C2, C3, C4.

Table 4.1: Summary demographics for participating households (n=382 homes). Note that because some participants chose not to answer all questions, the number of responses may not always equal 382.

Number of Households	*382*
Average number of participants per household (n=901 individuals)	2.4

Age (n=910 individuals)	Age 0-5	44 (4.8%)
	Age 6-18	116 (13%)
	Age 19-50	232 (26%)
	Age 51-65	184 (20%)
	Age 66+	334 (37%)
Race/ethnicity of household (n=367)	White/Caucasian	341 (93%)
	African American	7 (1.9%)
	Hispanic	4 (1.1%)
	Native American	2 (0.5%)
	Hawaiian	0 (0.0%)
	Multiracial	7 (1.9%)
Household income (n=307)	< $26,000	16 (5.2%)
	$27,000-$52,000	34 (11%)
	$53,000-$70,000	33 (11%)
	$71,000-$97,000	52 (17%)
	> $98,000	172 (56%)
Highest level of education of head of household (n=361)	Some high school	2 (0.6%)
	High school graduate	10 (2.8%)
	Some College	43 (12%)
	College graduate	132 (37%)
	Post-college (MS, PhD)	174 (48%)
Previous Well Water Testing (n=377)	Never	19 (5.0%)
	When I think there is problem	22 (5.8%)
	Once or twice	189 (50%)
	Every 5 years	28 (7.4%)
	Every other year	64 (17%)
	Every year	55 (15%)

Previous collaborative research with VAHWQP has suggested that household water quality varies by household income, with lower income homes more likely to submit samples that exceed MCLs for municipal systems (Smith et al. 2014; Lytle et al. 2025). While the average household income of participants in this study skewed higher than the state median of $89,931, it is worth noting that this varied by county (Figure 4.1). For example, the majority of participants in the highest income bracket were from Albemarle and Montgomery counties, both of which are home to major research universities, and Loudoun County, which is the wealthiest county in the state. In contrast, participants from Buckingham County represented the largest portion of the lowest income bracket; this is the most rural county in the study at 29 persons per square mile (Table 3.1).

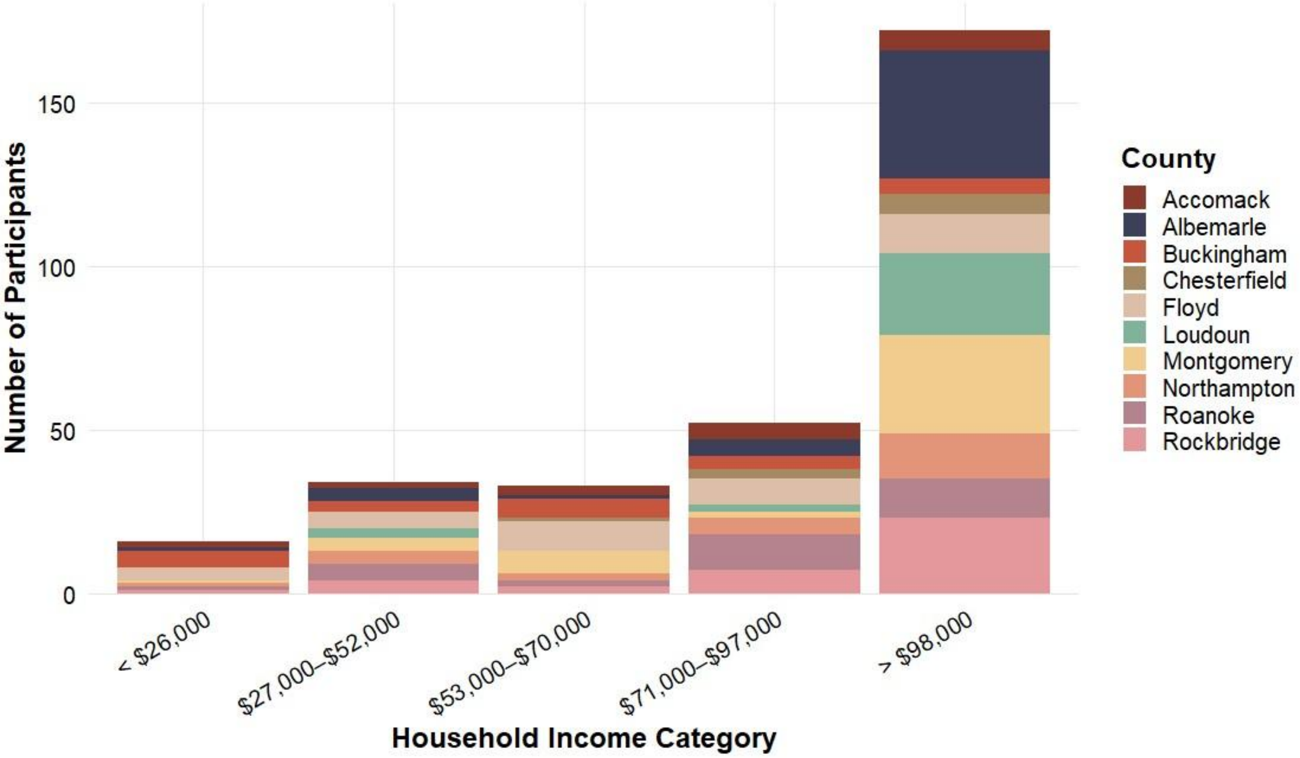


Figure 4.1: Income distribution of participants by county

While the population sampled is not representative of Virginia overall, it is in line with previous studies examining private water samples (Smith et al. 2014; Pieper et al. 2015; Hohweiler et al. 2024; Lytle et al. 2025) and expectations given participant eligibility.

Participants were recruited from contacts lists of previous water clinic participants, i.e., they were aware of the VAHWQP, had the time to be able to pick up kits, collect samples, and drop off their samples within a pre-arranged time frame, and are typically homeowners. This created bias towards higher educated, higher income, and older individuals who were able to participate in this study. It is worth noting that this project focused on rural areas, and the overall Virginia sociodemographic information incudes urban areas where people tend to be younger and more diverse (Hayes et al., 2025; "Urban-Rural by the Numbers," 2018).

4.1.2 Household PFAS usage

In addition to sociodemographic info, participants also self-reported usage rates of common household products that are likely to contain PFAS compounds (Table 4.2). The scores in this Table correspond to categorical data where respondents could select "Daily," " Weekly," "Occasionally," or "Never," these were converted to scores of 3, 2, 1, and 0, respectively. The most commonly used likely PFAS containing products were sunscreen and cosmetics, and the least common were lawn care products and pest control.

Table 4.2: PFAS product usage rates; although the total number of homes was 382, lower/inconsistent response rates reflect that participants sometimes left questions unanswered.

Household Products	Per Household score
Cosmetics (e.g., eyeliner) (n=357)	1.50
Sunscreen (n=370)	1.54
Mosquito repellent (n=365)	1.14
Microwave meals (n=367)	1.22
Microwave popcorn (n=354)	0.85

Nonstick cookware (n=364)	1.39
Waterproofed clothing (e.g., Gore-Tex) (n=367)	0.97
Pest control treatment (e.g., for termites) (n=354)	0.70
Lawn care service (n=339)	0.49
Dryer sheets/fabric softener (n=352)	1.14
Aluminum foil (n=378)	1.40
Stainmaster treatments for carpet or upholstery (n=345)	0.91

4.1.3 Onsite Water and Wastewater System Characteristics

Well construction type, depth, and age are compared across counties in Table 4.3. Previous work has stressed that private water system types can differ significantly according to local geology (Pieper et al., 2016); this was also observed in this study. For example, wells in Southwest Virginia (i.e., Montgomery and Rockbridge counties) in the Valley and Ridge aquifer region have more mountainous terrain and as a result is not conducive for shallow well construction. In comparison, the Blue Ridge-Piedmont Aquifer system (i.e., Chesterfield and Buckingham counties) have shallower wells reflecting lower depth to major aquifers. This is exemplified by low occurrence of dug/bored wells in the Valley and Ridge aquifer compared to the Blue Ridge-Piedmont where dug/bored wells are adequate to access shallower aquifers. While well construction patterns (e.g., dug/bored vs. drilled) are similar to Pieper et al., (2016), the average age of wells in this study are slightly younger than that presented in Lytle et al., (2025). This study could have skewed younger due to sampling younger population counties such as Loudoun and Chesterfield counties than Lytle et., al (2025) which focused in the older southwest VA regions.

Table 4.3: Well characteristics for participating households by county

County	Well (Unknown)	Drilled Well	Dug or Bored Well	Median Well Depth (ft)	Median Well Age (years)
Accomack (n=18)	17%	83%	0%	175	24.5
Albemarle (n=60)	22%	77%	2%	275	25
Buckingham (n=34)	26%	62%	12%	150	33
Chesterfield (n=15)	20%	33%	47%	58	28
Floyd (n=37)	35%	62%	3%	220	23.5
Loudoun (n=42)	29%	69%	2%	250	25.5
Montgomery (n=53)	43%	57%	0%	400	25
Northampton (n=39)	13%	79%	8%	165	17.5
Roanoke (n=33)	39%	58%	3%	194	37
Rockbridge (n=42)	7%	86%	7%	338	23
Total (n=373)	**26%**	**68%**	**6%**	**209**	**25**

Given previously documented high concentrations of lead and copper in point of use well water samples submitted through this Cooperative Extension program (Pieper et al., 2015), it is critical to consider pipe materials, which can become a source of contamination in corrosive waters. An overwhelming 64.2% of participants identified their plumbing as largely plastic (i.e., PEX) and only one participant responded that they relied on lead pipes (Figure 4.2). Plastic plumbing often still contains brass or other metal fittings, connectors and valves which could be prone to corrosion. However, Only 10% of participants reported corrosion as an issue via their survey.

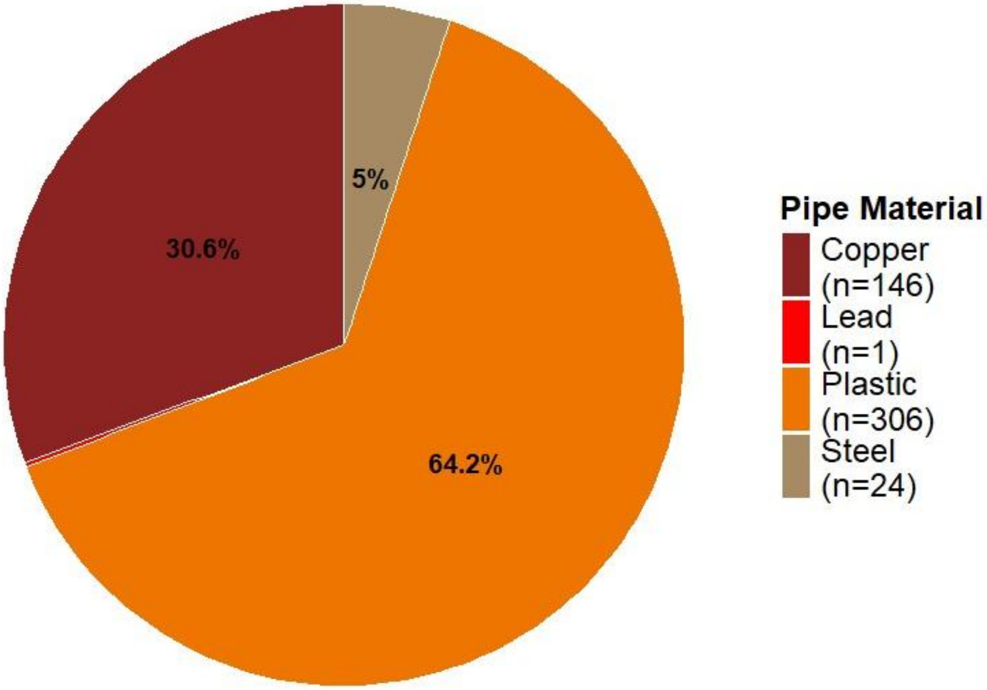


Figure 4.2: Participant identified household pipe materials

4.1.4 In-home Drinking Water Treatment and Water Use

The majority of homes (70.2%; n=268) employed at least one treatment process in their drinking water system prior to household use. This is notably higher than that recently observed by Lytle et al (2025), who reported that 65% of participants in six southwest Virginia counties participating in VAHWQP programming employed no treatment before use, before use. Again, this may reflect the eligibility requirements of this study (e.g., previous participation, availability to comply with study requirements) which resulted in a slightly wealthier and more educated demographic. For further comparison, treatment was classified as targeting health based contaminants versus primarily aesthetic contaminants, i.e., designed specifically to remove harmful exposures versus focused more on the taste, smell, and visual appeal of the water. As in Lytle et al., (2025), carbon filters, reverse osmosis, ultraviolet systems, and chlorinators were classified as health-based, while sediment filters, acid neutralizers, water softeners, and iron removal were classified as aesthetic-based (Figure 4.3).

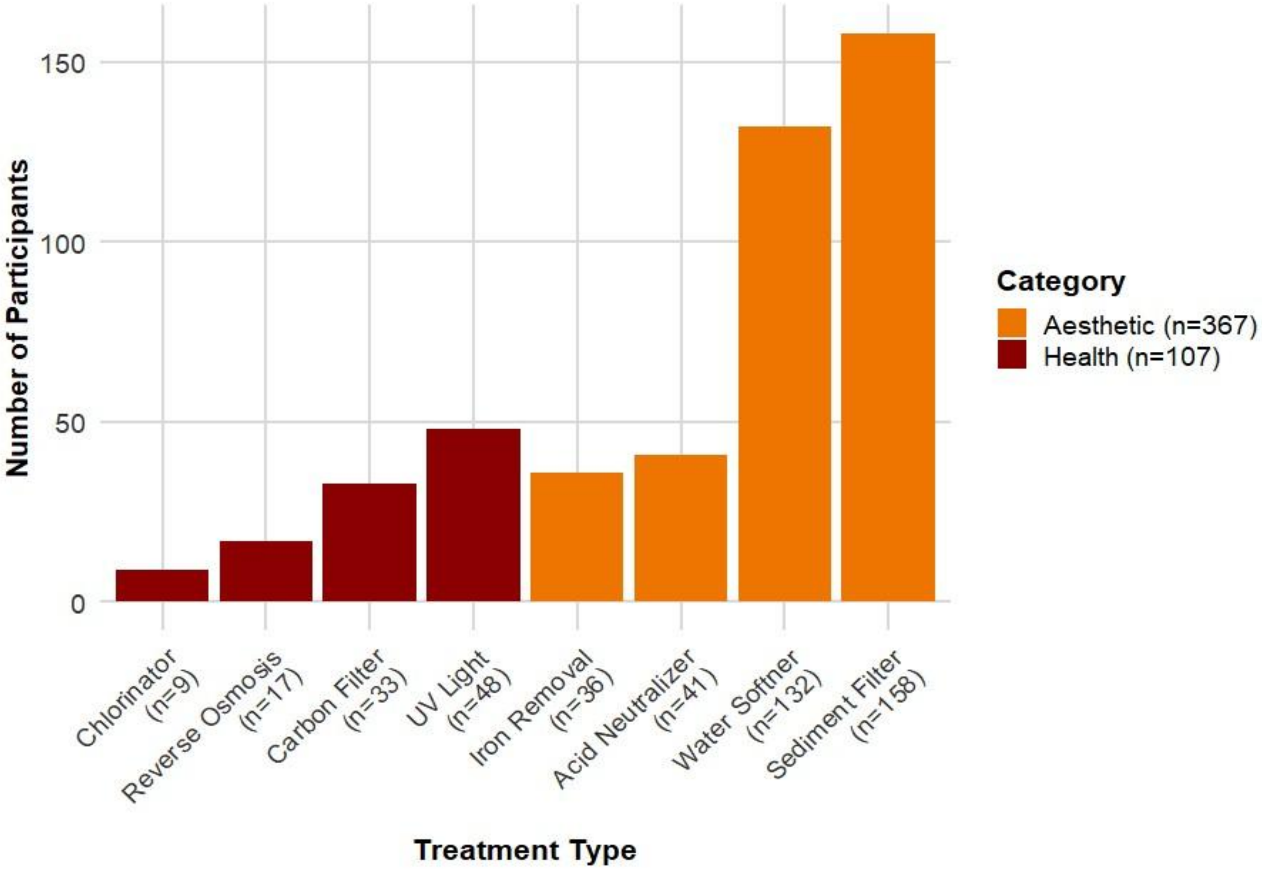


Figure 4.3: Reported drinking water treatment systems in participating households

Although the overall use of treatment was higher than reported in previous research partnerships engaging VAHWQP participants (Lytle et al., 2025; Smith et al., 2014), the majority of homes (66.8%) exclusively used treatment methods targeting aesthetic contaminants (i.e. particulates, pH, hardness, iron). Under a third (21.7%) of homes employed treatments targeting both aesthetic contaminants and contaminants of health concern, and 1.8% only used treatments targeting contaminants of health concern (i.e., organic chemicals, volatile organic compounds, heavy metals, and bacteria). The most common treatment types were sediment filters (41.4%) and water softeners (34.6%). Despite the common lack of treatments targeting health-based contaminants, the majority of participants in all counties did use their water for direct consumptive use (Figure 4.4).

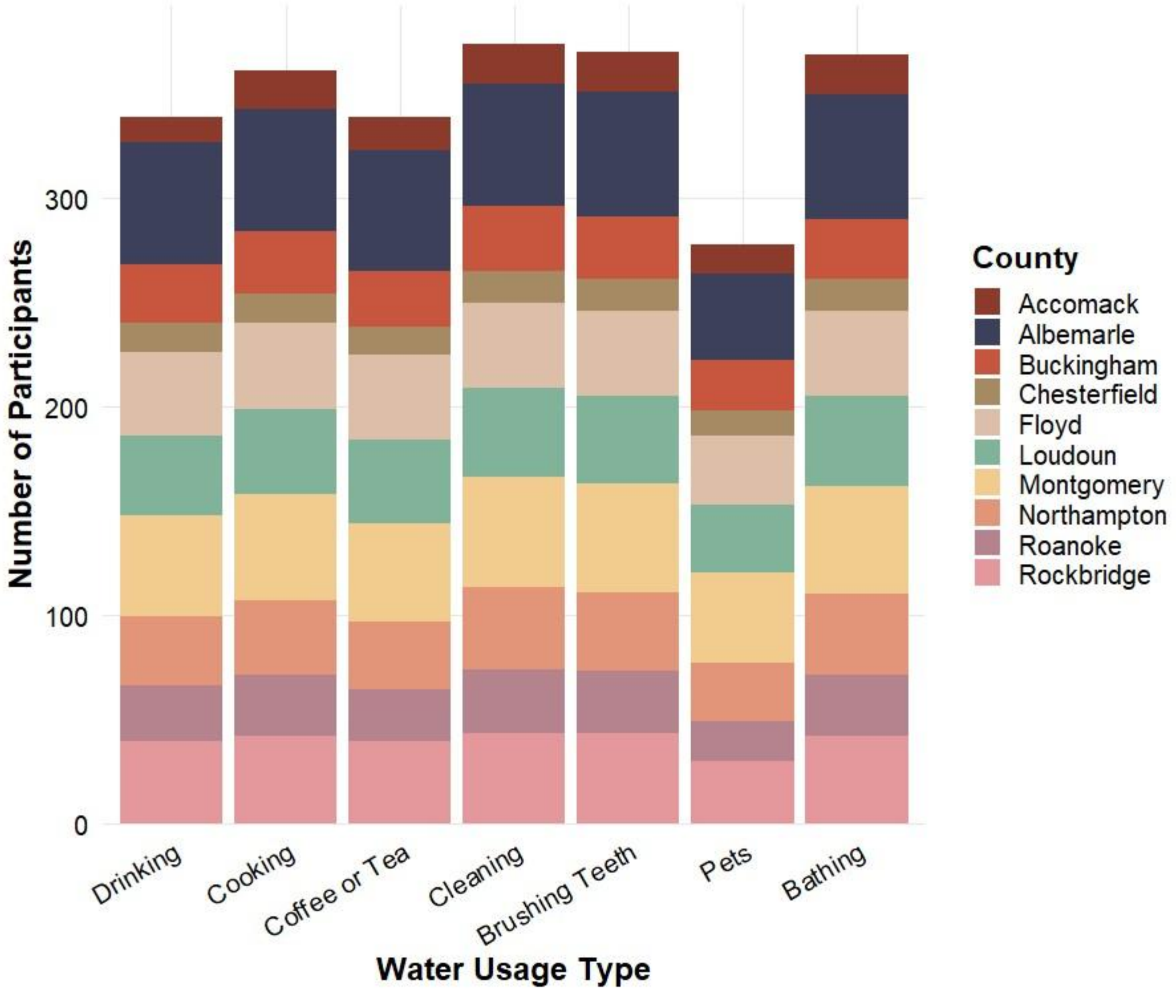


Figure 4.4: Water usage patterns of participants

4.1.5 Onsite Wastewater (Septic) Systems

Septic systems are common in rural areas; if improperly maintained, these systems can cause contamination of groundwater which serves as drinking water for private wells (Gyimah et al., 2024; Hernandez & Pierce, 2023). Survey information on the presence of septic systems, distance from the household, location relative to the house and well head, system ages, years since tank pump out, and past septic failures is provided in Figures 4.5, 4.6, and 4.7.

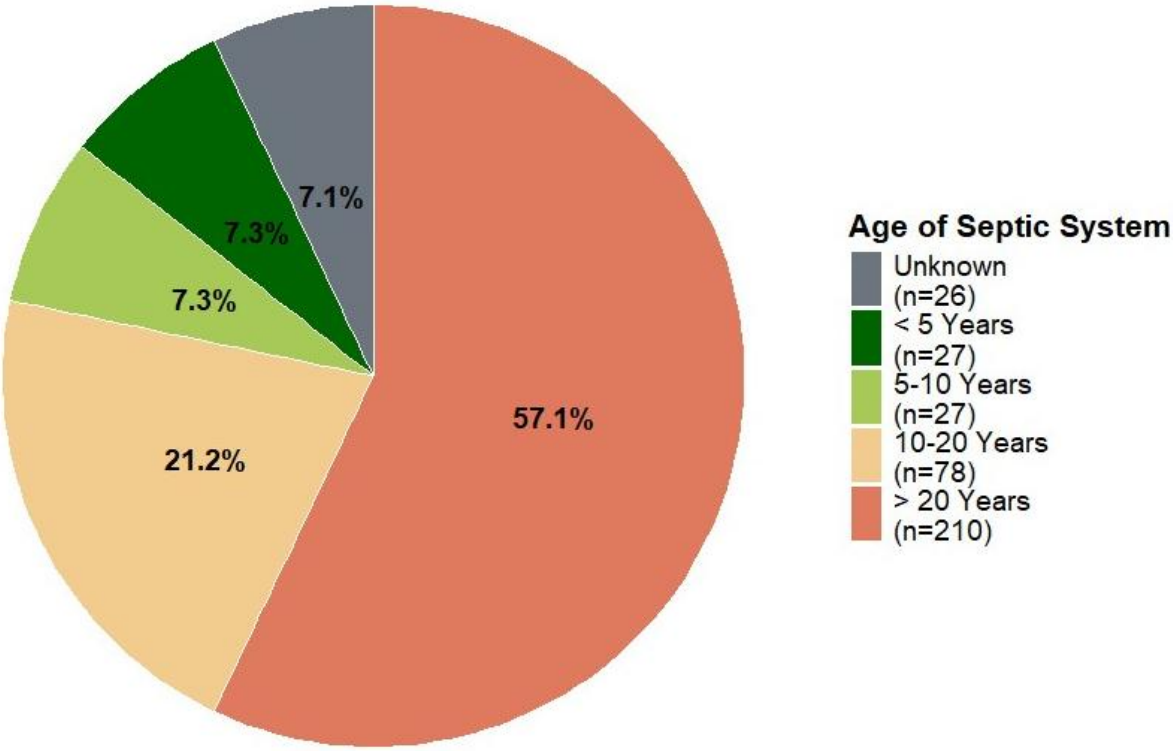


Figure 4.5: Participant identified household septic system age

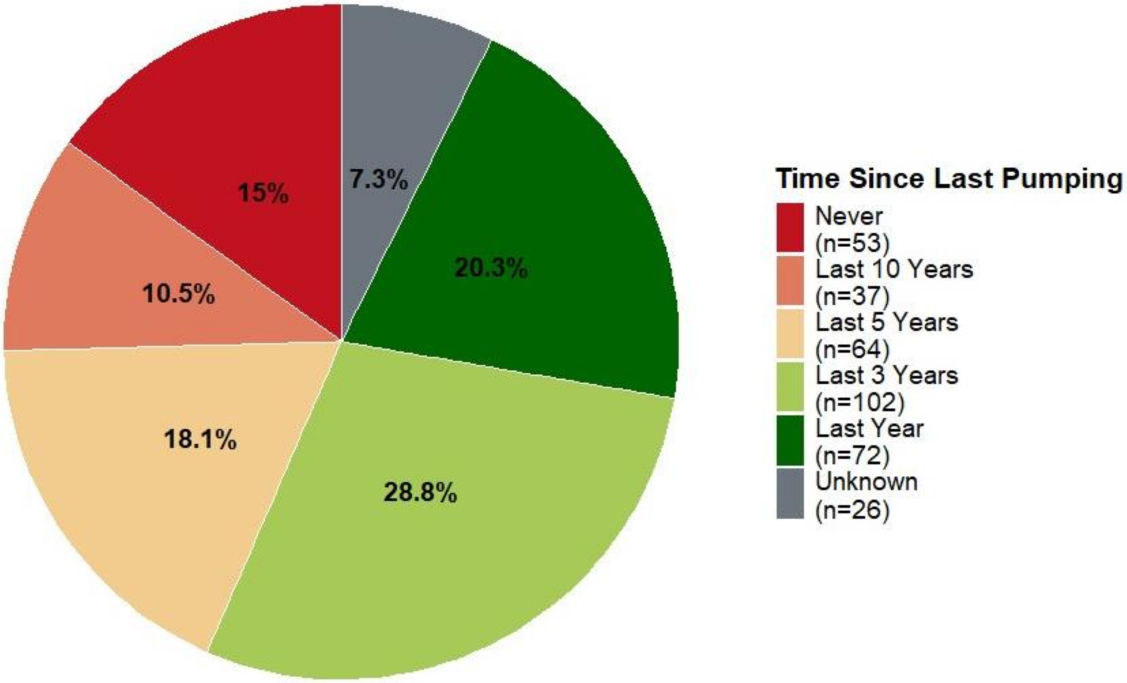


Figure 4.6: Participant identified septic pumping frequency

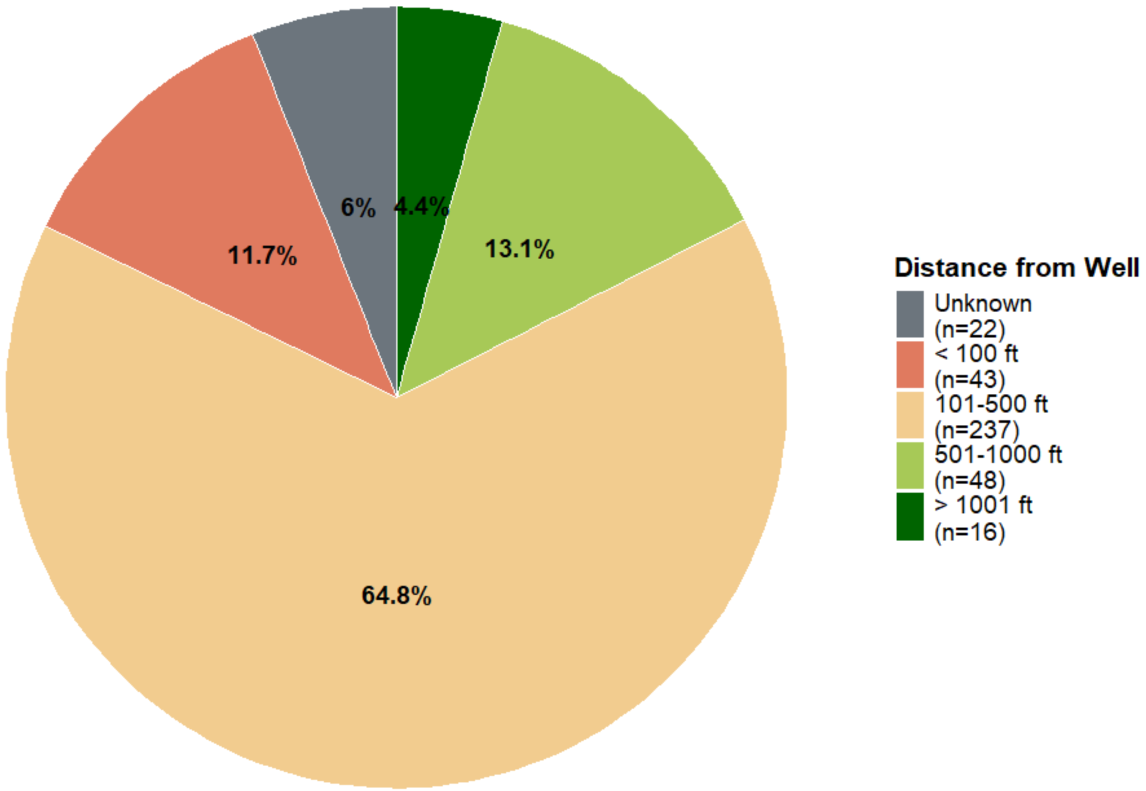


Figure 4.7: Septic System distance from well

In this study, 97% of participants relied on a septic system to manage their household wastewater, as was expected. The average system was 25 years of age and had been pumped out <5 years ago. The average system was 250 feet from their well head, and 65.1% of participants indicted their septic system was downhill of their well head, i.e., ideally hydrologically downstream, and less likely to result in contamination. However, 13.9% of participants had never pumped out their septic tank, and 10.5% reported a previous septic system failure/major repairs performed.

4.2 Water Quality Results

Observations of traditional water quality markers, including pH, conductivity, Total Dissolved Solids (TDS), presence of fecal indicator bacteria (total coliform and *E. coli*), and first draw samples for lead, manganese, and iron for the entire sample set are provided in Table 4.4;

county level incidences are available in Appendix D; Table D1. First draw metals values were not available for all samples due to a laboratory processing error, resulting in a smaller sample size for those parameters. The most commonly detected contaminants of concern were coliform and lead, though these were present at lower rates than in previous VAHWQP-based studies. For example, (Allevi et al., 2013) observed 41% (n=221) total coliform positive and 10% *E. coli* positive (n=53) samples, while (Pieper et al., 2016) observed 42% total coliform presence, 9% *E. coli* positive samples, and 19% of samples exceeded lead action levels at the time (0.015 mg/L) (n=2,885).

Table 4.4: Overall incidence of traditional water quality markers as compared to USEPA standards and guidelines for municipal systems

Measure of Water Quality	**Standard or Recommendation**	**% Exceeding Standard**	**Median (Mean ± Deviation)**	**Max Observed**
EPA MCLs/Action Level				
Total Coliform Bacteria (n=382)	0 MPN/100 mL (Absent)	34.8%	0 (75.5 ± 360)	2420
***E. coli* Bacteria (n=382)**	0 MPN/100 mL (Absent)	4.19%	0 (1.20 ± 13.7)	252
Lead (n=339)	> 0.010 mg/L	5.01%	0.0007 (0.0028 ± 0.007)	0.07
Lead MCLG (n=339)	0 mg/L (Absent)	93.2%		
EPA SMCLs/Action Level (Taste and Aesthetics)				
pH (n=382)	6.5 - 8.5	20.4%	7.15 (7.15 ± 0.74)	4.0, 9.3
Total Dissolved Solids (n=382)	< 500 mg/L	4.97%	180 (215 ± 157)	956
Manganese (n=339)	< 0.05 mg/L	4.72%	0.0017 (0.013 ± 0.038)	0.347
Iron (n=339)	< 0.3 mg/L	2.95%	0.0075 (0.0561 ± 0.246)	3.57

Although exceedance rates were slightly lower than in previous studies, the high incidence of fecal indicator bacteria (35% positive for coliform, 4% positive for *E. coli*) is somewhat concerning as participants are repeat testers. The goal of VAHWQP is to educate participants on the quality of their own drinking water and recommend strategies such as treatment to address concerns (i.e., fecal indicator bacteria). Though previous surveys of participants suggest many do implement VAHWQP suggestions (Benham et al. 2016), the remaining common detection of bacteria in these samples suggests additional assistance may be available. Although few first draw samples exceeded the newly established 10 ppb action level for lead, lead was detected in 93.2% of samples and the MCLG for lead is zero (non-detects). Only one household identified their system as reliant on lead piping, however lead may be present in samples due to brass alloy components (fittings, connectors, valves) in faucets and well construction and lead solder part of the in-home plumbing network (Pieper et al., 2015).

4.3 PFAS Incidence

At least one of the 30 PFAS compounds targeted by this standard method was detectable in all (100%, n=382) samples analyzed; 90% of samples included at least one quantifiable PFAS chemical (i.e., >MRL). PFAS was also essentially ubiquitous in a previous pilot program examining private water samples in Virginia (Hohweiler et al., 2024), However, it is critical to note that despite the high incidence of detectable compounds, the median total PFAS concentration in this study was well below commonly established health guidelines at only 1.50 ppt.

PFAS chemicals are commonly grouped by the number of carbons in the molecule; long chain PFAS chemicals (>= 6 carbons) are sometimes referred to as “legacy” PFAS as these were the first types of PFAS broadly manufactured. Of the 30 PFAS compounds targeted by EPA Methods 533/537.1, short chain chemicals include eight chemicals: PFBA, PFPeA, HFPO-DA (Gen-X), FBSA, L-PFBS, PFHxA, 4:2FTS, and L-PFPeS. The remaining 22 chemicals are long chain compounds, including: PFHpA, DONA, FHxSA, PFHxS, PFOA, 6:2FTS, L-PFHpS, PFNA, FOSA, PFOS, PFD, 8:2FTS, 9Cl-PF3ONS, L-PFNS, PFUdA, N-MeFOSAA, N-EtFOSAA, L-PFDS, PFDoA, 11Cl-PF3OUdS, PFTrDA, and PFTeDA. Though fewer short chain PFAS chemicals are targeted by this method, the sum total short chain median concentration was 1.12 ppt for samples collected in this study, while the sum total long chain PFAS median concentration was only 0.267 ppt (Table 4.5). The greater concentration of short chain PFAS may indicate that long chain compounds degrade into short chain compounds in the environment, and/or a greater prevalence of newer shorter chain PFAS compounds compared to legacy long chain compounds in daily human use.

Table 4.5: Sum total short chain vs long chain PFAS chemicals in participant samples (ND = not detectable)

Statistic	**Short Chain (ppt)**	**Long Chain (ppt)**
Median	1.12	0.267
Max	193	262
Min	ND	ND

Previous studies suggest that PFAS chemicals are typically detected in mixtures in drinking water (Teymourian et al., 2021; Hohweiler et al. 2024). The median sample contained 7 unique PFAS compounds; one sample from Roanoke contained 17 unique PFAS compounds (total sum PFAS in this sample = 40.1 ppt). Hohweiler et al., 2024 found a well water sample on average contained 3 detectable PFAS compounds and a maximum mixture of 8 detectable PFAS compounds (n=60). This difference is likely caused by differing MRLs as Hohweiler et al., 2024 used direct injection methods which have higher MRLs compared to this study which used solid phase extraction with lower MRLs. Illustrated in Figure 4.8, all targeted PFAS chemicals except L-PFNS, PFUdA, and L-PFDS were detectable in at least on participant submitted sample.

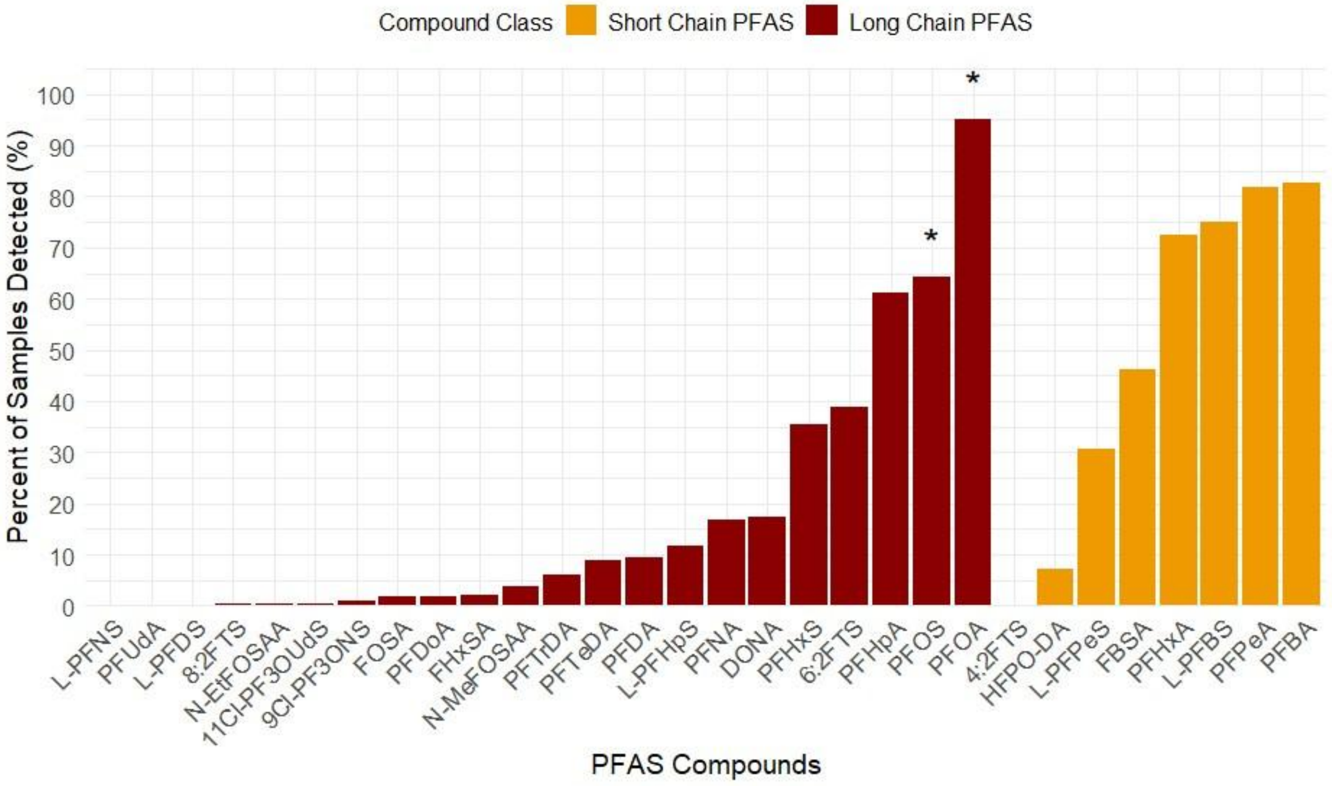


Figure 4.8: Detection rates of all 30 PFAS compounds targeted via USEPA Methods 533/537.1 in participant samples (n=382). Note that samples "<MRL" (method reporting limit), i.e., not quantifiable, were considered detectable. Asterisk denotes regulated PFAS compounds (PFOA and PFOS)

Concentrations of all compounds were quite variable (Figure 4.9). At present, the USEPA is poised to officially apply primary drinking water standards (MCLs) for two PFAS compounds in public drinking water by 2031: PFOA and PFOS. Although these regulations will not apply to private water systems, these are useful benchmarks to understand the scope of the issue in private drinking water. PFOA and PFOS were detectable in 95% and 64% of participant submitted samples (mean average concentrations of 0.46 ppt and 1.06 ppt, respectively). However, only 2.4% of samples exceeded the MCL of 4 ppt for PFOA and only 5.2% of samples exceeded the MCL of 4 ppt for PFOS. The overall high median PFOA concentration is due to a few very high sample concentrations, including a maximum detection of 122.45 ppt (sample collected in Loudoun County).

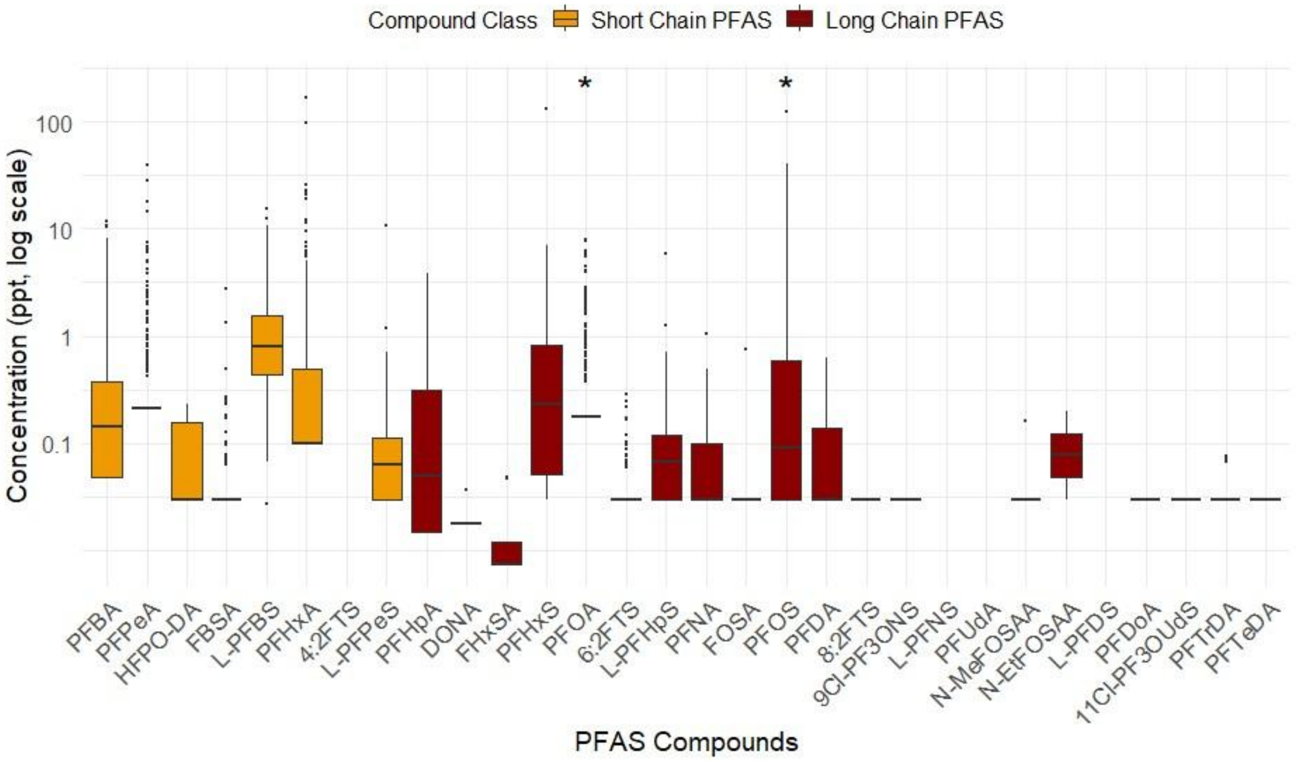


Figure 4.9: Concentrations of all 30 PFAS compounds targeted via USEPA Methods 533/537.1 in participant samples (n=382). Note that samples "<MRL" (method reporting limit), i.e., not quantifiable, were assigned half the value of the reporting limit for this calculation. Asterisk denotes regulated PFAS compounds (PFOA and PFOS)

The full range of sum PFAS concentrations (i.e., the sum total of all 30 target chemical concentrations) is provided in the cumulative distribution plot in Figure 4.10. Overall, 90% of participant samples yielded a total PFAS concentration of less than 10.03 ppt. The remaining 10% (n=39) of participant samples ranged from 10.03 ppt to 303 ppt sum total PFAS. Not surprisingly, samples with higher total concentrations also tended to contain more specific PFAS compounds. On average, samples with less than 10.03 ppt contained 7 PFAS compounds, while samples with greater than 10.03 ppt contained 13 PFAS compounds. The increase in total sum PFAS starting at the top 10% of homes and Smith et al., 2014 using the same grouping justified the binary characterization of high and low total sum PFAS homes.

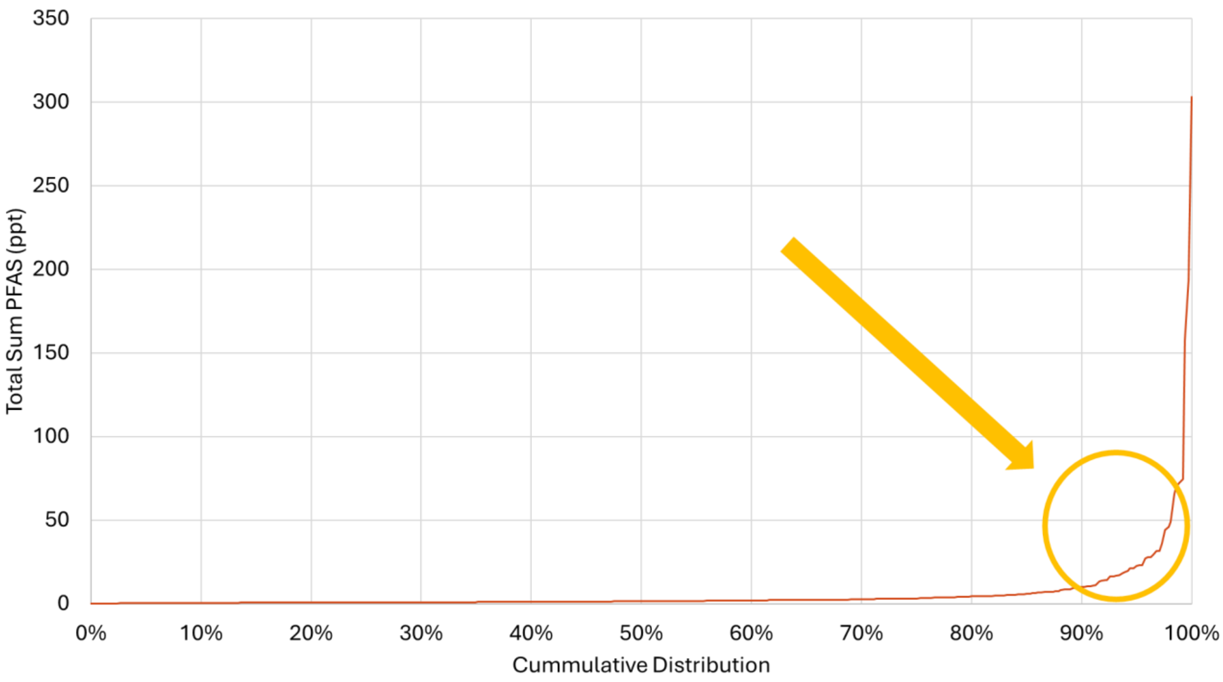
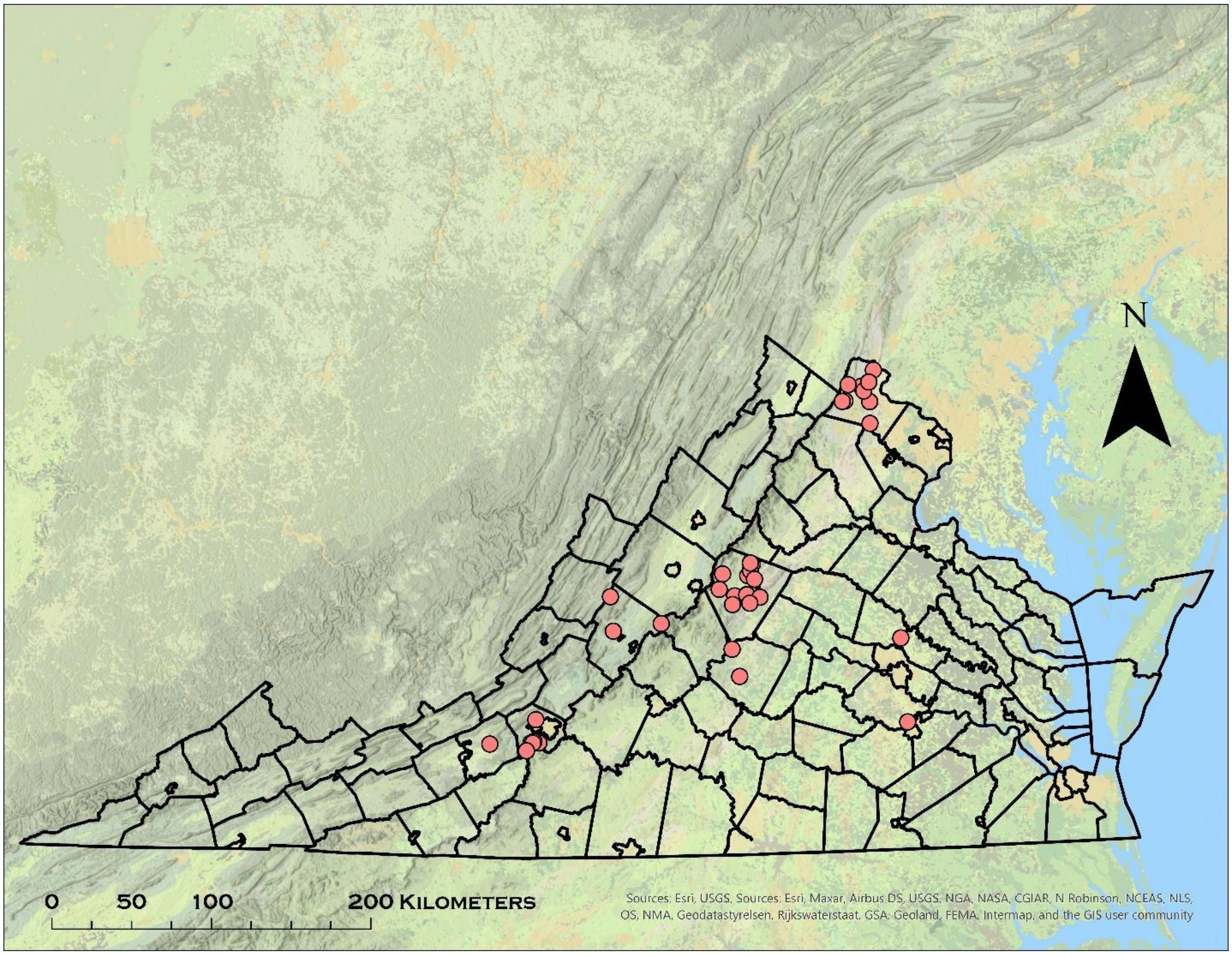


Figure 4.10: Cumulative distribution plot of total PFAS concentrations in participant samples

4.4 Statistical Analysis and Geospatial Trends of PFAS

4.4.1 Relationships between land cover and PFAS

An initial effort to geolocate samples where the sum PFAS concentration was greater than 10 ppt (Figure 4.11) did not yield any immediate visual trends. Though many of the greater than 10 ppt samples collected were in more urban counties, Albemarle (n=13), Loudoun (n=10), Roanoke (n=8), only one greater than 10 ppt sample was detected in Chesterfield, which has the highest population density of all the target counties (Table 3.1).



Sources: Esri, USGS, Sources: Esri, Maxar, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap, and the GIS user community

Figure 4.11: Locations of samples with sum PFAS concentrations >10.0 ppt, i.e., the highest 10% of observed sum PFAS concentrations in this study

Samples that had the highest total sum PFAS samples were collected in Loudoun (303 ppt and 157 ppt) and Albemarle (194 ppt) counties. The highest median sum total PFAS concentrations were observed in Loudoun (2.81 ppt), Albemarle (2.24 ppt), and Buckingham (1.72 ppt) counties. Although Loudoun and Albemarle are relatively “urban,” the population density of Buckingham County is quite low (Table 3.1). The lowest median sum total PFAS concentrations were observed in two highly rural counties (Accomack: 0.513 ppt; Floyd: 0.719 ppt), and the aforementioned most heavily populated county (Chesterfield: 0.909 ppt). Generally, high PFAS households were not clustered to just one singular location but rather appear across the state regardless of location in varying frequency.

Study samples are illustrated with surrounding land cover in Figure 4.12. As is evident in Table 4.6, which delineates the % landcover within a 5 km buffer of every sample, forest is the most common land cover overall, though urban and agricultural land cover are also common.

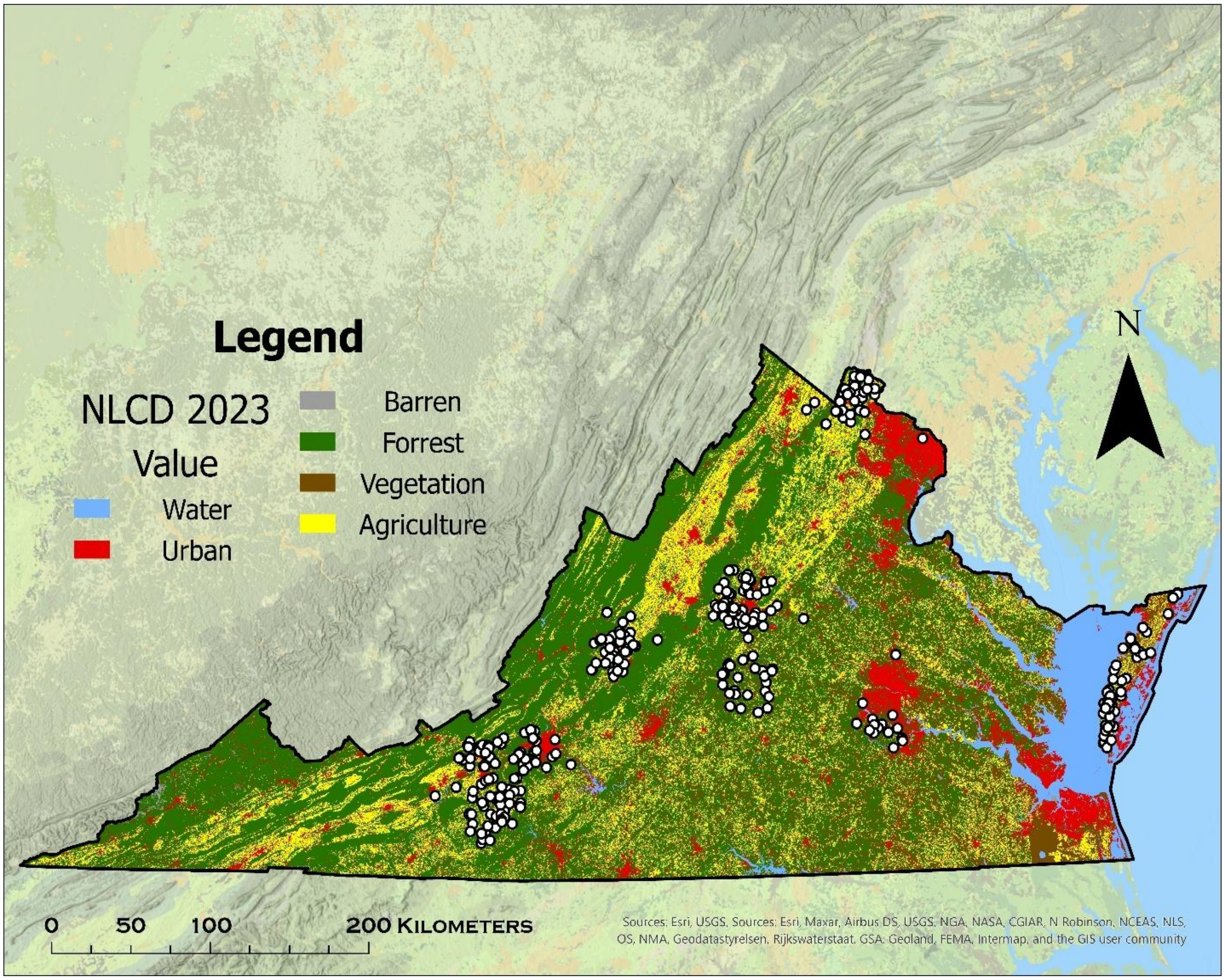


Figure 4.12: Study sample locations with Virginia land cover. Simplified land cover classifications are provided in Methods section 3.2.1

Table 4.6: 5 kilometer buffer land cover medians grouped by bottom 90%, top 10% and top 5% total sum PFAS concentrations

Land Cover	**Overall (N=382)**	**Bottom 90% (N=343)**	**Top 10% (N=39)**	**Top 5% (N=20)**

Water	0.32%	0.33%	0.24%	0.27%
Urban	10.3%	9.9%	12.6%	18.0%
Barren	0.01%	0.01%	0.00%	0.05%
Forest	54.6%	54.4%	55.3%	55.6%
Vegetation	1.39%	1.40%	1.32%	1.36%
Agriculture	23.0%	23.6%	18.7%	15.0%

The urban landcover percentage does rise as samples that represent the top 10% or 5% of total PFAS concentrations are considered. Urban areas often contain multiple PFAS sources such as industrial activity, consumer product waste, and stormwater runoff that could contribute to local contamination of groundwater sources. Notably, the percentage agriculture decreased as higher concentration samples were considered; this is unexpected given previous studies indicating agriculture land cover and particularly biosolid applications on agricultural fields is a major source of PFAS contamination of surface water (Breitmeyer et al., 2023; Silver et al., 2023). However, not all agricultural fields have bio solids applied and data attributing the agriculture land cover with having had biosolids applied is not readily available at this scale. These descriptive median observations were confirmed via a spearman's rho correlation analysis (Figure 4.13; full statistical output available in Appendix D; Table D4).

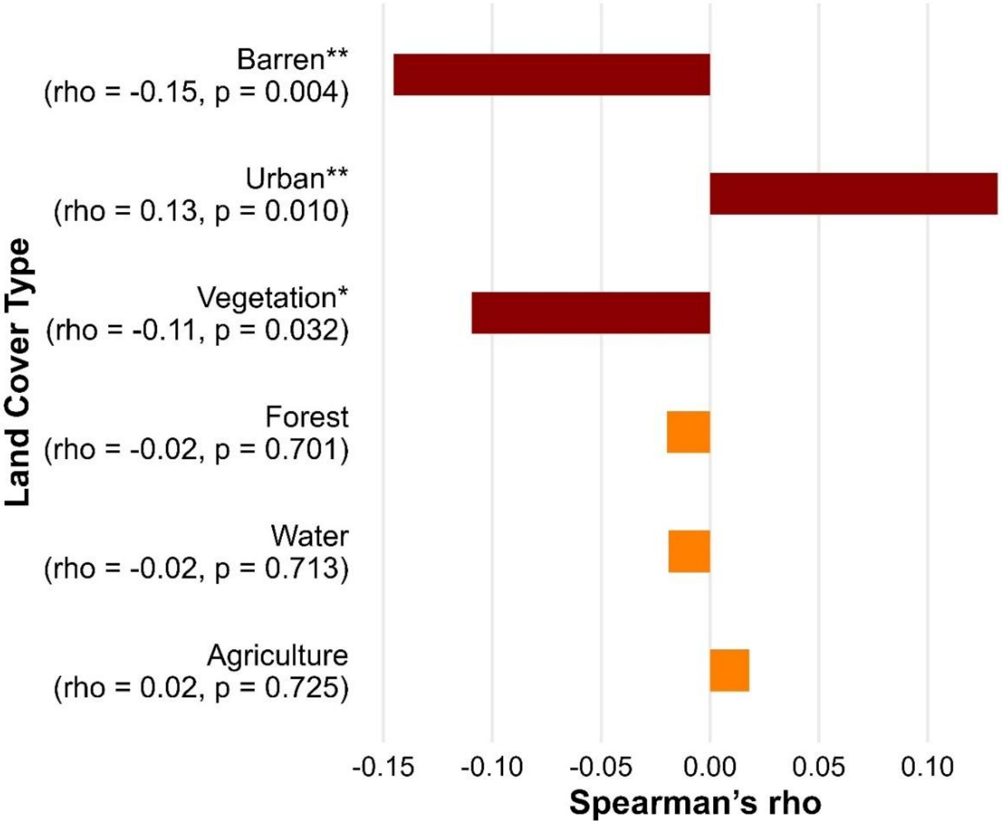


Figure 4.13: Spearman's Rho Correlation between land cover within a 5 km buffer and total sum PFAS. Statistically significant relationships are indicated by the marron color with * = $p<0.05$ and **= $p<0.01$.

The lack of a statistically significant correlation between agricultural land cover and sum PFAS in home water samples potentially contradicts prior research linking agricultural activity to surface water contamination (Breitmeyer et al., 2023; Sepulvado et al., 2011; Silver et al., 2023; Venkatesan & Halden, 2013). However, prior research focused on the impact of biosolid applications, which are not necessarily used on all agricultural fields. This discrepancy may also reflect differences in exposure pathways and timing, for example, the lag time between surface application and PFAS transport into groundwater aquifers.

Barren, Vegetation, and Urban land covers were statistically significantly associated with sum PFAS in household samples ($p<0.05$). Vegetated land cover exhibited a weak but significant negative correlation (ρ = -0.110, p = 0.032), suggesting lower total sum PFAS when vegetation increased as a percentage of surrounding landuse concentrations in more vegetated areas. Vegetation may reduce PFAS transport to groundwater through enhanced evapotranspiration reducing infiltration of contaminated surface water and/or root systems stabilizing soil and reducing erosion of PFAS-contaminated soils. However, this correlation may simply indicate that more vegetated areas tend to be located farther from urban centers and their associated contamination sources, making vegetation a proxy for distance from human activity rather than a direct protective factor. Interestingly, forested landcover was not significantly associated with sum PFAS. Although barren land cover was also inversely associated with sum PFAS in household samples, it is worth noting the range of % barren was quite small (min = 0.0%, max = 2.6%). It may be that barren land represents land unlikely to receive PFAS inputs or that this is a statistical artifact due to the limited frequency across the dataset.

Urban land cover was strongly positively associated with total sum PFAS concentrations (rho = 0.13, p = 0.010). This finding agrees with previous examinations of relationships between surface water and PFAS incidence by Breitmeyer et al., (2023) and Rafiei & Nejadhashemi (2023) which linked urban land cover with higher PFAS concentrations in surface water. In this study, counties with the highest PFAS concentrations (Loudoun and Albemarle) exemplify this urban influence: Loudoun has an international airport and close proximity to the intense urbanization associated with Washington D.C, and Albemarle contains the city of Charlottesville and associated industrial activity. Urban areas have greater human activity which is expected to result in more PFAS usage from likely PFAS containing products accumulating in urban areas, runoff carrying more pollutants including PFAS, and a higher density of point sources where PFAS is used or moves through. Given previously reported linkages between PFAS concentrations in surface water and urban landuse, it would be expected that PFAS would also influence underlying groundwaters that supply private drinking water systems.

4.4.2 Relationships between point sources and PFAS

The distance from sampled households to the nearest first instance of a point source was tested for statistical significance by Spearman's rho correlation in Figure 4.14. Results suggest a statistically significant inverse relationship between distance to point sources and total sum PFAS concentrations i.e., decreasing distance between households and specific point sources is associated with an increase in total sum PFAS concentrations in submitted samples.

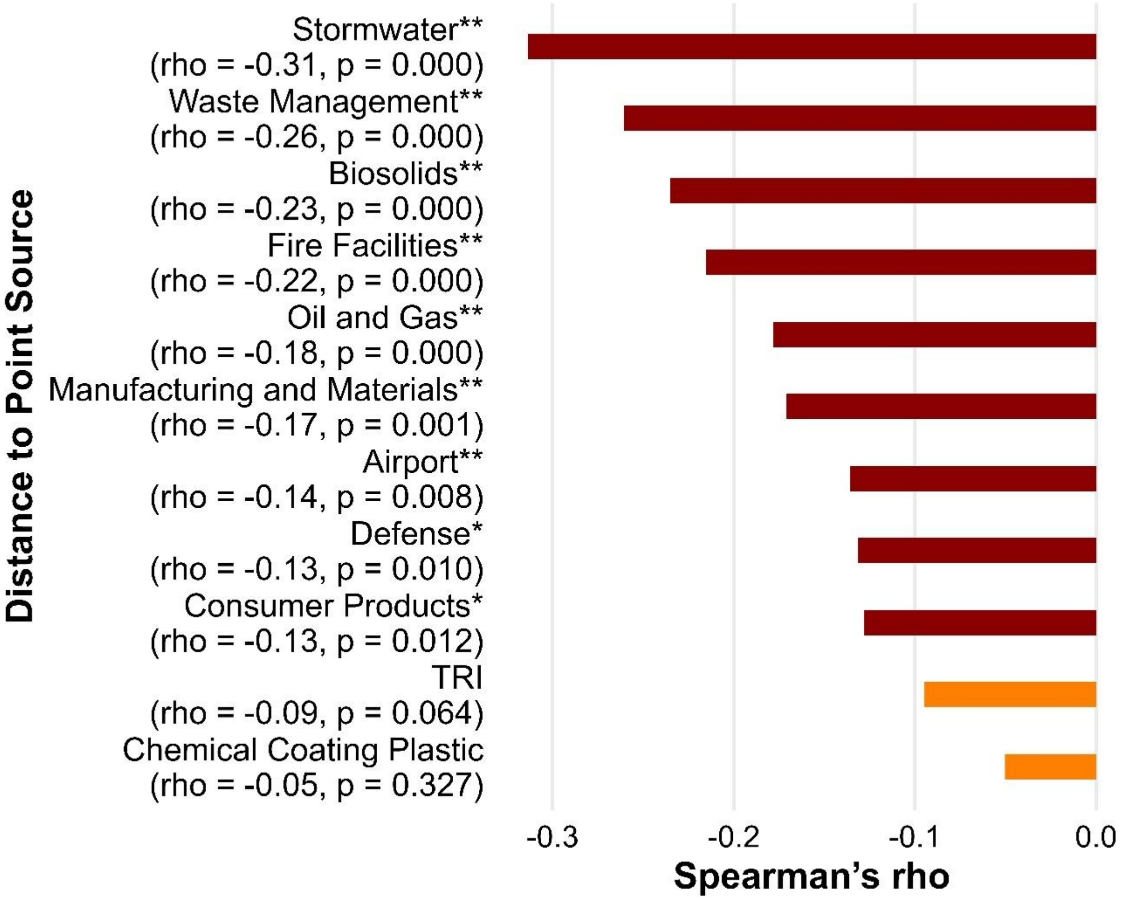


Figure 4.14: Spearman's Rho Correlation between distance to nearest type of point source and total sum PFAS. Statistically significant relationships are indicated by the marron color with * = p<0.05 and **= p<0.01.

The strongest relationships ($p<0.01$) were between total sum PFAS concentrations and distances to permitted stormwater outfalls, waste management facilities, permitted biosolid applied fields, fire facilities, oil and gas facilities, manufacturing and material industrial sites, and airports. These results agree with multiple studies (Breitmeyer et al., 2023; Hu et al., 2016; Rafiei & Nejadhashemi, 2023) which identified relationships between PFAS contamination and specific point sources such as airports, fire training facilities, and industrial sites. Notably, these results provided additional nuance to the previous lack of correlation between agricultural land cover and total sum PFAS concentrations (Figure 4.13).

A significant additional finding of the present study is the demonstration of a connections between distance to stormwater systems and sum PFAS observations. PFAS can be mobilized by stormwater and conveyed into both surface water and groundwater through local infrastructure (Chen et al., 2017; Codling et al., 2020; Kali et al., 2025).This is a particularly critical finding given the 32,000 stormwater outfalls permitted across the state (*Stormwater Permits Daily*, 2025.). Although stormwater outfalls are not point sources but rather represent transport pathways for potentially both point source and non-point source pollution from an aggregated area, they also potentially represent an opportunity to reduce PFAS dissemination into water sources. Initial reports do suggest that some best management practices and nature-based solutions can reduce PFAS concentrations in stormwater effluents (*Municipal Separate Storm Sewer System (MS4) Permit - Stormwater | Virginia DEQ*, 2025; Rieck et al., 2022).

To further examine the potential impact of permitted point sources, the number of permits within 5 km of a sampled household were compared for households yielding samples with sum PFAS concentrations <10.03 ppt (i.e. the bottom 90% of observations) vs those yielding samples with sum PFAS concentrations >10.03 ppt (i.e. the top 10% of observations) via a Wilcoxon test (Figure 4.15).

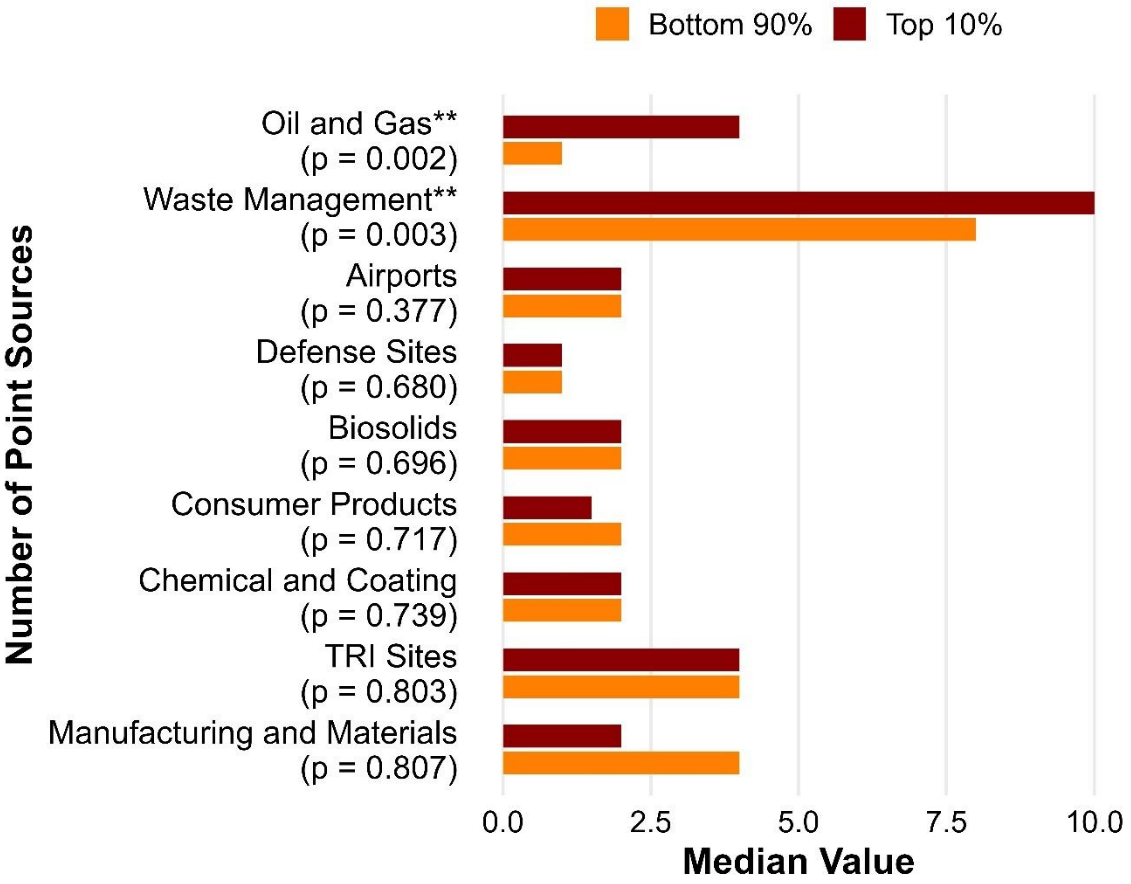


Figure 4.15: Wilcoxon test between number of point sources with 5 km and distribution between total sum PFAS concentrations bins of the bottom 90% and top 10% of households. Statistically significant relationships indicated by *=p<0.05 and **=p<0.01.

In interpreting these results it is important to note that not all point sources are necessarily active nor equal in magnitude. For example, Dulles international airport in Loudoun county has a significantly larger footprint and environmental impact than a small local airport in a rural area. No fire facilities were present within 5 km of any household and most point source types were statistically insignificant. However, the number of oil and gas facilities and waste management facilities within 5 km of a sampled site was statistically significant. An oil and gas facility can include places such as gas stations/storage facilities, petroleum wells, oil processing facilities, while waste management facilities can be places such as a disposal facilities, recycling plants, and sewer collection points. On average, among those homes submitting samples with <10.03 ppt total sum PFAS, there was one oil and gas facility and eight waste management facilities. In contrast, among homes that submitted samples with >10.03 ppt total sum PFAS, on average there were four oil and gas facilities and ten waste management facilities. The number of total point sources and permitted stormwater outfalls were analyzed the same way as those in Figure 4.15 but due to the significantly higher frequency of these categories they are in a separate Figure 4.16.

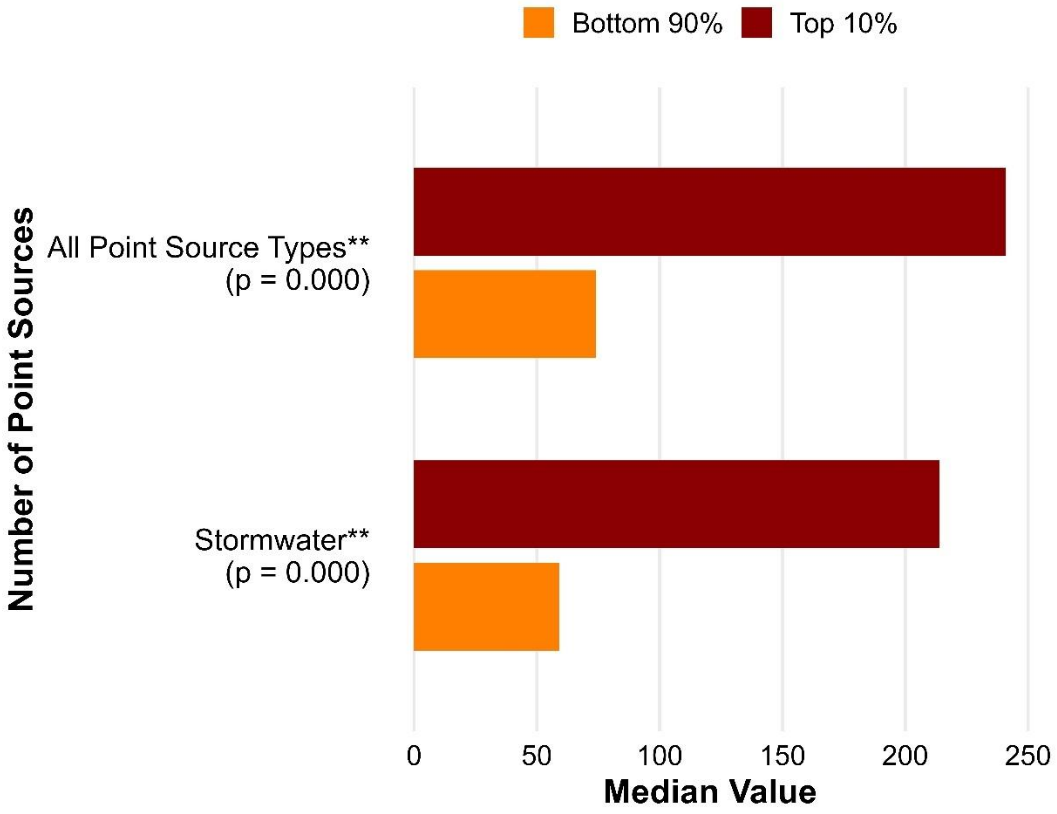


*Figure 4.16: Wilcoxon test between number of point sources with 5 km and distribution between total sum PFAS concentrations bins of the bottom 90% and top 10% of households, statistically significant relationships are indicated by * = p<0.05 and **= p<0.01.*

Both stormwater outfalls and all point source types (which is heavily influenced by stormwater due to sheer scale of permitted outfalls across the state) indicates a strong statistical significance. The median number of all point source types and stormwater outfalls in the bottom 90% of total sum PFAS concentrations was 74 and 59 respectively compared to the top 10% of household where it was 241 and 214 median number of all point sources or stormwater outfalls. This large difference and referring back to median household sample containing 7 unique PFAS compounds supports the idea that not one point source can determine exposure risk to PFAS as the increased complexity of mixtures in the top 10% (median=13 PFAS compounds) and significantly more point sources overall suggests multiple pathways of exposure rather than a single pathway. Generally, as human activity increases from more point sources and increased urbanized land cover there is a significant correlation to increased total sum PFAS risk. Importantly, prior studies (Breitmeyer et al., 2023; Hu et al., 2016; Rafiei & Nejadhashemi, 2023; Silver et al., 2023), have shown similar trends between increased human activity and PFAS presence in surface waters and drinking water.

4.4.3 Relationships between household characteristics and PFAS

The potential influence of household characteristics (e.g.… well age, well depth, pipe materials) were considered through comparison of homes submitting samples of sum total PFAS <10.03 ppt ("low PFAS," lowest 90% of observations) and homes submitting samples with total sum PFAS >10.03 ppt ("high PFAS", highest 10% of observations). Wells in low PFAS households were on average 210 feet deep (n=201) and 25 years old (n=242), while wells in high PFAS homes were on average 200 feet (n=21) and 37 years old (n=23). A spearman's rho correlation (Figure 4.17) indicated that while well age was significantly associated with total PFAS, well depth was not. This finding may suggest that older wells face elevated contamination risk, perhaps caused by deterioration in aging well casings, cracks, or corrosion which increases vulnerability to PFAS infiltration.

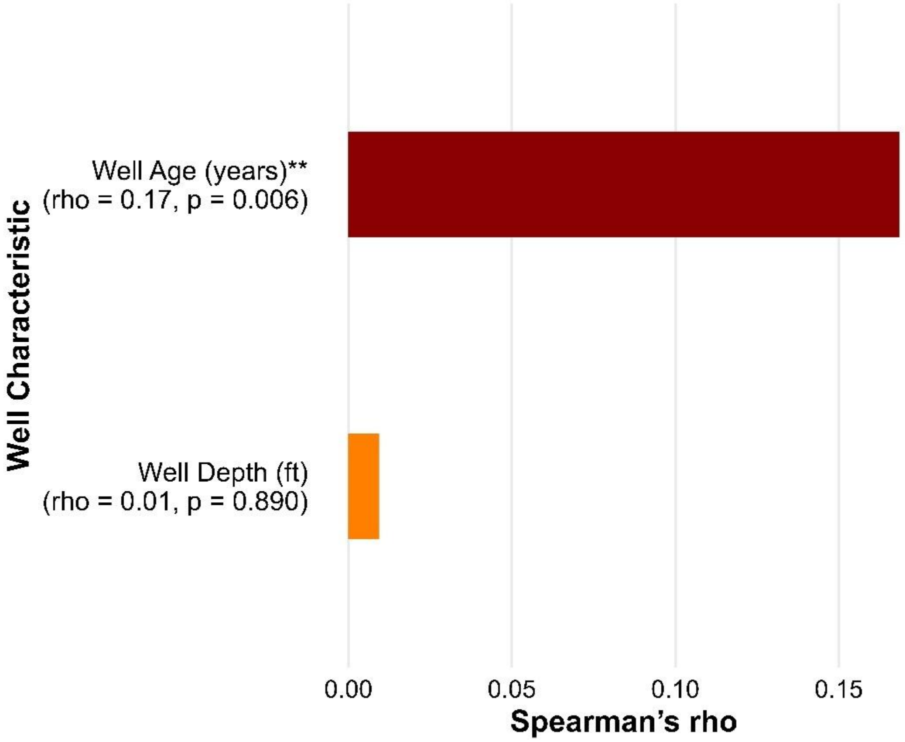


Figure 4.17: Spearman's Rho Correlation between well depth and age to total sum PFAS, Statistically significant relationships are indicated by the marron color with * = p<0.05 and **= p<0.01.

Previous work by Pieper et al. (2016) emphasizes that premise plumbing can serve as a source of household water contamination as lead in pipes corrodes. In this study, the two most common premise piping materials identified were copper (28.5%) and plastic (59.7%). No significant difference was observed in types of pipe between low and high PFAS homes (Figure 4.18). While some plastic pipes and fittings may contain PFAS compounds (e.g., Teflon), there was no demonstrable evidence that pipe material resulted in a change in PFAS concentration at the tap.

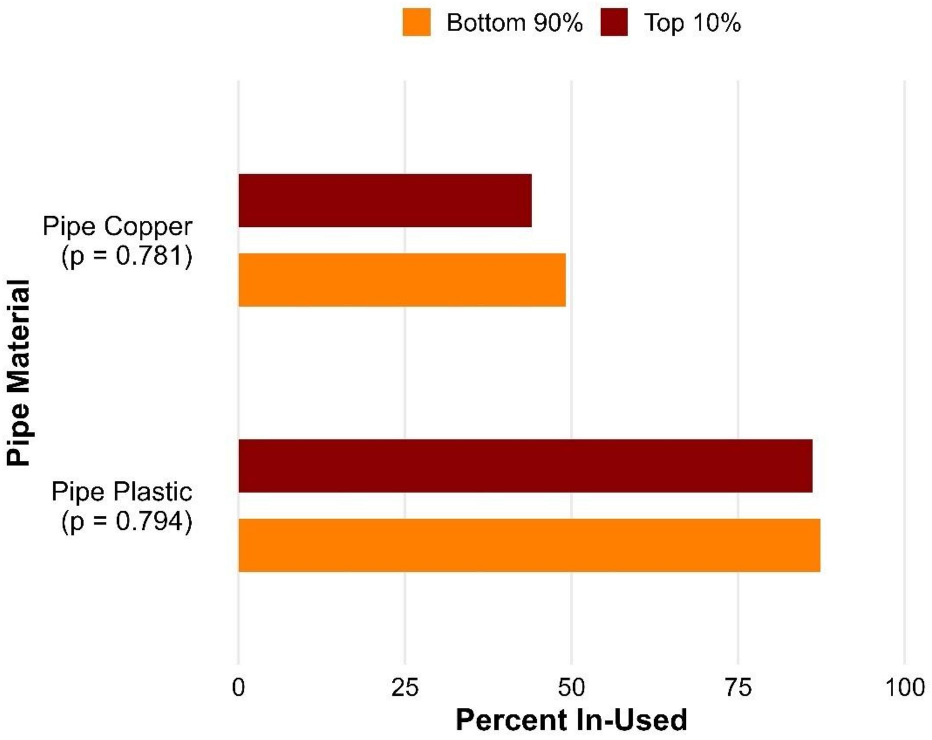


Figure 4.18: Chi Square test between pipe material presence (True or False) and bottom 90% to top 10% total sum PFAS concentrations, statistically significant relationships indicated by one asterisk ($p<0.05$) and two asterisks ($p<0.01$). Notably plastic pipes failed Chi-Square assumption ($n>5$ per bin) therefore Fisher's test was used

4.4.4 Relationships between household treatment and PFAS

As previously described, the majority of participating homes in this study did employ some treatment prior to point of use (70%), though this was most often a treatment process designed to remove contaminants of aesthetic concern, not PFAS (Figure 4.3). Although there is evidence that some at home treatments (e.g. reverse osmosis, activated carbon) removes some PFAS compounds (Herkert et al., 2020), there was difference in the presence of any treatment type between low and high PFAS homes (Table 4.8; Figure 4.19).

Table 4.8: Treatment patterns between the bottom 90% and top 10% total sum PFAS households

Treatment Group	Bottom 90% (n=349)	Top 10% (n=39)
Any Treatment	70.3%	69.2%

Aesthetic Treatment (AS)	67.1%	64.1%
Sediment filters	41.4%	41.0%
Acid neutralizers	10.5%	12.8%
Water softeners	35.6%	25.6%
Iron removal	9.9%	5.1%
Health Based Treatment (HB)	22.7%	30.8%
Carbon filters	8.5%	10.3%
Reverse osmosis	4.1%	7.7%
Ultraviolet systems	11.7%	20.5%
Chlorinators	2.3%	2.6%

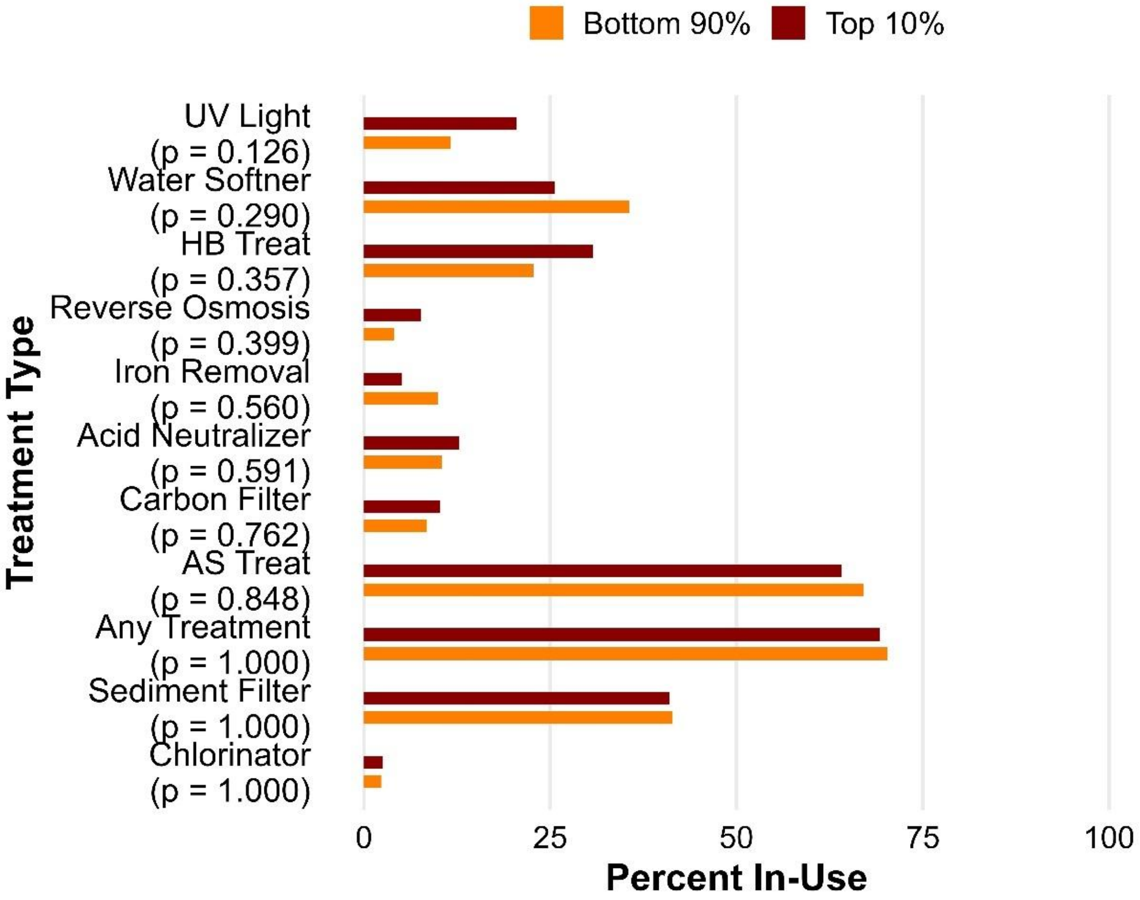


Figure 4.19: Chi Square test between treatment type presence (True or False) and bottom 90% to top 10% total sum PFAS concentrations. Statistically significant relationships indicated by

*=p<0.05) and **p<0.01. Notably some treatment types failed Chi-Square assumption (n>5 per bin) therefore Fisher's test was used

As previously stated, the majority of treatment systems fell into the aesthetic treatment category and included sediment filters, water softeners, iron removal systems, and acid neutralizers. These technologies are designed to address taste, odor, staining, and scale formation water quality issues that are immediately perceptible to homeowners but have limited or no efficacy for removing PFAS compounds. Health-based treatment systems focused on microbial inactivation (e.g., UV and chlorinators), would be expected to have limited to no impact on PFAS chemicals. which might be expected to provide better PFAS removal but were considerably less common. While activated carbon filtration and reverse osmosis are known to be effective for PFAS removal when properly designed, maintained, and operated (Herkert et al., 2020), the low adoption rates, particularly for reverse osmosis which provides the most comprehensive removal, suggests that few households are currently protected by treatment technologies capable of addressing PFAS contamination. However, efficacy of treatment does dwindle as PFAS chain lengths shorten and if the supplied water itself is particularly high in short chain PFAS, even properly working treatment methods may fail. Testing at the point of extraction rather than point-of-use would help identify whether PFAS concentrations are already high in the supplied water or increased as they go through in-home plumbing networks.

4.4.5 Water Quality Relationships to PFAS

A Spearman's rho correlation, Wilcoxon test, and Chi-Square test were used to determine statistically significant relationships between other water quality parameters and total sum PFAS concentrations (detailed statistical output available in Appendix D; Tables D4, D5, D6) Comparisons between high and low PFAS homes are provided in Table 4.9. The correlation analysis revealed a statistically significant positive relationship between lead concentrations and total sum PFAS (Figure 4.20). Among the other water quality parameters examined, lead, pH, and TDS/conductivity concentrations were significantly different between the bottom 90% and top 10% PFAS groups (Figure 4.21). Lastly, Chi-Square test for the presence or absence of fecal indicator bacteria in the bottom 90% and top 10% PFAS groups showed no statistically significant relationships (Figure 4.22).

Table 4.9: Traditional water quality parameter medians grouped by bottom 90% and top 10% total sum PFAS concentrations

Median Water Quality Parameter	**Bottom 90% (n=343)**	**Top 10% (n=39)**
pH	7.2	6.8
Conductivity (μs/cm)	344	454
TDS (mg/L)	177	264
Coliform Presence	34%	38%
E. coli Presence	4.1%	5.1%
Iron (mg/L)	0.008	0.006
Manganese (mg/L)	0.002	0.002
Lead (mg/L)	0.001	0.002

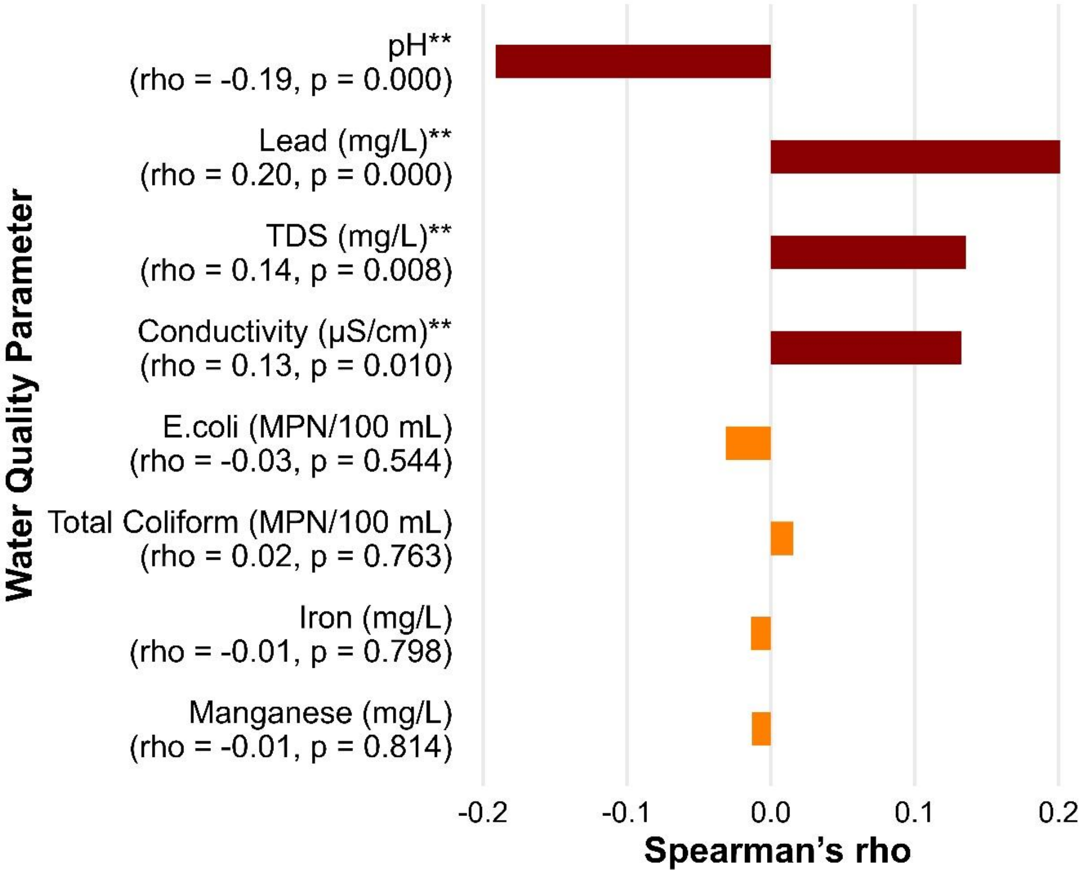


Figure 4.20: Spearman's Rho Correlation between traditional water quality markers and to total sum PFAS, statistically significant relationships indicated by marron bar and one asterisk ($p<0.05$) and two asterisks ($p<0.01$)

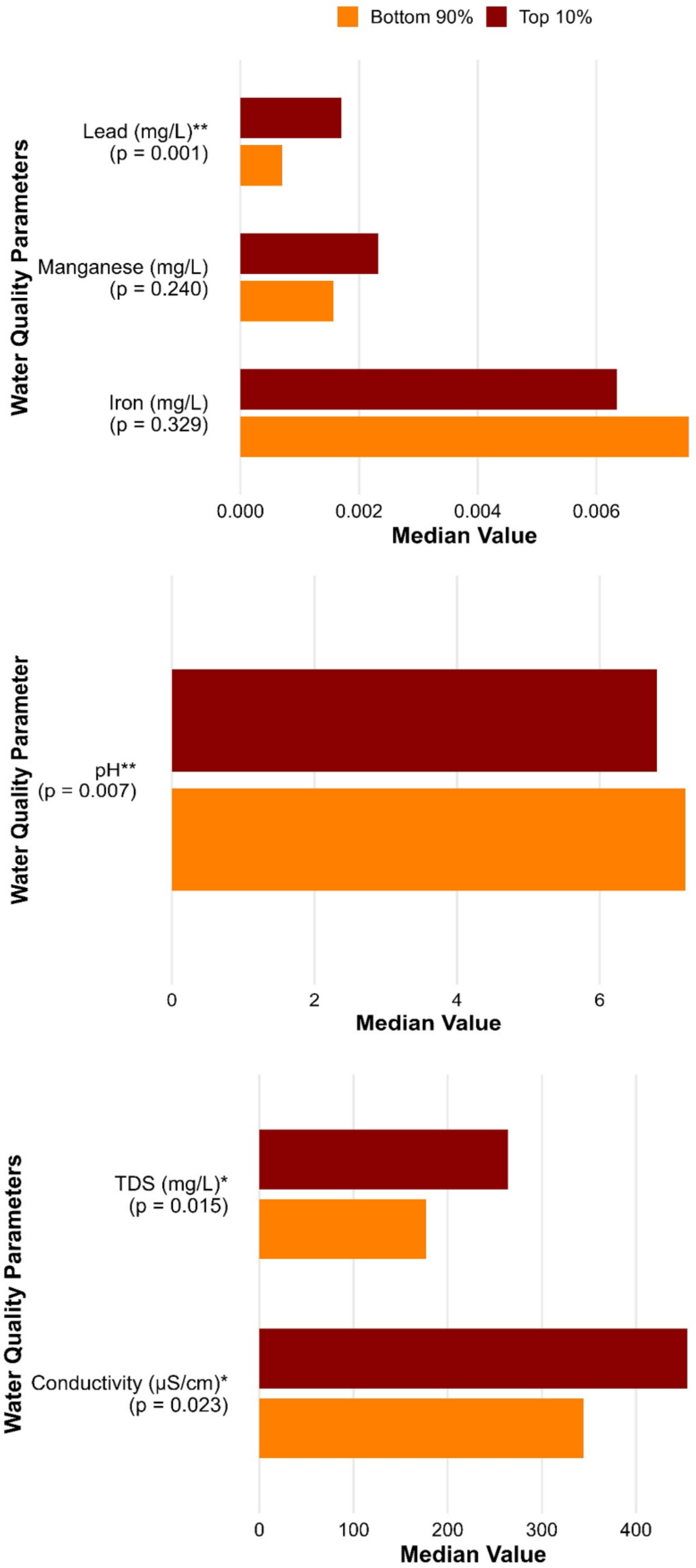


Figure 4.21: Wilcoxon test water quality parameters and distribution between total sum PFAS concentrations bins of the bottom 90% and top 10% of households, statistically significant

relationships indicated by one asterisk (p<0.05) and two asterisks (p<0.01). Top figure are first draw metals, middle figure is pH, and bottom figure is TDS/Conductivity

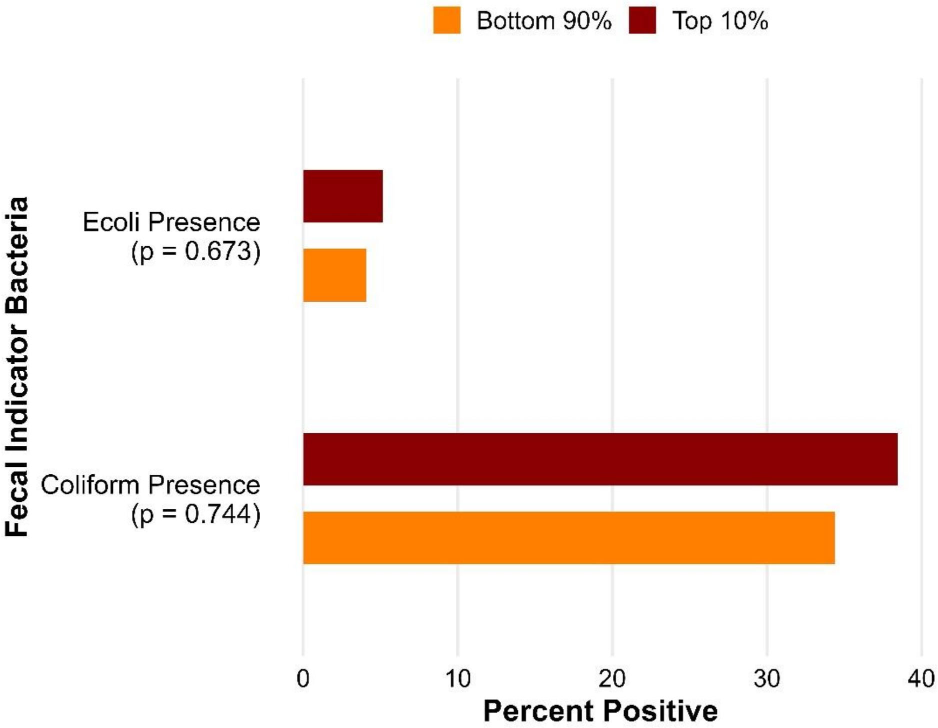


Figure 4.22: Chi-Square test of fecal indicator bacteria presence and total sum PFAS concentrations bins of the bottom 90% and top 10% of households, statistically significant relationships indicated by one asterisk (p<0.05) and two asterisks (p<0.01)

The statistically significant positive correlation between lead concentrations and total sum PFAS is intriguing. Samples from high PFAS households yielded a median lead concentration of 0.0017 mg/L, which is 2.4 times higher than the median of 0.0007 mg/L in low PFAS samples. Both lead and PFAS are anthropogenic in origin and neither derives from geological sources (lead can be geogenic but is atypical); however, a shared source for this co-occurrence is unclear. Lead was a common additive to gasoline in the past, and the presence and distance to oil and gas facilities was also related to PFAS occurrence in this study (Figures 4.14 and 4.15).

The apparent correlation between PFAS and lead may also be related to similar mobilizing chemical conditions. Lower pH values and higher TDS/conductivity were observed in high PFAS samples. High conductivity/TDS may reflect groundwater contamination and/or influences of home water softeners. These conditions could be mobilizing both lead and PFAS from the well, pipes, or other household components as the water moves through the plumbing network into the home due to corrosion from acidic conditions.

The presence of total coliform and *E. coli* did not appear significantly related with PFAS. Previous work has suggested septic systems may be sources of PFAS to local wells, however, if this is the case, then transport and/or degradation rates between bacteria and PFAS must be quite different.

5. Conclusion

The participating homes in this study largely relied on private drilled wells for drinking water and septic systems for disposal and treatment of wastewater. While 70% of homes had some form of drinking water treatment, the majority of homes used aesthetic-based (66.8%) rather than health-based (23.6%) treatment, leaving many households vulnerable to common contaminants. Given the high presence of fecal indicator bacteria (coliform bacteria=35%), increasing the use of health-based treatment is critical to protect households from waterborne illness; some health-based treatments reverse osmosis) will also reduce inorganic contaminants including metals and PFAS.

Of the 382 samples analyzed in this study, 100% contained at least one detectable PFAS compound and 90% of samples had quantifiable PFAS compounds. These are substantially higher detection rates than reported in previous surveys of PFAS in private drinking water. For example, Smalling et al., (2023) detected PFAS in 20% of private wells in a national sampling effort (n=269); McMahon et al. (2022) recovered PFAS from 20% of private well samples (n=50) collected in the eastern United States; and Silver et al. (2023) found reported a 71% detection rate in private well samples collected in Wisconsin (n=450).Variation across studies is expected as differing analysis standards and regulatory guidelines which have changed repeatedly over the past 5 years as well as differing geologies and system characteristics unique to each study. These differences could be attributed to Smalling et al., (2023) only analyzed six wells in Virginia, McMahon et al., (2022) examined point of extraction rather than point of use, and Silver et al., (2023) sampled significantly shallower wells (less than 40 feet) than this study. Despite the elevated detection rate in this study, it should be emphasized that the median total sum PFAS concentrations in this study was quite low (1.50 ppt). Total sum concentrations of short-chain PFAS compounds were generally higher (median=1.12 ppt) than long-chain (legacy) PFAS compounds (median=0.267 ppt), potentially reflecting either degradation of legacy compounds or the shifts in contemporary usage of more short chain compounds. Only 2.4% of samples exceeded the 4 ppt MCL for PFOA and only 5.2% exceeded the 4 ppt MCL for PFOS, which will apply to public drinking water systems in 2031.

This work identified statistically significant correlations between elevated total PFAS concentrations and multiple geospatial and water quality parameters. Increases in total sum PFAS were associated with elevated lead and total dissolved solids (TDS)/conductivity; decreased pH; increased urban land cover; decreased distances to point sources, and a greater number of point sources within 5 km. High PFAS samples (i.e. samples in the top 10% of total sum PFAS concentrations observed) were statistically more likely to contain higher concentrations of lead and TDS/conductivity and lower pH. High PFAS sampled homes had higher rates of urban land cover and number of point sources within a 5 km radius. These findings support previous work (Breitmeyer et al., 2023; Rafiei & Nejadhashemi, 2023; Silver et al., 2023; Smalling et al., 2023), demonstrating significant relationships between urbanization and point sources and elevated PFAS concentrations in surface water. However, unlike those studies no statistically significant relationships between number of airports or military defense sites and PFAS were observed in this study.

Traditional water quality markers including bacteria and lead remain a significant concern in private drinking supplies. While this study found slightly lower rates violations compared to past Cooperative Extension based efforts (Allevi et al., 2013; Lytle et al., 2025; Pieper et al., 2015) they are concerning given that all participants were repeat testers. Given well established health effects associated with these contaminants, as well as more readily available treatment options, continued focus on awareness and prevention of these exposures is recommended. Overall, this study highlights the broader challenges inherent in supporting private well stewardship, particularly in the context of emerging contaminants like PFAS where awareness, treatment options, and regulatory frameworks remain less developed than for traditional water quality parameters where concerns remain.

6. Future Work

This project focuses on the incidence of PFAS at the point of use in private drinking water; however, this does not necessarily provide information on the water quality in actual groundwater aquifers. Sampling groundwater directly from the point of extraction across all the major aquifers in Virginia is necessary to inform the public, regulators, and scientists whether PFAS are prevalent within groundwater or originating from the house or surface. Effective design of interventions to reduce exposure requires identification of specific sources. These data may also be useful to local municipal drinking water plants dependent on groundwater.

While point-of-use sampling from unsupervised participants could introduce some uncertainty to results, the method employed here was found to introduce no previous bias in a preliminary study (Hohweiler et al., 2024). Careful planning of instructions and guidelines helped ensure proper sample collection from participants, however homeowner generated statistics (i.e., well age) are less reliable. Collecting construction documentation that can back up system characteristics and retesting of homes with exceptionally high concentrations would ensure accuracy and consistency of the dataset, document temporal changes in PFAS concentrations at the tap, and validate the relationship between PFAS concentrations and systems characteristics.

Further testing of counties located near Washington DC in Northern Virginia, central Virginia around Richmond, and Southeastern Virginia around Norfolk is necessary to further validate or disprove that proximity to urban areas is the primary driver of PFAS incidence in private drinking water. Ideally this would be matched with more precise information on point sources, including specific identities and quantities of loads released, so that a relationship between a point source and drinking water PFAS could be identified based on unique compounds found in both.

Given previous speculation that atmospheric deposition may be a significant contributor to PFAS detection in private wells (Siegel et al 2023), rainwater should be collected across the state to determine the significance deposition could play in PFAS exposure. Data describing patterns of PFAS concentrations in rainwater could inform a relationship between point sources and PFAS incidence in drinking water. This may explain why PFAS is detectable across Virginia regardless of location; human activity in urban areas may directly impact rural communities.

While PFAS is a significant health concern in high exposure settings, the impacts of chronic low dose exposure remain uncertain. It is worth noting that exceedances of existing lead and bacteria regulations were more common here than exceedances of PFAS regulations. Future examinations of private well water quality examining emerging contaminants are encouraged to include measures of these known contaminants of human health concern.

7. References

Ahrens, L., & Bundschuh, M. (2014). Fate and effects of poly- and perfluoroalkyl substances in the aquatic environment: A review. *Environmental Toxicology and Chemistry*, *33*(9), 1921–1929. https://doi.org/10.1002/etc.2663

Allevi, G., Strina, C., Andreis, D., Zanoni, V., Bazzola, L., Bonardi, S., Foroni, C., Milani, M., Cappelletti, M. R., Gussago, F., Aguggini, S., Giardini, R., Martinotti, M., Fox, S. B., Harris, A. L., Bottini, A., Berruti, A., & Generali, D. (2013). Increased pathological complete response rate after a long-term neoadjuvant letrozole treatment in postmenopausal oestrogen and/or progesterone receptor-positive breast cancer. *British Journal of Cancer*, *108*(8), 1587–1592. https://doi.org/10.1038/bjc.2013.151

Andrews, D. Q., & Naidenko, O. V. (2020). Population-Wide Exposure to Per- and Polyfluoroalkyl Substances from Drinking Water in the United States. *Environmental Science & Technology Letters*, *7*(12), 931–936. https://doi.org/10.1021/acs.estlett.0c00713

Appleman, T. D., Higgins, C. P., Quiñones, O., Vanderford, B. J., Kolstad, C., Zeigler-Holady, J. C., & Dickenson, E. R. V. (2014). Treatment of poly- and perfluoroalkyl substances in U.S. full-scale water treatment systems. *Water Research*, *51*, 246–255. https://doi.org/10.1016/j.watres.2013.10.067

Ayotte, J. D., Medalie, L., Qi, S. L., Backer, L. C., & Nolan, B. T. (2017). Estimating the High-Arsenic Domestic-Well Population in the Conterminous United States. *Environmental Science & Technology*, *51*(21), 12443–12454. https://doi.org/10.1021/acs.est.7b02881

Barry, V., Winquist, A., & Steenland, K. (2013). Perfluorooctanoic Acid (PFOA) Exposures and Incident Cancers among Adults Living Near a Chemical Plant. *Environmental Health Perspectives*, *121*(11–12), 1313–1318. https://doi.org/10.1289/ehp.1306615

Bassler, J., Ducatman, A., Elliott, M., Wen, S., Wahlang, B., Barnett, J., & Cave, M. C. (2019). Environmental perfluoroalkyl acid exposures are associated with liver disease characterized by apoptosis and altered serum adipocytokines. *Environmental Pollution*, *247*, 1055–1063. https://doi.org/10.1016/j.envpol.2019.01.064

Bell, E. M., De Guise, S., McCutcheon, J. R., Lei, Y., Levin, M., Li, B., Rusling, J. F., Lawrence, D. A., Cavallari, J. M., O’Connell, C., Javidi, B., Wang, X., & Ryu, H. (2021). Exposure, health effects, sensing, and remediation of the emerging PFAS contaminants – Scientific challenges and potential research directions. *Science of The Total Environment*, *780*, 146399. https://doi.org/10.1016/j.scitotenv.2021.146399

Benham, B., Ling, E., Ziegler, P., & Krometis, L. A. (2016). What’s in Your Water? Development and Evaluation of the Virginia Household Water Quality Program and Virginia Master Well Owner Network. *Journal of Human Sciences and Extension*. https://doi.org/10.54718/ATYW3374

Berger, U., Glynn, A., Holmström, K. E., Berglund, M., Ankarberg, E. H., & Törnkvist, A. (2009). Fish consumption as a source of human exposure to perfluorinated alkyl substances in Sweden—Analysis of edible fish from Lake Vättern and the Baltic Sea. *Chemosphere*, *76*(6), 799–804. https://doi.org/10.1016/j.chemosphere.2009.04.044

Bradley, P. M., LeBlanc, D. R., Romanok, K. M., Smalling, K. L., Focazio, M. J., Cardon, M. C., Clark, J. M., Conley, J. M., Evans, N., Givens, C. E., Gray, J. L., Earl Gray, L., Hartig, P. C., Higgins, C. P., Hladik, M. L., Iwanowicz, L. R., Loftin, K. A., Blaine McCleskey, R., McDonough, C. A., … Wilson, V. S. (2021). Public and private tapwater: Comparative analysis of contaminant exposure and potential risk, Cape Cod, Massachusetts, USA. *Environment International*, *152*, 106487. https://doi.org/10.1016/j.envint.2021.106487

Breitmeyer, S. E., Williams, A. M., Duris, J. W., Eicholtz, L. W., Shull, D. R., Wertz, T. A., & Woodward, E. E. (2023). Per- and polyfluorinated alkyl substances (PFAS) in Pennsylvania surface waters: A statewide assessment, associated sources, and land-use relations. *Science of The Total Environment*, *888*, 164161. https://doi.org/10.1016/j.scitotenv.2023.164161

Butt, C. M., Muir, D. C. G., & Mabury, S. A. (2014). Biotransformation pathways of fluorotelomer-based polyfluoroalkyl substances: A review. *Environmental Toxicology and Chemistry*, *33*(2), 243–267. https://doi.org/10.1002/etc.2407

Census Bureau Search. (n.d.). Retrieved July 1, 2025, from https://data.census.gov/all?g=040XX00US51

Chen, H., Reinhard, M., Nguyen, T. V., You, L., He, Y., & Gin, K. Y.-H. (2017). Characterization of occurrence, sources and sinks of perfluoroalkyl and polyfluoroalkyl substances (PFASs) in a tropical urban catchment. *Environmental Pollution*, *227*, 397–405. https://doi.org/10.1016/j.envpol.2017.04.091

Codling, G., Yuan, H., Jones, P. D., Giesy, J. P., & Hecker, M. (2020). Metals and PFAS in stormwater and surface runoff in a semi-arid Canadian city subject to large variations in temperature among seasons. *Environmental Science and Pollution Research*, *27*(15), 18232–18241. https://doi.org/10.1007/s11356-020-08070-2

Desktop GIS Software | Mapping Analytics | ArcGIS Pro. (n.d.). Retrieved July 1, 2025, from https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview

Dieter, C. A., Maupin, M. A., Caldwell, R. R., Harris, M. A., Ivahnenko, T. I., Lovelace, J. K., Barber, N. L., & Linsey, K. S. (2018). Estimated use of water in the United States in 2015. In *Circular* (1441). U.S. Geological Survey. https://doi.org/10.3133/cir1441

EPA's PFAS Strategic Roadmap: Second Annual Progress Report. (2023). *December, 2023*, 14.

Gomis, M. I., Vestergren, R., Borg, D., & Cousins, I. T. (2018). Comparing the toxic potency in vivo of long-chain perfluoroalkyl acids and fluorinated alternatives. *Environment International*, *113*, 1–9. https://doi.org/10.1016/j.envint.2018.01.011

Grandjean, P., Andersen, E. W., Budtz-Jørgensen, E., Nielsen, F., Mølbak, K., Weihe, P., & Heilmann, C. (2012). Serum Vaccine Antibody Concentrations in Children Exposed to Perfluorinated Compounds. *JAMA*, *307*(4), 391–397. https://doi.org/10.1001/jama.2011.2034

Gyimah, R., Lebu, S., Owusu-Frimpong, I., Semiyaga, S., Salzberg, A., & Manga, M. (2024). Effluents from septic systems and impact on groundwater contamination: A systematic review. *Environmental Science and Pollution Research*, *31*(54), 62655–62675. https://doi.org/10.1007/s11356-024-35385-1

Hayes, W., Jones, C. N., Osman, K. K., Eaves, L. A., Mize, W., Fowlkes, J., Fry, R. C., & Pieper, K. J. (2025). Exploring Demographic Disparities in Private Well Water Testing in North Carolina. *Environmental Science & Technology*, *59*(2), 1232–1242. https://doi.org/10.1021/acs.est.4c05437

Herkert, N. J., Merrill, J., Peters, C., Bollinger, D., Zhang, S., Hoffman, K., Ferguson, P. L., Knappe, D. R. U., & Stapleton, H. M. (2020). Assessing the Effectiveness of Point-of-Use Residential Drinking

Water Filters for Perfluoroalkyl Substances (PFASs). *Environmental Science & Technology Letters*, *7*(3), 178–184. https://doi.org/10.1021/acs.estlett.0c00004

Hernandez, A., & Pierce, G. (2023). The geography and socioeconomic characteristics of U.S. households reliant on private wells and septic systems. *JAWRA Journal of the American Water Resources Association*, *59*(6), 1397–1412. https://doi.org/10.1111/1752-1688.13135

Hohweiler, K., Krometis, L.-A., Ling, E. J., & Xia, K. (2024). Incidence of per- and polyfluoroalkyl substances (PFAS) in private drinking water supplies in Southwest Virginia, USA. *Science of The Total Environment*, *929*, 172539. https://doi.org/10.1016/j.scitotenv.2024.172539

Hu, X. C., Andrews, D. Q., Lindstrom, A. B., Bruton, T. A., Schaider, L. A., Grandjean, P., Lohmann, R., Carignan, C. C., Blum, A., Balan, S. A., Higgins, C. P., & Sunderland, E. M. (2016). Detection of Poly- and Perfluoroalkyl Substances (PFASs) in U.S. Drinking Water Linked to Industrial Sites, Military Fire Training Areas, and Wastewater Treatment Plants. *Environmental Science & Technology Letters*, *3*(10), 344–350. https://doi.org/10.1021/acs.estlett.6b00260

Jernbro, S., Rocha, P. S., Keiter, S., Skutlarek, D., Färber, H., Jones, P. D., Giesy, J. P., Hollert, H., & Engwall, M. (2007). Perfluorooctane sulfonate increases the genotoxicity of cyclophosphamide in the micronucleus assay with V79 cells. Further proof of alterations in cell membrane properties caused by PFOS. *Environmental Science and Pollution Research International*, *14*(2), 85–87. https://doi.org/10.1065/espr2007.01.384

Kali, S. E., Österlund, H., Viklander, M., & Blecken, G.-T. (2025). Stormwater discharges affect PFAS occurrence, concentrations, and spatial distribution in water and bottom sediment of urban streams. *Water Research*, *271*, 122973. https://doi.org/10.1016/j.watres.2024.122973

Kelly, B. C., Ikonomou, M. G., Blair, J. D., Surridge, B., Hoover, D., Grace, R., & Gobas, F. A. P. C. (2009). Perfluoroalkyl contaminants in an Arctic marine food web: Trophic magnification and wildlife exposure. *Environmental Science & Technology*, *43*(11), 4037–4043. https://doi.org/10.1021/es9003894

Latała, A., Nędzi, M., & Stepnowski, P. (2009). Acute toxicity assessment of perfluorinated carboxylic acids towards the Baltic microalgae. *Environmental Toxicology and Pharmacology*, *28*(2), 167–171. https://doi.org/10.1016/j.etap.2009.03.010

Law, R. K., Murphy, M. W., & Choudhary, E. (2017). Private well groundwater quality in West Virginia, USA–2010. *The Science of the Total Environment*, *586*, 559–565. https://doi.org/10.1016/j.scitotenv.2017.02.018

Lee, D., & Murphy, H. M. (2020). Private Wells and Rural Health: Groundwater Contaminants of Emerging Concern. *Current Environmental Health Reports*, *7*(2), 129–139. https://doi.org/10.1007/s40572-020-00267-4

Lee, Y. J., Jung, H. W., Kim, H. Y., Choi, Y.-J., & Lee, Y. A. (2021). Early-Life Exposure to Per- and Poly-Fluorinated Alkyl Substances and Growth, Adiposity, and Puberty in Children: A Systematic Review. *Frontiers in Endocrinology*, *12*, 683297. https://doi.org/10.3389/fendo.2021.683297

Liddie, J. M., Schaider, L. A., & Sunderland, E. M. (2023). Sociodemographic Factors Are Associated with the Abundance of PFAS Sources and Detection in U.S. Community Water Systems. *Environmental Science & Technology*, *57*(21), 7902–7912. https://doi.org/10.1021/acs.est.2c07255

Liu, C., Deng, J., Yu, L., Ramesh, M., & Zhou, B. (2010). Endocrine disruption and reproductive impairment in zebrafish by exposure to 8:2 fluorotelomer alcohol. *Aquatic Toxicology (Amsterdam, Netherlands)*, *96*(1), 70–76. https://doi.org/10.1016/j.aquatox.2009.09.012

Liu, G., Dhana, K., Furtado, J. D., Rood, J., Zong, G., Liang, L., Qi, L., Bray, G. A., DeJonge, L., Coull, B., Grandjean, P., & Sun, Q. (2018). Perfluoroalkyl substances and changes in body weight and resting metabolic rate in response to weight-loss diets: A prospective study. *PLOS Medicine*, *15*(2), e1002502. https://doi.org/10.1371/journal.pmed.1002502

Lytle, J. A., Krometis, L.-A., & Ling, E. (2025). Linking access to private drinking water system treatment, demographics, and water quality in southwest Virginia. *Journal of Water and Health*, *23*(10), 1215–1223. https://doi.org/10.2166/wh.2025.051

McMahon, P. B., Tokranov, A. K., Bexfield, L. M., Lindsey, B. D., Johnson, T. D., Lombard, M. A., & Watson, E. (2022). Perfluoroalkyl and Polyfluoroalkyl Substances in Groundwater Used as a Source of Drinking Water in the Eastern United States. *Environmental Science & Technology*, *56*(4), 2279–2288. https://doi.org/10.1021/acs.est.1c04795

Municipal Separate Storm Sewer System (MS4) Permit—Stormwater | Virginia DEQ. (n.d.). Retrieved November 14, 2025, from https://www.deq.virginia.gov/news-info/shortcuts/permits/water/ms4

Murray, A., Hall, A., Weaver, J., & Kremer, F. (2021). Methods for Estimating Locations of Housing Units Served by Private Domestic Wells in the United States Applied to 2010. *JAWRA Journal of the American Water Resources Association*, *57*(5), 828–843. https://doi.org/10.1111/1752-1688.12937

National Land Cover Database | U.S. Geological Survey. (n.d.). Retrieved July 1, 2025, from https://www.usgs.gov/centers/eros/science/national-land-cover-database

Pieper, K. J., Krometis, L.-A., Gallagher, D., Benham, B., & Edwards, M. (2015a). Profiling Private Water Systems to Identify Patterns of Waterborne Lead Exposure. *Environmental Science & Technology*, *49*(21), 12697–12704. https://doi.org/10.1021/acs.est.5b03174

Pieper, K. J., Krometis, L.-A. H., Benham, B. L., & Gallagher, D. L. (2016). Simultaneous Influence of Geology and System Design on Drinking Water Quality in Private Systems. *Journal of Environmental Health*, *79*(2), E1–E9.

Pieper, K. J., Krometis, L.-A. H., Gallagher, D. L., Benham, B. L., & Edwards, M. (2015b). Incidence of waterborne lead in private drinking water systems in Virginia. *Journal of Water and Health*, *13*(3), 897–908. https://doi.org/10.2166/wh.2015.275

Post, G. B., Louis, J. B., Cooper, K. R., Boros-Russo, B. J., & Lippincott, R. L. (2009). Occurrence and potential significance of perfluorooctanoic acid (PFOA) detected in New Jersey public drinking water systems. *Environmental Science & Technology*, *43*(12), 4547–4554. https://doi.org/10.1021/es900301s

Rafiei, V., & Nejadhashemi, A. P. (2023). Watershed scale PFAS fate and transport model for source identification and management implications. *Water Research*, *240*, 120073. https://doi.org/10.1016/j.watres.2023.120073

Reynolds, K. A., Mena, K. D., & Gerba, C. P. (2008). Risk of Waterborne Illness Via Drinking Water in the United States. In D. M. Whitacre (Ed.), *Reviews of Environmental Contamination and Toxicology* (pp. 117–158). Springer. https://doi.org/10.1007/978-0-387-71724-1_4

Rieck, L., Carson, C., Hawley, R. J., Heller, M., Paul, M., Scoggins, M., Zimmerman, M., & Smith, R. F. (2022). Phase II MS4 challenges: Moving toward effective stormwater management for small municipalities. *Urban Ecosystems*, *25*(3), 657–672. https://doi.org/10.1007/s11252-021-01179-3

Sanderson, H., Boudreau, T. M., Mabury, S. A., & Solomon, K. R. (2004). Effects of perfluorooctane sulfonate and perfluorooctanoic acid on the zooplanktonic community. *Ecotoxicology and Environmental Safety*, *58*(1), 68–76. https://doi.org/10.1016/j.ecoenv.2003.09.012

Sepulvado, J. G., Blaine, A. C., Hundal, L. S., & Higgins, C. P. (2011). Occurrence and Fate of Perfluorochemicals in Soil Following the Land Application of Municipal Biosolids. *Environmental Science & Technology*, *45*(19), 8106–8112. https://doi.org/10.1021/es103903d

Seyam, M. M. H., Haque, M. R., & Rahman, M. M. (2023). Identifying the land use land cover (LULC) changes using remote sensing and GIS approach: A case study at Bhaluka in Mymensingh, Bangladesh. *Case Studies in Chemical and Environmental Engineering*, *7*, 100293. https://doi.org/10.1016/j.cscee.2022.100293

Shearer, J. J., Callahan, C. L., Calafat, A. M., Huang, W.-Y., Jones, R. R., Sabbisetti, V. S., Freedman, N. D., Sampson, J. N., Silverman, D. T., Purdue, M. P., & Hofmann, J. N. (2020). Serum Concentrations of Per- and Polyfluoroalkyl Substances and Risk of Renal Cell Carcinoma. *JNCI Journal of the National Cancer Institute*, *113*(5), 580–587. https://doi.org/10.1093/jnci/djaa143

Shi, Y., Wang, J., Pan, Y., & Cai, Y. (2012). Tissue distribution of perfluorinated compounds in farmed freshwater fish and human exposure by consumption. *Environmental Toxicology and Chemistry*, *31*(4), 717–723. https://doi.org/10.1002/etc.1758

Shoeib, M., Harner, T., & Vlahos, P. (2006). Perfluorinated chemicals in the arctic atmosphere. *Environmental Science & Technology*, *40*(24), 7577–7583. https://doi.org/10.1021/es0618999

Siegel, H. G., Nason, S. L., Warren, J. L., Prunas, O., Deziel, N. C., & Saiers, J. E. (2023). Investigation of Sources of Fluorinated Compounds in Private Water Supplies in an Oil and Gas-Producing Region of Northern West Virginia. *Environmental Science & Technology*, *57*(45), 17452–17464. https://doi.org/10.1021/acs.est.3c05192

Silver, M., Phelps, W., Masarik, K., Burke, K., Zhang, C., Schwartz, A., Wang, M., Nitka, A. L., Schutz, J., Trainor, T., Washington, J. W., & Rheineck, B. D. (2023). Prevalence and Source Tracing of PFAS in Shallow Groundwater Used for Drinking Water in Wisconsin, USA. *Environmental Science & Technology*, *57*(45), 17415–17426. https://doi.org/10.1021/acs.est.3c02826

Simones, T. L., Evans, C., Goossen, C. P., Kersbergen, R., Mallory, E. B., Genualdi, S., Young, W., & Smith, A. E. (2024). Uptake of Per- and Polyfluoroalkyl Substances in Mixed Forages on Biosolid-Amended Farm Fields. *Journal of Agricultural and Food Chemistry*, *72*(42), 23108–23117. https://doi.org/10.1021/acs.jafc.4c02078

Smalling, K. L., Bradley, P. M., Romanok, K. M., Elliot, S. M., Lambert, J. de, Focazio, M. J., Gordon, S. E., Gray, J. L., Kanagy, L. K., Hladik, M. L., Loftin, K. A., McCleskey, R. B., Medlock-Kakaley, E. K., Cardon, M. C., Evans, N., & Weis, C. P. (2023). Exposures and potential health implications of contaminant mixtures in linked source water, finished drinking water, and tapwater from public-supply drinking water systems in Minneapolis/St. Paul area, USA. *Environmental Science: Water Research & Technology*, *9*(7), 1813–1828. https://doi.org/10.1039/D3EW00066D

Smith, T., Krometis, L.-A. H., Hagedorn, C., Lawrence, A. H., Benham, B., Ling, E., Ziegler, P., & Marmagas, S. W. (2014). Associations between fecal indicator bacteria prevalence and demographic data in private water supplies in Virginia. *Journal of Water and Health*, *12*(4), 824–834. https://doi.org/10.2166/wh.2014.026

Stahl, L. L., Snyder, B. D., Olsen, A. R., Kincaid, T. M., Wathen, J. B., & McCarty, H. B. (2014). Perfluorinated compounds in fish from U.S. urban rivers and the Great Lakes. *The Science of the Total Environment*, *499*, 185–195. https://doi.org/10.1016/j.scitotenv.2014.07.126

Steenland, K., Fletcher, T., & Savitz, D. A. (2010). Epidemiologic evidence on the health effects of perfluorooctanoic acid (PFOA). *Environmental Health Perspectives*, *118*(8), 1100–1108. https://doi.org/10.1289/ehp.0901827

Stormwater Permits Daily. (n.d.). Retrieved November 14, 2025, from https://geohub-vadeq.hub.arcgis.com/datasets/6a3f36483f14459abcf274412ef6690e_303/explore?location=37.659422,-78.656690,7.83

Sunderland, E. M., Hu, X. C., Dassuncao, C., Tokranov, A. K., Wagner, C. C., & Allen, J. G. (2019). A review of the pathways of human exposure to poly- and perfluoroalkyl substances (PFASs) and present understanding of health effects. *Journal of Exposure Science & Environmental Epidemiology*, *29*(2), 131–147. https://doi.org/10.1038/s41370-018-0094-1

Teymourian, T., Teymoorian, T., Kowsari, E., & Ramakrishna, S. (2021). A review of emerging PFAS contaminants: Sources, fate, health risks, and a comprehensive assortment of recent sorbents for PFAS treatment by evaluating their mechanism. *Research on Chemical Intermediates*, *47*(12), 4879–4914. https://doi.org/10.1007/s11164-021-04603-7

Urban-Rural by the Numbers. (2018, September 27). *National League of Cities*. https://www.nlc.org/article/2018/09/27/urban-rural-by-the-numbers/

US EPA, O. (2013, January 31). *Toxics Release Inventory (TRI) Program* [Collections and Lists]. https://www.epa.gov/toxics-release-inventory-tri-program

US EPA, O. (2015, April 1). *Overview of the Safe Drinking Water Act* [Other Policies and Guidance]. https://www.epa.gov/sdwa/overview-safe-drinking-water-act

US EPA, O. (2024, July 11). *EPA Releases New Science-Based Recommendations to Help More States, Tribes, and Territories Reduce Exposure to PFAS in Fish* (United States) [News Release]. https://www.epa.gov/newsreleases/epa-releases-new-science-based-recommendations-help-more-states-tribes-and-territories

US EPA, O. (2025, May 14). *EPA Announces It Will Keep Maximum Contaminant Levels for PFOA, PFOS* [News Release]. https://www.epa.gov/newsreleases/epa-announces-it-will-keep-maximum-contaminant-levels-pfoa-pfos

US State Boundaries. (n.d.). Retrieved June 26, 2025, from https://hub.arcgis.com/datasets/TrainingServices::us-state-boundaries/explore?location=7.313844,0.315549,1.65

Venkatesan, A. K., & Halden, R. U. (2013). National inventory of perfluoroalkyl substances in archived U.S. biosolids from the 2001 EPA National Sewage Sludge Survey. *Journal of Hazardous Materials*, *252–253*, 413–418. https://doi.org/10.1016/j.jhazmat.2013.03.016

Vieira, V. M., Hoffman, K., Shin, H.-M., Weinberg, J. M., Webster, T. F., & Fletcher, T. (2013). Perfluorooctanoic Acid Exposure and Cancer Outcomes in a Contaminated Community: A Geographic Analysis. *Environmental Health Perspectives*, *121*(3), 318–323. https://doi.org/10.1289/ehp.1205829

Virginia Environmental Data Hub. (n.d.). Retrieved August 12, 2025, from https://geohub-vadeq.hub.arcgis.com/search?q=industrial%20sites

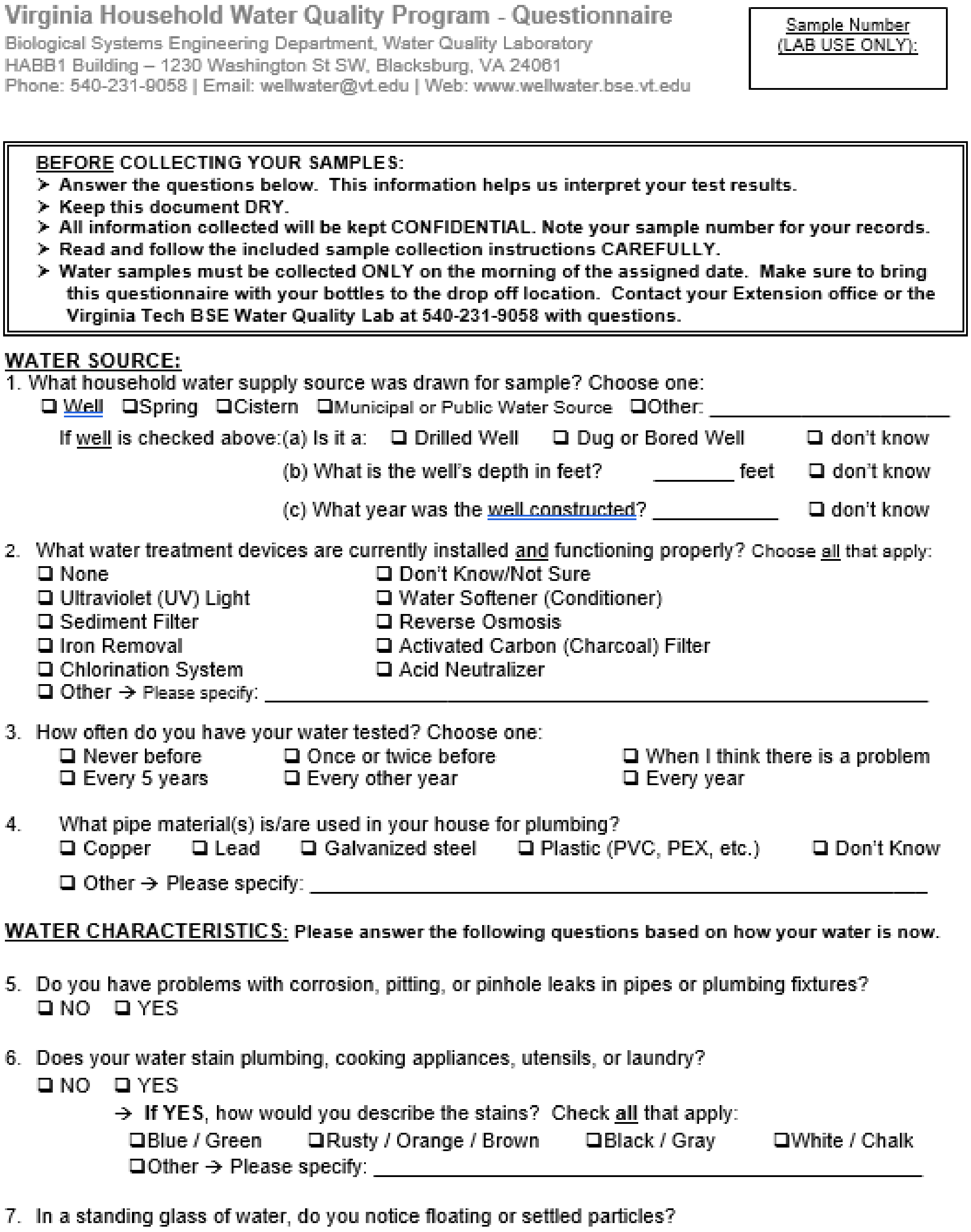
Wallender, E. K., Ailes, E. C., Yoder, J. S., Roberts, V. A., & Brunkard, J. M. (2014). Contributing factors to disease outbreaks associated with untreated groundwater. *Ground Water*, *52*(6), 886–897. https://doi.org/10.1111/gwat.12121

Washington, J. W., Yoo, H., Ellington, J. J., Jenkins, T. M., & Libelo, E. L. (2010). Concentrations, Distribution, and Persistence of Perfluoroalkylates in Sludge-Applied Soils near Decatur, Alabama, USA. *Environmental Science & Technology*, *44*(22), 8390–8396. https://doi.org/10.1021/es1003846

Young, C. J., & Mabury, S. A. (2010). Atmospheric Perfluorinated Acid Precursors: Chemistry, Occurrence, and Impacts. In P. De Voogt (Ed.), *Reviews of Environmental Contamination and Toxicology Volume 208: Perfluorinated alkylated substances* (pp. 1–109). Springer. https://doi.org/10.1007/978-1-4419-6880-7_1

8. Appendices

8.1 Appendix A – Surveys



Virginia Household Water Quality Program - Questionnaire

Biological Systems Engineering Department, Water Quality Laboratory
HABB1 Building – 1230 Washington St SW, Blacksburg, VA 24061
Phone: 540-231-9058 | Email: wellwater@vt.edu | Web: www.wellwater.bse.vt.edu

Sample Number (LAB USE ONLY):

BEFORE COLLECTING YOUR SAMPLES:
- **Answer the questions below. This information helps us interpret your test results.**
- **Keep this document DRY.**
- **All information collected will be kept CONFIDENTIAL. Note your sample number for your records.**
- **Read and follow the included sample collection instructions CAREFULLY.**
- **Water samples must be collected ONLY on the morning of the assigned date. Make sure to bring this questionnaire with your bottles to the drop off location. Contact your Extension office or the Virginia Tech BSE Water Quality Lab at 540-231-9058 with questions.**

WATER SOURCE:

1. What household water supply source was drawn for sample? Choose one:
☐ Well ☐Spring ☐Cistern ☐Municipal or Public Water Source ☐Other: ____________________
If well is checked above:(a) Is it a: ☐ Drilled Well ☐ Dug or Bored Well ☐ don't know
(b) What is the well's depth in feet? _______ feet ☐ don't know
(c) What year was the well constructed? __________ ☐ don't know

2. What water treatment devices are currently installed and functioning properly? Choose all that apply:
☐ None
☐ Ultraviolet (UV) Light
☐ Sediment Filter
☐ Iron Removal
☐ Chlorination System
☐ Don't Know/Not Sure
☐ Water Softener (Conditioner)
☐ Reverse Osmosis
☐ Activated Carbon (Charcoal) Filter
☐ Acid Neutralizer
☐ Other → Please specify: ____________________

3. How often do you have your water tested? Choose one:
☐ Never before ☐ Once or twice before ☐ When I think there is a problem
☐ Every 5 years ☐ Every other year ☐ Every year

4. What pipe material(s) is/are used in your house for plumbing?
☐ Copper ☐ Lead ☐ Galvanized steel ☐ Plastic (PVC, PEX, etc.) ☐ Don't Know
☐ Other → Please specify: ____________________

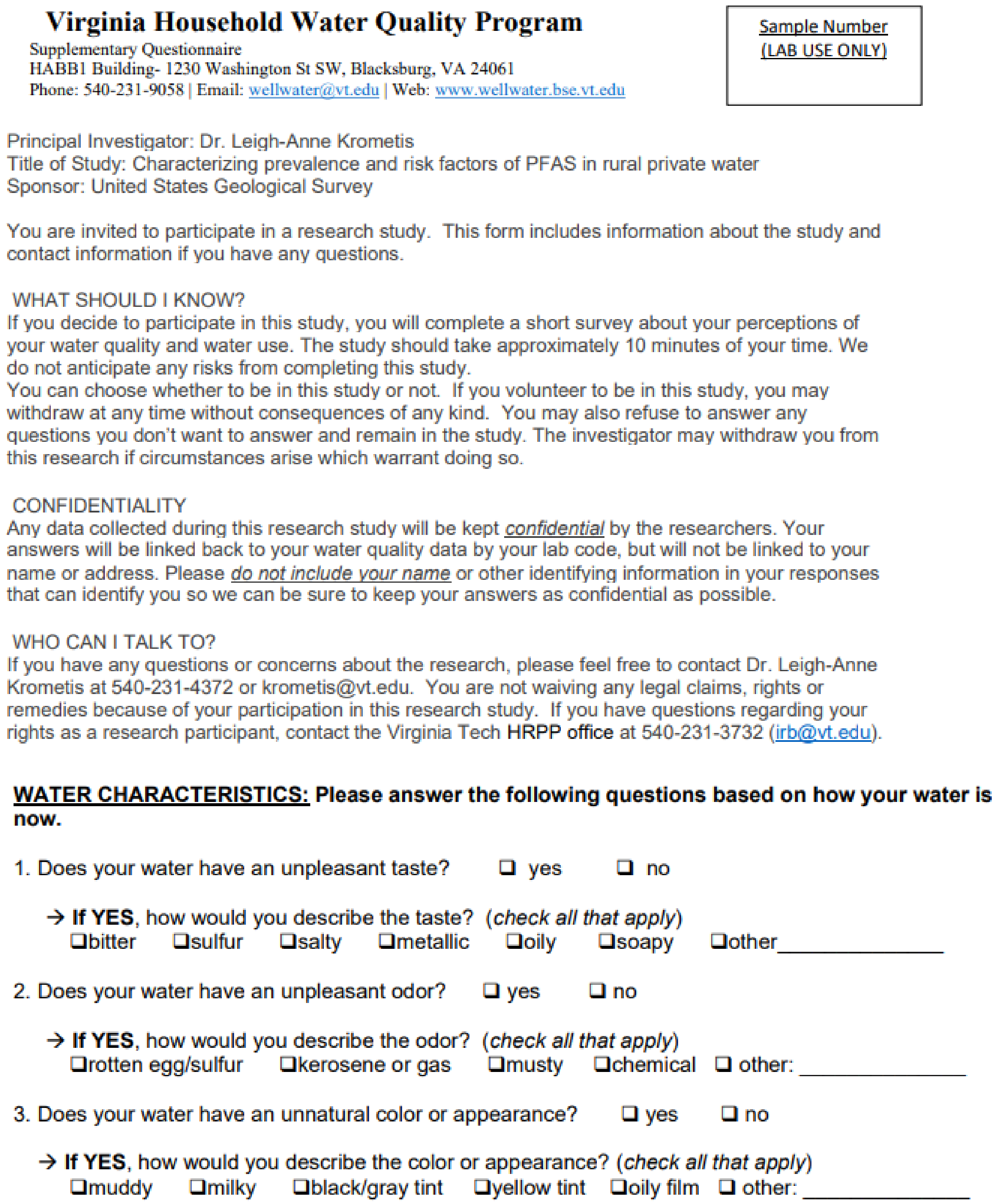
WATER CHARACTERISTICS: **Please answer the following questions based on how your water is now.**

5. Do you have problems with corrosion, pitting, or pinhole leaks in pipes or plumbing fixtures?
☐ NO ☐ YES

6. Does your water stain plumbing, cooking appliances, utensils, or laundry?
☐ NO ☐ YES
→ **If YES**, how would you describe the stains? Check all that apply:
☐Blue / Green ☐Rusty / Orange / Brown ☐Black / Gray ☐White / Chalk
☐Other → Please specify: ____________________

7. In a standing glass of water, do you notice floating or settled particles?

Figure A1:Page 1 of VAHWQP Standard Survey Page 1



Virginia Household Water Quality Program

Supplementary Questionnaire
HABB1 Building- 1230 Washington St SW, Blacksburg, VA 24061
Phone: 540-231-9058 | Email: wellwater@vt.edu | Web: www.wellwater.bse.vt.edu

Sample Number
(LAB USE ONLY)

Principal Investigator: Dr. Leigh-Anne Krometis
Title of Study: Characterizing prevalence and risk factors of PFAS in rural private water
Sponsor: United States Geological Survey

You are invited to participate in a research study. This form includes information about the study and contact information if you have any questions.

WHAT SHOULD I KNOW?

If you decide to participate in this study, you will complete a short survey about your perceptions of your water quality and water use. The study should take approximately 10 minutes of your time. We do not anticipate any risks from completing this study.
You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you don't want to answer and remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

CONFIDENTIALITY

Any data collected during this research study will be kept *confidential* by the researchers. Your answers will be linked back to your water quality data by your lab code, but will not be linked to your name or address. Please *do not include your name* or other identifying information in your responses that can identify you so we can be sure to keep your answers as confidential as possible.

WHO CAN I TALK TO?

If you have any questions or concerns about the research, please feel free to contact Dr. Leigh-Anne Krometis at 540-231-4372 or krometis@vt.edu. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research participant, contact the Virginia Tech HRPP office at 540-231-3732 (irb@vt.edu).

WATER CHARACTERISTICS: Please answer the following questions based on how your water is now.

1. Does your water have an unpleasant taste? ☐ yes ☐ no

→ **If YES**, how would you describe the taste? (*check all that apply*)
☐bitter ☐sulfur ☐salty ☐metallic ☐oily ☐soapy ☐other_______________

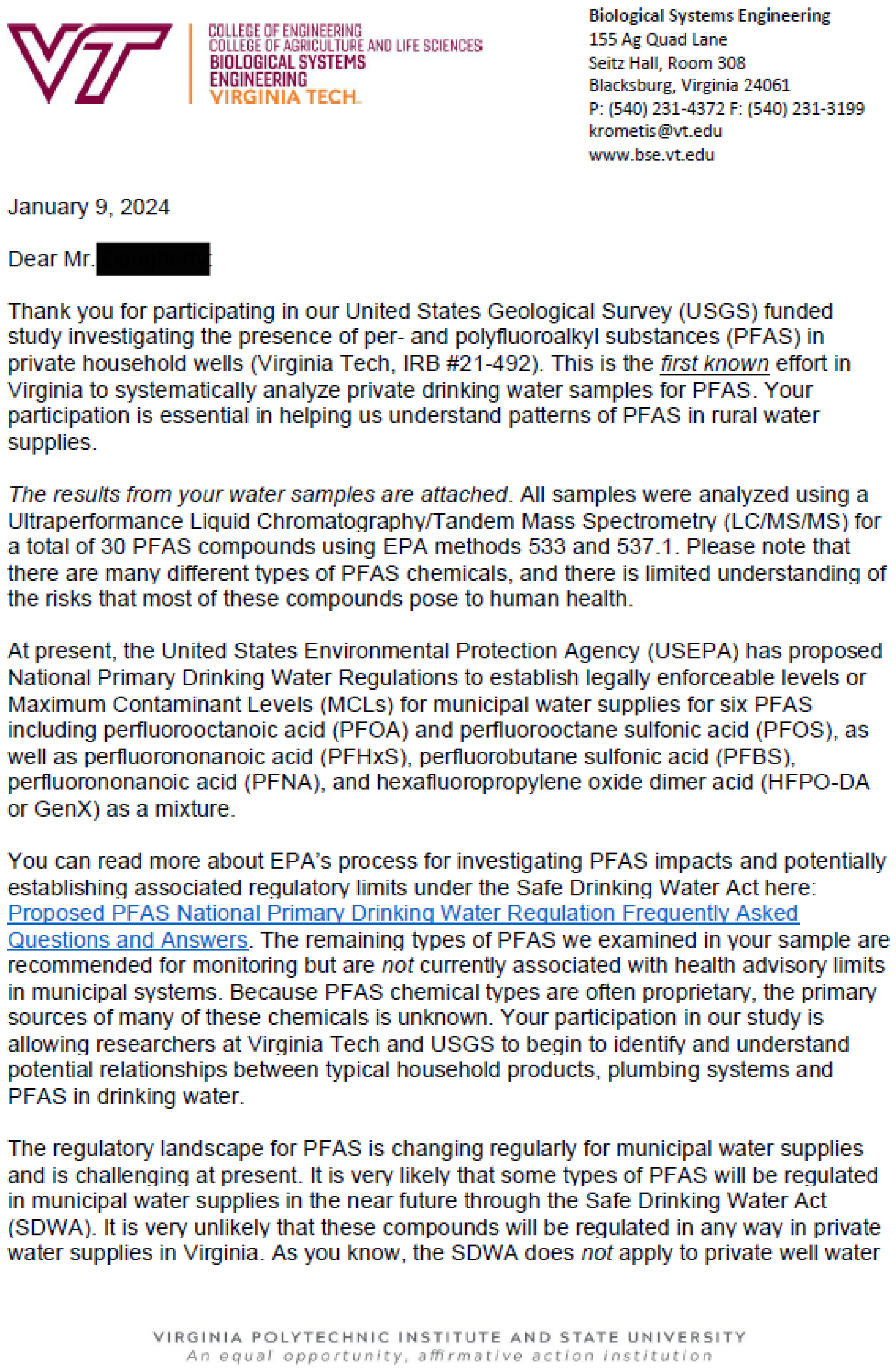
2. Does your water have an unpleasant odor? ☐ yes ☐ no

→ **If YES**, how would you describe the odor? (*check all that apply*)
☐rotten egg/sulfur ☐kerosene or gas ☐musty ☐chemical ☐ other: _______________

3. Does your water have an unnatural color or appearance? ☐ yes ☐ no

→ **If YES**, how would you describe the color or appearance? (*check all that apply*)
☐muddy ☐milky ☐black/gray tint ☐yellow tint ☐oily film ☐ other: _______________

Figure A2: Page 1 of Supplemental survey



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January 9, 2024

Dear Mr. [redacted]

Thank you for participating in our United States Geological Survey (USGS) funded study investigating the presence of per- and polyfluoroalkyl substances (PFAS) in private household wells (Virginia Tech, IRB #21-492). This is the *first known* effort in Virginia to systematically analyze private drinking water samples for PFAS. Your participation is essential in helping us understand patterns of PFAS in rural water supplies.

The results from your water samples are attached. All samples were analyzed using a Ultraperformance Liquid Chromatography/Tandem Mass Spectrometry (LC/MS/MS) for a total of 30 PFAS compounds using EPA methods 533 and 537.1. Please note that there are many different types of PFAS chemicals, and there is limited understanding of the risks that most of these compounds pose to human health.

At present, the United States Environmental Protection Agency (USEPA) has proposed National Primary Drinking Water Regulations to establish legally enforceable levels or Maximum Contaminant Levels (MCLs) for municipal water supplies for six PFAS including perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), as well as perfluorononanoic acid (PFHxS), perfluorobutane sulfonic acid (PFBS), perfluorononanoic acid (PFNA), and hexafluoropropylene oxide dimer acid (HFPO-DA or GenX) as a mixture.

You can read more about EPA's process for investigating PFAS impacts and potentially establishing associated regulatory limits under the Safe Drinking Water Act here: Proposed PFAS National Primary Drinking Water Regulation Frequently Asked Questions and Answers. The remaining types of PFAS we examined in your sample are recommended for monitoring but are *not* currently associated with health advisory limits in municipal systems. Because PFAS chemical types are often proprietary, the primary sources of many of these chemicals is unknown. Your participation in our study is allowing researchers at Virginia Tech and USGS to begin to identify and understand potential relationships between typical household products, plumbing systems and PFAS in drinking water.

The regulatory landscape for PFAS is changing regularly for municipal water supplies and is challenging at present. It is very likely that some types of PFAS will be regulated in municipal water supplies in the near future through the Safe Drinking Water Act (SDWA). It is very unlikely that these compounds will be regulated in any way in private water supplies in Virginia. As you know, the SDWA does *not* apply to private well water

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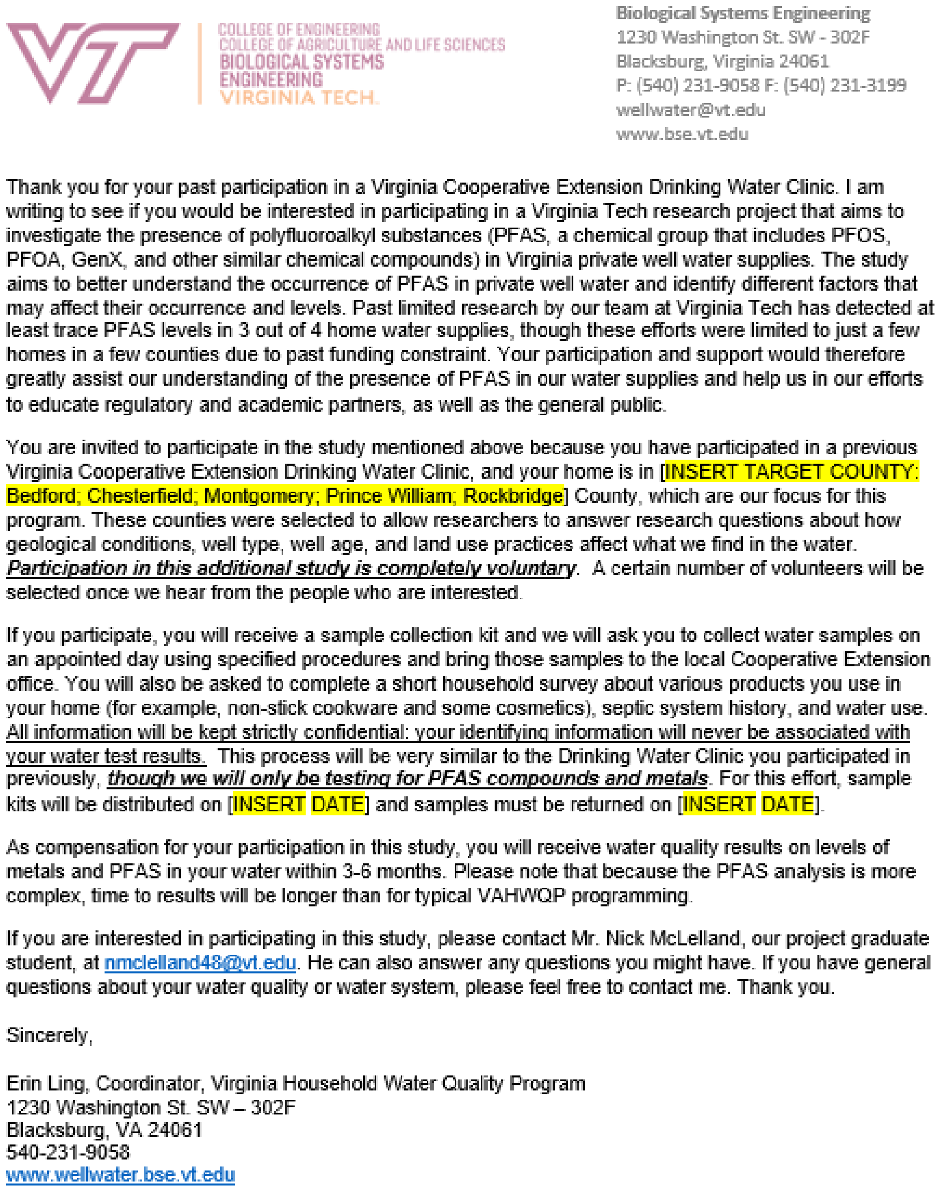
Figure A3: Standard VAHWQP Results Letter



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1230 Washington St. SW - 302F
Blacksburg, Virginia 24061
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wellwater@vt.edu
www.bse.vt.edu

Thank you for your past participation in a Virginia Cooperative Extension Drinking Water Clinic. I am writing to see if you would be interested in participating in a Virginia Tech research project that aims to investigate the presence of polyfluoroalkyl substances (PFAS, a chemical group that includes PFOS, PFOA, GenX, and other similar chemical compounds) in Virginia private well water supplies. The study aims to better understand the occurrence of PFAS in private well water and identify different factors that may affect their occurrence and levels. Past limited research by our team at Virginia Tech has detected at least trace PFAS levels in 3 out of 4 home water supplies, though these efforts were limited to just a few homes in a few counties due to past funding constraint. Your participation and support would therefore greatly assist our understanding of the presence of PFAS in our water supplies and help us in our efforts to educate regulatory and academic partners, as well as the general public.

You are invited to participate in the study mentioned above because you have participated in a previous Virginia Cooperative Extension Drinking Water Clinic, and your home is in [INSERT TARGET COUNTY: Bedford; Chesterfield; Montgomery; Prince William; Rockbridge] County, which are our focus for this program. These counties were selected to allow researchers to answer research questions about how geological conditions, well type, well age, and land use practices affect what we find in the water. ***Participation in this additional study is completely voluntary***. A certain number of volunteers will be selected once we hear from the people who are interested.

If you participate, you will receive a sample collection kit and we will ask you to collect water samples on an appointed day using specified procedures and bring those samples to the local Cooperative Extension office. You will also be asked to complete a short household survey about various products you use in your home (for example, non-stick cookware and some cosmetics), septic system history, and water use. All information will be kept strictly confidential: your identifying information will never be associated with your water test results. This process will be very similar to the Drinking Water Clinic you participated in previously, ***though we will only be testing for PFAS compounds and metals***. For this effort, sample kits will be distributed on [INSERT DATE] and samples must be returned on [INSERT DATE].

As compensation for your participation in this study, you will receive water quality results on levels of metals and PFAS in your water within 3-6 months. Please note that because the PFAS analysis is more complex, time to results will be longer than for typical VAHWQP programming.

If you are interested in participating in this study, please contact Mr. Nick McLelland, our project graduate student, at nmclelland48@vt.edu. He can also answer any questions you might have. If you have general questions about your water quality or water system, please feel free to contact me. Thank you.

Sincerely,

Erin Ling, Coordinator, Virginia Household Water Quality Program
1230 Washington St. SW – 302F
Blacksburg, VA 24061
540-231-9058
www.wellwater.bse.vt.edu

Figure A4: PFAS results letter

8.2 Appendix B – Analytical Standards

Table B1:Analytical Standards for Metals and PFAS compounds

Metal	MRL (ppb)	PFAS Compound	MRL (ppt)
Lithium	0.1	PFBA	0.048
Sodium	0.1	PFPeA	0.213
Magnesium	0.1	HFPO-DA	0.03

Aluminum	0.1	FBSA	0.03
Silicon	0.1	L-PFBS	0.027
Phosphorus	0.1	PFHxA	0.099
Sulfur	0.1	4:2FTS	0.03
Chlorine	0.1	L-PFPeS	0.03
Potassium	0.1	PFHpA	0.015
Calcium	0.1	DONA	0.018
Titanium	0.1	FHxSA	0.0075
Vanadium	0.1	PFHxS	0.03
Chromium	0.1	PFOA	0.177
Iron	0.1	6:2FTS	0.03
Manganese	0.1	L-PFHpS	0.03
Cobalt	0.1	PFNA	0.03
Nickle	0.1	FOSA	0.03
Copper	0.1	PFOS	0.03
Zinc	0.1	PFDA	0.03
Arsenic	0.1	8:2FTS	0.03
Selenium	0.1	9Cl-PF3ONS	0.03
Strontium	0.1	L-PFNS	0.03
Molybdenum	0.1	PFUdA	0.03
Silver	0.1	N-MeFOSAA	0.03
Cadmium	0.1	N-EtFOSAA	0.03
Tin	0.1	L-PFDS	0.03
Barium	0.1	PFDoA	0.03
Lead	0.1	11Cl-PF3OUdS	0.03
Uranium	0.1	PFTrDA	0.03

8.3 Appendix C – Supplemental Demographic and Survey Data

Table C1: Sociodemographic information from the US Census for sampled counties and Virginia at large (Census Bureau Search, 2025.)

County	Accomack	Albermarle	Buckingham	Chesterfield	Floyd	Loudoun	Montgomery	Northampton	Roanoke	Rockbridge	Virginia
Total Population	33,413	112,395	16,824	364,548	15,476	420,959	99,721	12,282	96,929	22,650	8,631,393
Median Household Income	$57,500	$103,413	$59,199	$101,543	$61,401	$174,148	$68,079	$55,933	$80,809	$63,975	$89,931
Bachelor's Degree or Higher	21.8%	61.8%	13.5%	45.7%	23.0%	65.2%	48.9%	32.5%	35.5%	31.5%	42.4%
Employment Rate	53.3%	60.7%	46.6%	64.2%	60.7%	70.4%	53.8%	49.5%	57.1%	53.9%	61.1%
Total Housing Units	21,703	47,291	7,133	151,853	7,924	142,074	41,134	7,373	42,147	11,261	3,618,247
Without Health Care	9.3%	5.0%	9.6%	7.0%	7.2%	4.7%	4.0%	8.2%	3.7%	5.3%	6.4%

Total Employer Establishments	706	2,874	255	8,257	331	11,720	1,991	304	2,051	439	206,271
Total Households	14,302	46,900	6,062	147,465	6,659	145,601	37,229	5,338	40,176	9,552	3,402,670
Median Age	47.5	42.1	43.7	39.2	48.0	38.3	29.8	51.6	42.9	49.7	39.3
Poverty %	14.9%	8.0%	13.7%	7.2%	8.3%	4.5%	26.0%	17.1%	6.8%	8.0%	10.2%
Hispanic or Latino	3,430	8,453	413	40,236	487	59,744	4,651	1,068	3,507	513	908,749
Black or African American	8,639	9,793	5,390	83,107	234	29,725	4,054	3,756	5,650	565	1,578,090
White	19,825	80,335	10,314	216.290	14,114	216,865	77,918	6,932	79,928	21,276	5,058,363
Other	1,519	13,814	707	24,916	641	114,625	13,098	526	7,844	296	1,086,191

Table C2: Demographic information grouped by county at state level

County	Average Head of Household age (years)	Participants Who Identify White	U.S. Census White Population
Accomack	54	94%	59%
Albemarle	46	95%	71%
Buckingham	51	100%	61%
Chesterfield	50	86%	0%
Floyd	53	95%	91%
Loudoun	40	88%	52%
Montgomery	47	88%	78%
Northampton	55	90%	56%
Roanoke	49	91%	82%
Rockbridge	63	100%	94%
Total	49	93%	59%

Table C3: Income distribution by county and at state level

County	< $26,000	$27,000 - $52,000	$53,000 - $70,000	$71,000 - $97,000	> $98,000
Accomack (N=18)	11%	11%	17%	28%	33%
Albemarle (N=50)	2%	8%	2%	10%	78%
Buckingham (N=23)	22%	13%	26%	17%	22%

Chesterfield (N=10)	0%	0%	10%	30%	60%
Floyd (N=38)	11%	13%	24%	21%	32%
Loudoun (N=30)	0%	10%	0%	7%	83%
Montgomery (N=44)	2%	9%	16%	5%	68%
Northampton (N=26)	4%	15%	8%	19%	54%
Roanoke (N=31)	3%	16%	6%	35%	39%
Rockbridge (N=37)	3%	11%	5%	19%	62%
Virginia (N=307)	5%	11%	11%	17%	56%

Table C4: Education distribution

County	**Some HS**	**HS Grad**	**Some College**	**College Grad**	**Post Grad**
Accomack (N=20)	0%	0%	10%	50%	40%
Albemarle (N=57)	0%	0%	2%	19%	79%
Buckingham (N=29)	0%	0%	24%	34%	41%
Chesterfield (N=12)	0%	0%	17%	58%	25%
Floyd (N=42)	2%	10%	33%	50%	5%
Loudoun (N=41)	0%	2%	5%	39%	54%
Montgomery (N=51)	0%	2%	2%	29%	67%
Northampton (N=35)	3%	6%	9%	34%	49%
Roanoke (N=32)	0%	6%	25%	63%	6%
Rockbridge (N=42)	0%	0%	7%	24%	69%
Total (N=361)	1%	3%	12%	37%	48%

Table C5: Household piping materials across VA

County	**Copper Pipes**	**Lead Pipes**	**Steel Pipes**	**Plastic Pipes**	**Other Pipe**

Accomack (N=18)	28%	0%	0%	94%	11%
Albemarle (N=55)	40%	0%	7%	96%	9%
Buckingham (N=30)	37%	0%	7%	97%	13%
Chesterfield (N=14)	29%	0%	0%	93%	7%
Floyd (N=39)	13%	0%	5%	100%	8%
Loudoun (N=40)	50%	3%	5%	75%	8%
Montgomery (N=48)	56%	0%	15%	75%	10%
Northampton (N=37)	41%	0%	5%	84%	5%
Roanoke (N=29)	72%	0%	7%	72%	14%
Rockbridge (N=39)	41%	0%	8%	95%	10%
Total (N=349)	42%	0%	7%	88%	9%

Table C6: Septic characteristics by county

County	Septic	Downhill from home	Average Distance from home (ft)	Average Age (years)	Average Septic Pumped Last (years)	Septic Never Pumped percent	Septic Failed
Accomack	95%	47%	287	15.6	3.4	16%	26%
Albemarle	100%	73%	378	17.9	4.1	9%	12%
Buckingham	91%	61%	322	20.5	6.2	22%	6%
Chesterfield	100%	67%	283	18.9	3.6	7%	7%
Floyd	98%	66%	382	17.0	4.8	31%	2%
Loudoun	93%	55%	405	17.7	3.2	8%	13%
Montgomery	94%	80%	357	18.7	3.0	19%	10%
Northampton	100%	33%	225	16.5	3.5	11%	8%
Roanoke	97%	88%	330	19.3	4.6	15%	22%
Rockbridge	98%	88%	345	18.5	3.2	18%	10%
Total	97%	67%	341	18.0	3.9	15%	11%

Table C7: Treatment patterns by county

County	Accomack	Albemarle	Buckingham	Chesterfield	Floyd	Loudoun	Montgomery	Northampton	Roanoke	Rockbridge	Total
Treatment	45%	85%	56%	73%	81%	84%	81%	26%	67%	77%	70%

HB Treat	44%	25%	32%	36%	18%	50%	40%	40%	32%	33%	34%
AS Treat	89%	92%	84%	100%	94%	100%	100%	90%	95%	97%	95%
Acid Neutralizer	0%	35%	26%	9%	9%	17%	5%	0%	23%	3%	15%
UV Light	0%	18%	11%	27%	12%	39%	14%	0%	23%	15%	18%
Water Softener	89%	27%	16%	0%	6%	75%	86%	30%	59%	76%	49%
Sediment Filter	22%	75%	68%	91%	82%	50%	40%	30%	41%	61%	59%
Reverse Osmosis	11%	6%	0%	0%	3%	6%	14%	0%	5%	9%	6%
Iron Removal	0%	6%	11%	9%	9%	22%	16%	50%	23%	6%	13%
Carbon Filter	22%	8%	16%	9%	0%	17%	16%	40%	5%	15%	12%
Chlorinator	22%	0%	5%	0%	3%	3%	5%	0%	9%	0%	3%
Other Treatment	11%	6%	5%	0%	9%	0%	0%	0%	0%	12%	4%

8.4 Appendix D - Supplemental PFAS and Water Quality and Statistical Results

Table D1: County level traditional water quality markers

County	pH Median	Conductivity (µS/cm) Median	TDS (mg/L) Median	Total Coliform Present	E. coli Present
Accomack (N=20)	8.10	443	221	25%	0.0%
Albemarle (N=60)	6.85	363	182	27%	0.0%
Buckingham (N=34)	6.65	172	86.1	50%	15%
Chesterfield (N=15)	6.34	144	71.8	60%	6.7%
Floyd (N=42)	6.90	139	70.0	50%	14%
Loudoun (N=43)	6.85	372	186	21%	2.3%
Montgomery (N=53)	7.39	594	297	25%	3.8%
Northampton (N=39)	8.10	362	181	31%	0.0%
Roanoke (N=33)	7.10	391	196	39%	3.0%
Rockbridge (N=43)	7.18	617	309	42%	0.0%
Total (N=382)	7.19	359	180	35%	4.2%

Table D2: County level PFAS Incidence

County	Min PFAS Yield	Max PFAS Yield	Median PFAS Yield	Median Unique PFAS	Median Short Chain Sum	Median Long Chain Sum
Accomack (N=20)	0.018	3.19	0.513	3.5	0.330	0.201
Albemarle (N=60)	0.370	70.1	2.24	8	1.85	0.360
Buckingham (N=34)	0.853	27.7	1.72	7	1.48	0.230
Chesterfield (N=15)	0.468	74.6	0.909	7	0.497	0.312
Floyd (N=42)	0.443	4.75	0.724	8	0.417	0.279
Loudoun (N=43)	0.399	303	2.81	8	1.53	0.817
Montgomery (N=53)	0.537	22.6	1.59	9	1.18	0.255
Northampton (N=39)	0.030	5.04	1.42	5	1.16	0.222
Roanoke (N=33)	0.420	72.5	1.30	11	0.547	0.625
Rockbridge (N=43)	0.460	193	1.49	7	1.05	0.222
Virginia (N=382)	0.018	303	1.50	7	1.12	0.267

Table D3: Detection and MCL exceedance rates of PFAS by county

County	Detectable PFAS	Quantifiable PFAS	Detectable PFOA	Detectable PFOS	PFOA Exceed MCL	PFOS Exceed MCL
Accomack (N=20)	100%	60%	80%	20%	0%	0%
Albemarle (N=60)	100%	100%	98%	53%	6.7%	10%
Buckingham (N=34)	100%	100%	94%	65%	0%	2.9%
Chesterfield (N=15)	100%	87%	100%	80%	6.7%	13%
Floyd (N=42)	100%	69%	83%	64%	0%	0
Loudoun (N=43)	100%	100%	98%	88%	2.3%	12%
Montgomery (N=53)	100%	96%	98%	77%	1.9%	0%
Northampton (N=39)	100%	92%	97%	26%	0%	0%
Roanoke (N=33)	100%	70%	97%	88%	6.1%	12%
Rockbridge (N=43)	100%	98%	98%	72%	0%	4.7%
Virginia (N=382)	100%	90%	95%	64%	2.4%	5.2%

Table D4: Spearman's Rho Correlation Results

Variable	Spearman_rho	p_value	Significant (p<0.05)	Significant (p<0.01)
Water	-0.018913413	0.713	NO	NO
Urban	0.13201269	0.010	YES	YES
Barren	-0.145397035	0.004	YES	YES
Forest	-0.019714168	0.701	NO	NO

Vegetation	-0.109511788	0.032	YES	NO
Agriculture	0.018028454	0.725	NO	NO
Manufacturing and Materials Dist	-0.170934376	0.001	YES	YES
Chemical Coating Plastic Dist	-0.050298991	0.327	NO	NO
Oil and Gas Dist	-0.178252448	0.000	YES	YES
Consumer Products Dist	-0.128038061	0.012	YES	NO
Fire Facilities Dist	-0.21516077	0.000	YES	YES
Airport Dist	-0.135827155	0.008	YES	YES
Defense Dist	-0.131388715	0.010	YES	NO
Waste Management Dist	-0.260578714	0.0000	YES	YES
Biosolids Dist	-0.234962017	0.000	YES	YES
Stormwater Dist	-0.313786398	0.0000	YES	YES
TRI Dist	-0.094748087	0.064	NO	NO
pH	-0.19122086	0.000	YES	YES
Conductivity uS cm	0.132362675	0.010	YES	YES
TDS mg L	0.135768119	0.008	YES	YES
Total Coliform (MPN/100 mL)	0.015448767	0.763	NO	NO
Total E. coli (MPN/100 mL)	-0.031119282	0.544	NO	NO
Iron mg/L	-0.013921039	0.798	NO	NO
Manganese mg/L	-0.012849728	0.814	NO	NO
Lead mg/L	0.200924137	0.000	YES	YES
Well Depth	0.009366313	0.890	NO	NO
Well Age	0.168465828	0.006	YES	YES

Table D5: Wilcoxon Test Results

Variable	**Median_Bottom_90_PFAS**	**Median_Top_10_PFAS**	**W_statistic**	**p_value**	**Signifcant (p<0.05)**	**Signifcant (p<0.01)**
# All Point Source Types	74	241	3692	0.000	YES	YES
# Stormwater	59	214	3749	0.000	YES	YES
# Oil and Gas	1	4	652.5	0.002	YES	YES
# Waste Management	8	10	4247.5	0.003	YES	YES
# Airports	2	2	5411	0.377	NO	NO
# Defense Sites	1	1	872.5	0.680	NO	NO
# Biosolids	2	2	455	0.696	NO	NO
# Consumer Products	2	1.5	49.5	0.717	NO	NO
# Chemical and Coating	2	2	1709.5	0.739	NO	NO
# TRI Sites	4	4	1368	0.803	NO	NO

# Manufacturing and Materials	4	2	1767.5	0.807	NO	NO
Lead mg/L	0.00069858	0.001701576	3999	0.001	YES	YES
pH	7.2	6.8	8442.5	0.007	YES	YES
TDS mg/L	176.88	263.98	5102	0.015	YES	NO
Conductivity uS/cm	344	454.26	5206.5	0.023	YES	NO
Manganese mg/L	0.00157017	0.002321788	5173	0.240	NO	NO
Iron mg/L	0.007553052	0.006340704	6412	0.329	NO	NO
Total Coliform (MPN/100 mL)	0	0	6496.5	0.730	NO	NO
Total E. coli (MPN/100 mL)	0	0	6629.5	0.796	NO	NO

Table D6: Chi-Square Results

Variable	Test_Type	Chi2_statistic	p_value	Percent_Bottom90_Positive	Percent_Top10_Positive	Significant (p<0.05)
UV Light	Fisher's Exact	NA	0.126	11.66180758	20.51282051	NO
Water Softener	Chi-squared	1.118694815	0.290	35.56851312	25.64102564	NO
HB Treat	Chi-squared	0.847228745	0.357	22.74052478	30.76923077	NO
Reverse Osmosis	Fisher's Exact	NA	0.399	4.081632653	7.692307692	NO
Iron Removal	Fisher's Exact	NA	0.560	9.912536443	5.128205128	NO
Acid Neutralizer	Fisher's Exact	NA	0.591	10.49562682	12.82051282	NO
Carbon Filter	Fisher's Exact	NA	0.762	8.454810496	10.25641026	NO
AS Treat	Chi-squared	0.036696198	0.848	67.05539359	64.1025641	NO
Any Treatment	Chi-squared	9.74E-31	1.000	70.26239067	69.23076923	NO
Sediment Filter	Chi-squared	0	1.000	41.39941691	41.02564103	NO
Chlorinator	Fisher's Exact	NA	1.000	2.332361516	2.564102564	NO
E. coli Presence	Fisher's Exact	NA	0.673	4.081632653	5.128205128	NO
Coliform Presence	Chi-squared	0.106841254	0.744	34.40233236	38.46153846	NO

Pipe Copper	Chi-squared	0.077630962	0.781	49.09090909	44	NO
Pipe Plastic	Fisher's Exact	NA	0.794	87.3015873	86.11111111	NO