Residential Per- and Poly-fluoroalkyl Substances (PFAS) Sources

A Major Qualifying Project
Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
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Abstract

Per- and poly-fluoroalkyl substances (PFAS) are fluorinated organic polymers which are highly stable and recalcitrant, making them useful in many household products and persistent in the environment. The goal of this project was to investigate the transport of PFAS from household products, through domestic septic systems, and into groundwater. From four Massachusetts towns, 233 addresses were selected as viable testing sites. Two sites underwent testing for PFAS in septic systems and were surveyed about their household product use. Both had a higher concentration of PFAS in septic liquid than tap water. The types and concentrations of PFAS present varied between the sites. It is recommended that a Phase II study be done to gather more conclusive data.

Acknowledgements

We would like to thank our faculty advisors John Bergendahl and Stephen Kmiotek, as well as the Massachusetts Department of Environmental Protection, for their advice and guidance on this project.

Executive Summary

PFAS Exposure and Occurance

Per- and Polyfluoroalkyl (PFAS) are fluorinated organic polymers. They are a group of many different compounds that due to their carbon fluorine bonds are highly stable and therefore used in many household products. They can be found in many products including makeup, waterproof clothes, and cleaning products (Schaider et al., 2017; Whitehead et al., 2021). This means that people are often exposed to these compounds. One large source of exposure to PFAS is working directly with the substance, which affects those working in factories that produce it or using fire fighting foam. Other pathways of exposure are through dietary intake. Biosolids that are used in agriculture as fertilizers often will have PFAS in them (Venkatesan et al., 2013). This, in turn, gets into food and is transferred to humans. It is also found in food packaging which is another way that it can be ingested by humans (U.S. Food and Drug Administration, 2022). Exposure to PFAS is very dangerous as they tend to have negative health effects on people. Studies have shown PFOA and other PFAS substances to be linked to many adverse health effects. These include kidney cancer, high cholesterol, ulcerative colitis and more (Frisbee et al., 2009; Roth et al., 2022). PFAS are not only found in food, but also the items used around the house. Products used everyday such as cosmetics, laundry detergent, and water-resistant clothing all contain significant amounts of PFAS which contribute to everyday exposure. PFAS are everywhere in daily life and because of this they are also everywhere within the environment. The main ways PFAS enter the environment is through large industrial or waste treatment sites. However, they can also enter through residential sources such as septic systems (Schaider et al., 2016). The biggest problem with PFAS entering is that they are difficult to get rid of. They are often called the “forever chemicals" because due to the strength of their bonds they are resistant to breaking down (Liou et al., 2010). Most PFAS compounds when they do break down will only break down into other PFAS compounds (Zhang et al., 2022).

Objectives

The goal of this project was to investigate the transport of PFAS from household products, through domestic septic systems, and into groundwater. The main objectives were to:

1. Find viable testing locations
2. Survey homeowners for product use and septic information
3. Identify the change in PFAS concentrations between tap water and septic liquid

Methods

Objective 1:Finding Locations

First, a criteria for their location selection was established. The homes must have septic, be on town water, source water must have low or non-detectable levels of

PFAS, and be located in Central Massachusetts. Once these requirements were met, the data portal from the Massachusetts Executive Office of Energy and Environmental Affairs was used to collect the four towns Pepperell, Groton, Rutland, and West Boylston. The public water supply of these towns listed PFAS as non-detect. These towns were then researched on ArcGIS or through local sewer maps. Any neighborhood outside of the sewer map was considered viable for testing as they are on septic. Finally, the DPW was called to ensure these neighborhoods indeed had septic. After this the Massachusetts Interactive Property Map was used to collect the 233 addresses to be mailed surveys.

Objective 2: Surveying Homeowners

Two surveys were generated through the course of this project. The first survey was sent to houses to gauge if people would be willing to participate in this survey. It also asked questions about their septic systems specifications, age, and when it would be, or was last, pumped. Once this survey was completed, willing and suitable respondents were identified. These houses were then sent a follow up survey to find out what products they used in order to gather data on where potential PFAS in their system is coming from.

Objective 3: Identifying PFAS Delta

Selected Respondents then had their homes put through testing to determine data about their PFAS usage - specifically to find the change in PFAS concentrations between the house tap water and the houses septic tank effluent. This was done using EPA-1633 testing. To collect from the tap it first had to run for five minutes. Then two containers worth of samples were taken from the tap. After, they were placed in a cooler to remain cold until they were sent to be tested. To collect from the septic first the cover was excavated and removed. A bailer was then lowered into the effluent and filled with fluid. It was then lifted and emptied into a container which was also placed in a cooler.

Findings

First, willing participants in this study were found. Of the 233 surveys sent, only 10 responses were received, which was a 4.3% response rate. As can be seen in Table 1, two of the towns displayed a much higher response rate than the other towns involved.

Table 1. Response Rate by Town

Town	Surveys Mailed	Responses Received	Response Rate (%)
Rutland	56	1	1.8
Groton	73	4	5.5
West Boylston	70	5	7.1
Pepperell	34	0	0.0
Total	233	10	4.3

The low response rate observed is not unexpected but the discrepancy between towns was. The other unexpected result was a high amount, 4.3%, of return to senders due to out of date addresses.

This project also investigated the change in PFAS concentration between tap and septic. Only two data points were able to be obtained for this study so conclusions of statistical significance cannot be made. However, some observations about the data may be noted. As can be seen in Figures 1 & 2, both Site 1 and Site 2 had PFAS present in both tap and septic. An increase in certain PFAS substances from tap to septic was observed.

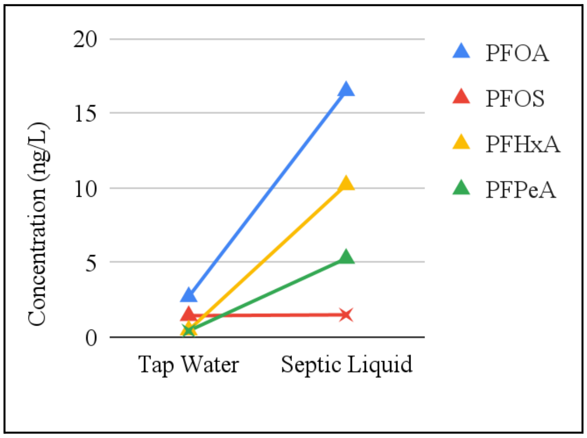

Figure 1: Site 1 PFAS Concentrations Between Septic and Tap

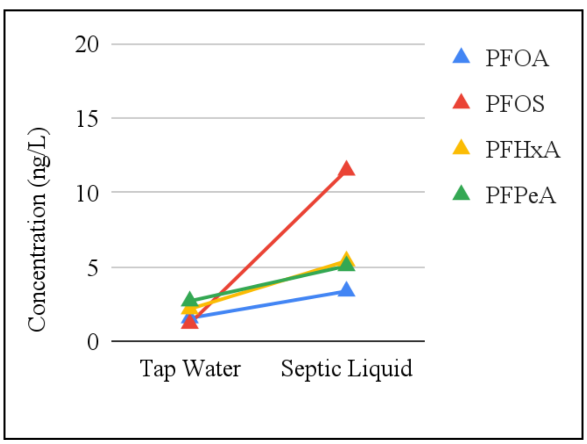

Figure 2: Site 2 PFAS Concentrations Between Septic and Tap.

Another observation to be noted in the difference in substances present in both sites. In Site 1 PFOA is the most concentrated species of PFAS, whereas in Site 2 PFOA is barely present. As well in Site 1 PFOS is hardly present but in Site 2 it has the highest concentration.

Conclusions & Recommendations

The main conclusion to be drawn from this project is that future testing needs to be done. From the little data that was acquired, it can be seen that PFAS is indeed found in septic tanks and therefore is leaching into the environment. It can also be seen that the PFAS is possibly not consistent from septic tank to septic tank.

It is recommended that a Phase II Data Collection trial be done in order to draw more significant conclusions. Phase II could use the same methodology as Phase I simply with more sites selected and tested or it could be a more robust testing methodology. It is recommended that a testing method that involves testing of both Scum and Sludge layers of the septic tank be adopted along with the tap and effluent samples. This would give more data on where the PFAS goes within the septic tank as well as allow for better analysis of the possible products contributing to the PFAS contamination.

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PE Licensure Statement

Engineers use principles of math and science to solve problems and design products, structures, and systems. The word ‘engineer’ comes from the 14th century application of ‘engine’er’ as someone who constructed military engines. The word ‘engine’ comes from Latin ‘ingenium’, which means “innate quality, especially mental power, hence a clever invention” (The Welding Institute, 2023). Engineering developed beyond military into civilian (civil) applications and branched off into fields and disciplines with specific education and training. To ensure quality of work and public welfare and safety, engineers must have a license to stamp plans. There are 3 steps towards licensure as a professional engineer: education, experience, and exams (NCEES, 2023).

Engineering education typically requires a bachelor’s degree in a program accredited by the Accreditation Board for Engineering and Technology (ABET)’s Engineering Accreditation Commission (EAC). College seniors and recent graduates then take the Fundamentals of Engineering (FE) Exam, administered by The National Council of Examiners for Engineering and Surveying (NCEES). After four years of acceptable, progressive, and verifiable work experience under the supervision of a licensed Professional Engineer, candidates are eligible to take the Professional Engineering (PE) exam. The PE license is state specific (NSPE, 2023).

Becoming a Professional Engineer provides opportunities for growth and increased responsibility within a company, which is often accompanied by higher salaries. Professional Engineers must continue to demonstrate competency and meet their state’s continuing education requirements in order to retain their license (NSPE, 2023).

Design Statement

This project fulfills the requirements of the Major Qualifying Project and capstone design at Worcester Polytechnic Institute. The purpose of this project was to investigate the potential transport of PFAS from household products into septic systems into groundwater. The report is intended as a Phase I study which may be continued and expanded upon in future years. In this project we designed: (1) two surveys to identify appropriate sampling locations, and (2) a sampling protocol for obtaining samples from septic systems for PFAS analysis. Neighborhoods were chosen to meet design criteria and homeowners were surveyed for willingness to have their septic systems sampled. Samples were collected and data was analyzed to compare the PFAS profiles in the tap water versus the septic liquid. Follow up surveys were completed to gather information on potential PFAS-containing household product usage in each home sampled. The project met capstone design requirements by considering the following factors: health and safety, lifecycle and transport of contaminants in the environment, and economics.

Health and safety drive engineering decisions. More research needs to be done on emerging contaminants like PFAS to determine long-term impacts, but the available data is concerning. This project researched exposure pathways, known locations of contamination, and health impacts. Transport and transformation of contaminants in the environment must be considered to determine where chemicals end up and how they break down (or don't break down, in the case of PFAS). An existing figure on the lifecycle of PFAS was adapted from the Michigan Department of Environment, Great Lakes, and Energy to add the hypothesized route from septic systems into groundwater. Economics are always a key factor in engineering design. A budget was drafted to estimate the cost of a Phase II expansion to collect more data.

1. Background

1.1 What are PFAS?

Per- and polyfluoroalkyl substances (PFAS) are fluorinated organic polymers, meaning that some carbons in the chain have two fluorine atoms bonded to them. The carbon-fluorine bonds are very strong, making the compounds highly stable, and they are both hydrophobic and oleophobic. For these reasons, PFAS have been used for a wide variety of applications, including firefighting foam, non-stick cookware, stain resistant clothing, and other products designed to resist oil, heat, or water. This stability also causes them to persist in the environment and bioaccumulate in fish and other wildlife.

There is some debate in the scientific community over the exact bounds of what substances count as PFAS. For this study, we define PFAS as aliphatic substances (carbon chains) containing, in at least one location in their structure, the moiety C_nF_{2n+1}- or -C_nF_{2n}-. Over 9000 individual species of PFAS have been identified (Centers for Disease Control and Prevention, 2022a). They are loosely categorized by the length of their carbon chain, with "long-chain" referring to PFAS with more than 6-8 carbon atoms, and "short-chain" referring to PFAS with less. A few PFAS which have been singled out in recent research as especially harmful or prevalent can be seen in Table 1.

A few of these compounds are particularly notable. PFOA and PFOS were the first PFAS to be widely used, making them the most prevalent and widely studied. Both are eight carbon chains and have been largely phased out of commercial products as research into their persistence and detrimental health effects expands. HFPO-DA and its ammonium salt, also known as GenX chemicals, were originally introduced in 2009 as a replacement for PFOA in the production of a variety of goods. Since then, however, research has shown that they cause many of the same detrimental effects as PFOA. GenX chemicals are among the several PFAS still being produced and distributed today.

Table 1. Common PFAS and their Properties.

Regulated by	Full Name	Common Acronym	Chemical Formula	MA PFAS 6 MCL	EPA Proposed MCL
MA & EPA	perfluorooctanoic acid	PFOA	$C_8HF_{15}O_2$	20 ppt total	4 ppt
	perfluorooctane sulfonic acid	PFOS	$C_8HF_{17}O_3S$		4 ppt
	perfluorohexane sulfonic acid	PFHxS	$C_6HF_{13}O_3S$		1.0 (unitless) Hazard Index
	perfluorononanoic acid	PFNA	$C_9HF_{17}O_2$		
MA	perfluoroheptanoic acid	PFHpA	$C_7HF_{13}O_2$		
	perfluorodecanoic	PFDA	$C_{10}HF_{19}O_2$		
EPA	Perfluorobutane sulfonic acid	PFBS	$C_4HF_9O_3S$		1.0 (unitless) Hazard Index
	Hexafluoropropylene oxide dimer acid	HFPO-DA	$C_6HF_{11}O_3$		
Neither	perfluorohexanoic acid	PFHxA	$C_6HF_{11}O_2$		
	perfluoropentanoic acid	PFPeA	$C_5HF_9O_2$		
	polytetrafluoroethylene	PTFE	$(C_2F_4)_n$		
	perfluorononanoic acid	PFNA	$C_9HF_{17}O_2$		

1.2 Exposure Pathways

Perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) are two of the earliest produced PFAS. Beginning production in the 1940s, their prevalence in consumer products has led to widespread exposure to the public (Sunderland et al., 2019; Wang et al., 2017). A 2020 study estimated that 6%-24% (8-80 million) of the U.S. population were served drinking water containing combined PFOA and PFOS levels at or above 10 ng/L (Andrews et al., 2020). However, the people most at risk for elevated exposure levels are workers in PFAS manufacturing (Sunderland et al., 2019), firefighters/military personnel who were in stations that contain older aqueous film-forming foams AFFFs or gear (Rotander et al., 2015), and those living in or around those places (Steenland et al., 2013). In Cape Cod, Massachusetts, there is evidence that organic wastewater compounds, including PFAS, may emanate from septic systems, landfill leachate, and commercial development wastewater into private, domestic wells (Schaider et al., 2016). Dermal contact to PFAS, which is thought to be low, and inhalation of indoor air and dust are other sources of exposure (Trudel et al., 2008). Inhalation of precursor chemicals that can undergo biotransformation into PFAAs needs more investigation (Sunderland et al., 2019),

Dietary intake also contributes to a considerable amount of PFAS exposure. Sewage from wastewater treatment plants is often used as fertilizer, also known as biosolids. Using data from the EPA's 2001 National Sewage Sludge Survey, of the estimated 5.1-6.4 metric tonnes of biosolids produced that year, the mean loading rate of PFAS in the solids was 2749–3450 kg/year, of which 1375–2070 kg was used for agricultural application (Venkatesan et al., 2013). As livestock eat and graze on plants grown in the soil, PFAS bioaccumulates in the livestock and may transfer to humans (Lupton et al., 2014). Several studies have indicated that PFAS can be absorbed in the roots and the leaves of vegetation (Navarro et al., 2017; Liu et al., 2019; Gu et al., 2023), which can lead to transmission to humans through fresh and frozen produce (Piva et al., 2023). Another highly common dietary pathway is through the consumption of seafood products. Studies have shown that fish and other seafood accounts for a large percentage of PFAS intake in European and Asian countries due to the uptake of water, suspended solids, and/or sediment through the gills of sea animals (Domingo et al., 2017; Young et al., 2022). One particularly concerning pathway is to newborns who are breastfed. PFAS can contaminate the breast milk with data showing the decline of PFOA and PFOS with “halving times of 8.1 and 17 years, respectively,” but an increase of “current-use short-chain” PFAS with a doubling time of 4.1 years (Zheng et al., 2021). There is also concern that PFAS is potentially contaminating formula milk as well, but there is not enough data to be conclusive (LaKind et al., 2023).

Along with diet, food packaging is also a major source of exposure. PFAS are applied to many food contact materials, such as nonstick cookware and grease-proof packaging like fast-food wrappers, popcorn bags, pet-food bags, and paperboard containers (U.S. Food and Drug Administration. 2022). Data shows that the more people consume food from these containers, the higher the concentration of PFAS in their blood serum (Susmann et al., 2019). Although there is a growing body of research on PFAS occurrence in various food products, more research is required on how much PFAS in a typical diet is absorbed by the human body.

1.3 Health Effects of PFAS

Studies have shown that PFOA is linked to many ailments including kidney and testicular cancer, renal disease, high cholesterol, lower birth weight, ulcerative colitis, and type-2 diabetes (Frisbee et al., 2009; Roth et al., 2022). In addition to PFOA and PFOS, other PFAS such as PFNA and PFHxS are particularly damaging to children as they are correlated with disruptive thyroid function/disease (Lopez-Espinosa et al., 2012), as well as reducing vaccine efficacy and immune response (von Holst et al., 2021). There is evidence that PFAS can bioaccumulate in the liver, tissue, blood and kidneys of humans and animals (Brunn et al., 2023; Pérez et al., 2013). The half-life or excretion of PFAS varies depending on the type. For example, a study of serum levels estimated the average half-life of PFOA was 2.7 years, 5.3 years for PFHxS, and 3.4 years for PFOS (Li et al., 2018)

As data continues to mount on their damaging effects on human health, companies have phased out long-chain PFAS, mainly PFOA and PFOS, in favor of novel short-chain PFAS (Brendel et al., 2018). These phase-outs have been highly successful in reducing PFOA and PFOS exposure. According to the CDC, from 1999 to 2018, blood PFOS levels declined by more than 85% and PFOA levels by more than 70% (Centers for Disease Control and Prevention, 2022b). However, there are still concerns that short-chain PFAS may also have negative effects on living organisms, especially with their rampant contamination of aquatic systems and soil due to high mobility (Cousins et al., 2020). Although short-chain PFAS are not as bioaccumulative, they do have toxic effects in the developmental health of mice (Chambers et al., 2021). Short-chain PFAS: PFBS, PFHxS, PFBA, and PFHxA can also disrupt stem cell renewal in humans, potentially leading to cyto- and developmental toxicity (Liu et al., 2020). Conversely, GenX was also shown not to be associated with developmental toxicity in zebrafish (Gaballah et al., 2020). Overall, the health effects of short-chain PFAS needs more investigation to draw more conclusive data.

1.4 Occurrence of PFAS in Household Products

PFAS have been found in a wide range of household products, as seen in Figure 1. A couple of branches (water-resistant clothing, cosmetics, fast food packaging, and pesticides) were chosen for further analysis of total fluorine concentrations and specific PFAS present.

Figure 1. Products That Contain PFAS. (Riverside, CA Public Utilities, 2020)

<u>Water-Resistant Clothing</u>

PFAS are used in outdoor apparel such as rain jackets for their waterproof properties. Bedding and tablecloths and napkins also benefit from stain-resistant properties. A 2022 study by Toxic Free Future tested outdoor apparel found PFAS in 75% (15 of 20 tested) outdoor apparel, 69% (9 of 13 tested) bedding, and 71% (10 of 14 tested) tablecloths and napkins marketed as stain- or water- repellent. Specific PFAS found in apparel include PFOA, FTOHs in 6, 8, 10, and

12 chain lengths, PFBA, PFPeA, PFHxA, PFHpA, PFBS, PFBSA, PFNA, PFDA, PFUdA, PFDoA, PFTeDA, & PFODA. Of the 47 products tested for total fluorine, 35 underwent mass spectrometry testing for specific PFAS components. 25 of these 35 contained a long chain PFAS, specifically perfluorocarboxylic acids with carbon chain lengths of eight or more and perfluoroalkane sulfonic acids with carbon chain lengths of six or more, which are banned in the European Union and supposedly phased out by major U.S. manufacturers (Schreder & Goldberg, 2022). Concentrations of total PFAS in apparel items are shown in Appendix A. The highest total fluorine concentration in items tested was the Rei Co-op Westwinds GTX Jacket, Women's, at 83,300 ppm.

Cosmetics

PFAS in cosmetics are used for properties such hydrophobicity and film-forming ability, which are thought to increase product wear, durability, and spreadability. A 2021 study published in Environmental Science and Technology analyzed 231 cosmetics for total fluorine using particle-induced gamma-ray emission (PIGE) spectroscopy. Total fluorine was split into 3 categories: low (0–0.127 µg F/cm^2), medium (0.127–0.384 µg F/cm^2), and high ((>0.384 µg F/cm^2). 32% of products tested had low levels of total fluorine, 16% were medium, and 52% were high. The cosmetic categories that had the highest percentage of high fluorine products were foundations (63%), eye products (58%), mascaras (47%), and lip products (55%).

“PFAS concentrations ranged from 22–10,500 ng/g product weight, with an average and a median of 264 and 1050 ng/g product weights, respectively. Here, 6:2 and 8:2 fluorotelomer compounds, including alcohols, methacrylates, and phosphate esters, were most commonly detected. The ingredient lists of most products tested did not disclose the presence of fluorinated compounds exposing a gap in U.S. and Canadian labeling laws" (Whitehead et al., 2021). Every day, the average woman uses 12 personal care products that contain 168 different ingredients. The average man uses six products daily with 85 unique ingredients (Amarelo, 2017). The retail value of North American personal care products was $100 billion in 2019, with $20 billion dedicated to cosmetics (Whitehead et al., 2021).

Fast Food Packaging

Fast food packaging utilizes PFAS for their grease-resistant properties. 407 samples were collected from 27 large fast food chains and 4 individual fast food restaurants in America. 33% of all samples had detectable total fluorine concentrations. Dessert and Bread Wrappers was the category with the highest proportion of samples containing fluorine, at 56%, followed by Sandwich & Burger wrappers (38%), and Paperboard (20%) (Schaider et al., 2017). Percentage of items testing positive for fluorine at each fast food restaurant are shown in Appendix B.

Pesticides

PFAS are used in pesticides as surfactants, dispersants, and anti-foaming agents. Concentrations of up to 250 ng/L PFOA & 500 ppt HFPO-DA (a GenX replacement for PFOA) were found in Anvil 10+10, a pesticide used in the aerial spraying programs of Massachusetts, parts of Florida, New York, and many other states. In 2019, Massachusetts aerially sprayed 2.2 million acres of the state with this pesticide and, in 2020, sprayed more than 200,000 acres. PFAS are not listed as an active ingredient, and the EPA has approved PFAS as an "inert" ingredient, which does not require disclosure (Bennett, 2020).

1.5 Current & Proposed Regulations

Due to the health concerns presented by PFAS, a number of regulatory bodies in the United States have proposed or implemented standards. Currently, PFAS is regulated on a state-by-state basis, and nearly half of states have established recommendations, notification levels, or Maximum Contaminant Levels (MCL)s for PFAS in drinking water. Massachusetts enforces an MCL of 20 parts per trillion (ppt) for the sum of six PFAS compounds, sometimes referred to as the PFAS6: PFOS, PFOA, PFHxS, PFNA, PFHpA, and PFDA.

On March 14th, the EPA proposed a new National Primary Drinking Water Regulation (NPDWR) that created an MCL of 4 ppt for PFOA and PFOS and a Hazard Index (HI) of 1.0 (unitless) for the total of PFHxS, PFNA, PFBS, HFPO-DA (aka GenX), and their associated salts. This is expected to be finalized by the end of 2023, and will require monitoring of PFAS levels, public notification of levels exceeding the MCL, and taking treatment steps to reduce levels exceeding the MCL (U.S. EPA, 2023a). The HI is a quantity commonly used for the monitoring of contaminants which have interacting or compounding effects, and therefore should be regulated as a collective. It is calculated by first calculating a hazard quotient for each of the four PFAS it includes. The hazard quotient is determined by dividing the measured concentration of each contaminant by its Health Based Water Concentration (HBWCs), a health reference value based on research into the effects of those species on the body. For the proposed rule, the HBWCs have been set at 9.0 ppt for PFHxS; 10.0 ppt for HFPO-DA; 10.0 ppt for PFNA; and 2000 ppt for PFBS. The resulting hazard quotients are then summed, yielding the HI. An HI of less than 1.0 indicates that there is little to no risk of adverse human health effects, while an HI of greater than 1.0 indicates that there may be a risk. (PFAS NPDWR, 2023)

1.6 Transport & Lifecycle of Contaminants

PFAS compounds most often make their way into the environment from industrial sites as these are the most common place in which materials like these are used. Due to the frequency of PFAS usagage within those sites it often causes contamination to the surrounding environment. From a 2014-15 study on PFAS detects in water sheds nationwide there was found to be a steep correlation between PFAS detects and Industrial sites within the area. Areas with one or more industrial sites had PFAS detects nearby 50% of the time while those without had detects less than 10% of the time (Xindi et al., 2016). This study's data can be used to estimate the effect each of these sites will have on surrounding areas. Table 2 below shows data from the study on how much the amount of certain PFAS compounds increase with the addition of certain sites.

Table 2. PFAS Increase For Each Additional Site In Area (Adapted from: Xindi et al. 2016)

Compound	Industrial Sites	MFTA
PFHxS	24%	20%
PFHpA	10%	10%
PFOA	81%	10%
PFOS	46%	35%

This data shows an 81% increase in detected PFOA amounts for each industrial site in the area, it also shows a 35% increase in PFOS for each military fire training area (MFTA) in the area.

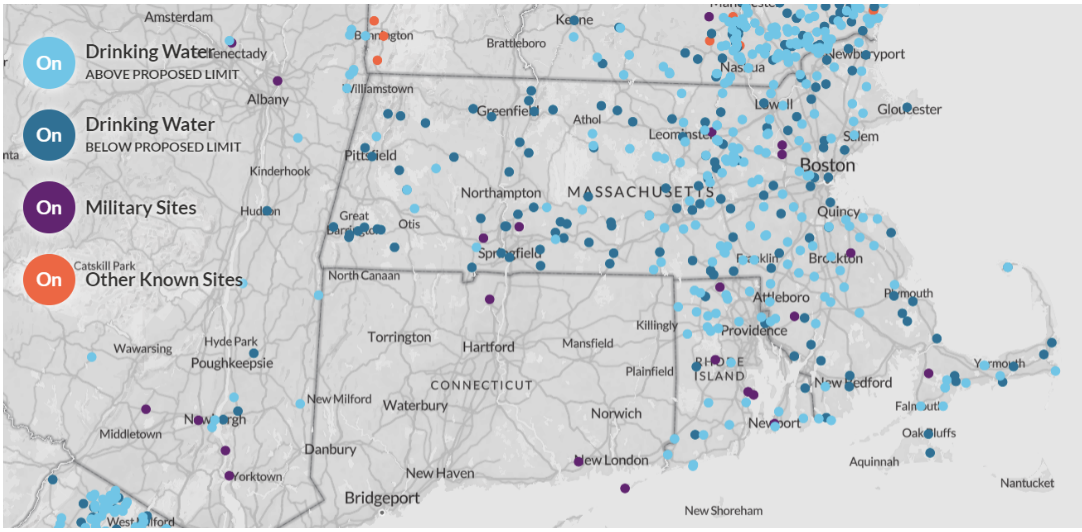

Figure 2. PFAS Contamination Map (Environmental Working Group, 2022)

The issue is prominent in all of the US, "as of June 2022, 2,858 locations in 50 states and two territories are known to be contaminated" (Environmental Working Group, 2022). As can be seen above in Figure 2 from the same study drinking water near known contaminated sites and military installations is often found above proposed limits. This also shows that in most areas of Massachuchetts, PFAS is found above limits in areas across the state, even those not directly near known industrial and military. These could be a cause of one of the many less common sources of PFAS. PFAS has a plethora of possible contamination sites.

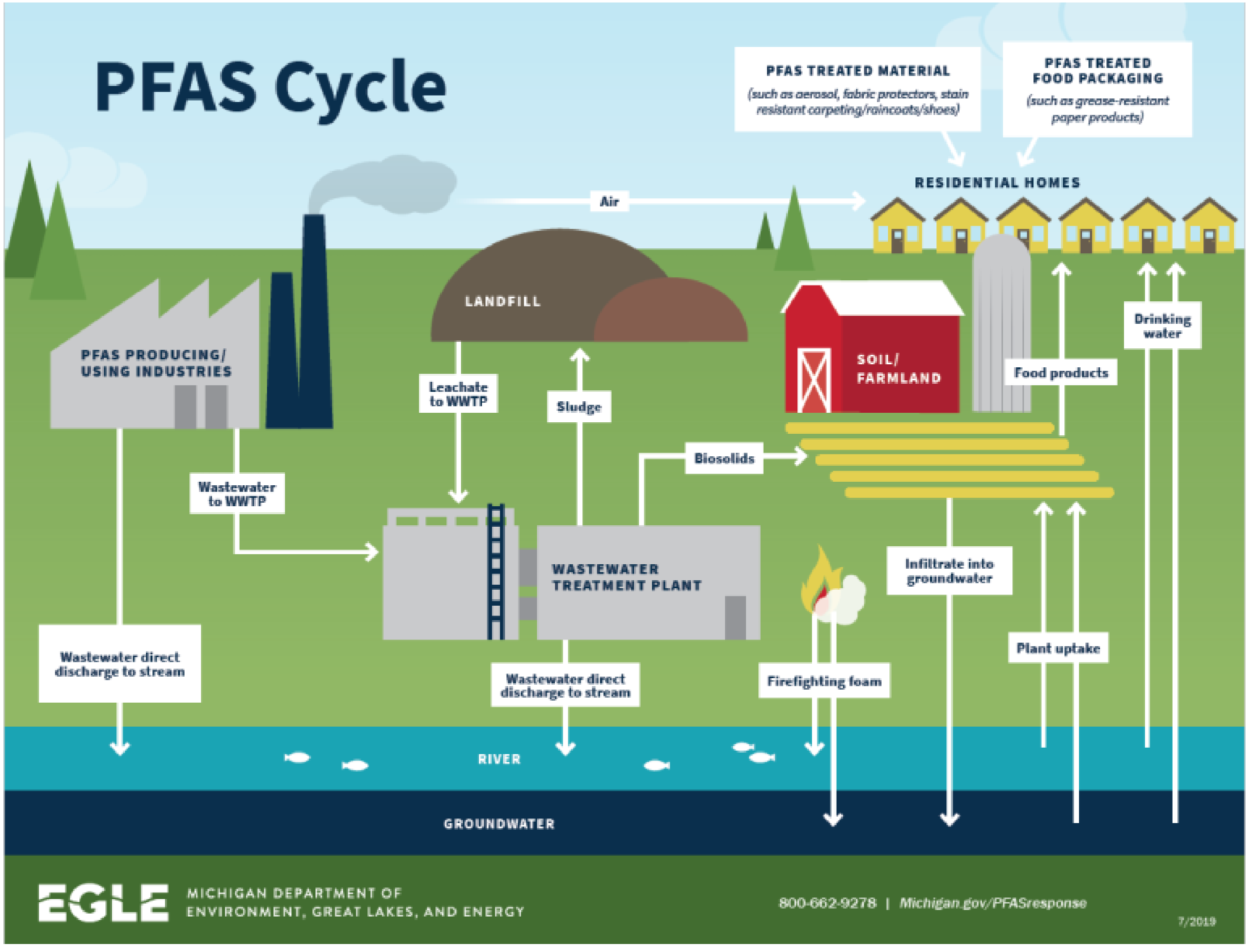

Figure 3. PFAS Cycle (Michigan Dept. of Environment, Great Lakes, and Energy, 2019)

As can be seen in Figure 3 above PFAS can come from everything from the industrial sites to produce from farms. While this figure is an accurate summation of the common PFAS sources there are still other less common sources that can be addressed.

There have been studies done on residential sources of contaminants like PFAS making their way into the environment. One of the first ever studies to prove this was in 2015, it was a study done by the Silent Springs Institute in Cape Cod Massachusetts. This study was done to find out if chemicals are able to make their way from residential septic systems into nearby wells and water systems. This was done using tracer chemicals as well as testing specifically for PFAS and other harmful chemicals. This study found that four PFAS ,PFOS, PFHxS, PFBS, and PFHx, were found present in 50% of wells, PFHpA was also found to be in 30% of the wells tested (Schaider 2016). With no nearby major contamination sites or military installations in the area the only logical source of contamination was the septic tanks being studied.

PFAS are also known as “Forever Chemicals” due to their resistance to breaking down once let into the environment. Due to their strong bonds and structure they are highly thermally and chemically resistant which is what has led to their widespread use. Studies have shown that they are strongly resistant to bio transformation, especially the two most common PFOA and PFOS (Liou et al., 2010). Even though PFAS are incredibly resistant to biodegradation it does not mean that all PFAS compounds are completely recalcitrant. In recent years extensive testing has been done on certain PFAS to find their breakdown pathways. One of these is FTOH, this specific compound has been found to break down into 5:3 acid, 6:2 FTUCA, PFHxA, 6:2 FTCA, 5:2 ketone, PFBA, PFPeA, and 5:2 sFTOH (Zhang et al., 2022). While it is promising to see that PFAS can indeed break down in the environment, the end products are almost all PFAS as well.

1.7 Testing & Treatment Options

The EPA has produced several testing methods to test for PFAS in various types of media. For example, Methods 537.1 and 533 are both used to test for potable drinking water, while Methods 8327 and 1633 is used for non potable water and other environmental media, with 1633 testing for PFAS in biosolids, landfill leachate, sediment, and fish tissue (U.S. EPA, 2023b). Each method is also designed to test for differing quantities or types of PFAS, such as 537.1 having the ability to detect 18 PFAS and 533 detecting 25 short-chain (U.S. EPA, 2023b). A variety of laboratory techniques constitute these tests such as solid phase extraction (SPE), SPE isotope dilution anion exchange, liquid chromatography (LC), tandem mass spectrometry

(MS). There are also tests for air emissions such as OTM-45, SW-846, Modified Method TO-15, while the EPA is developing more tests for ambient air and total organics (U.S. EPA, 2023b).

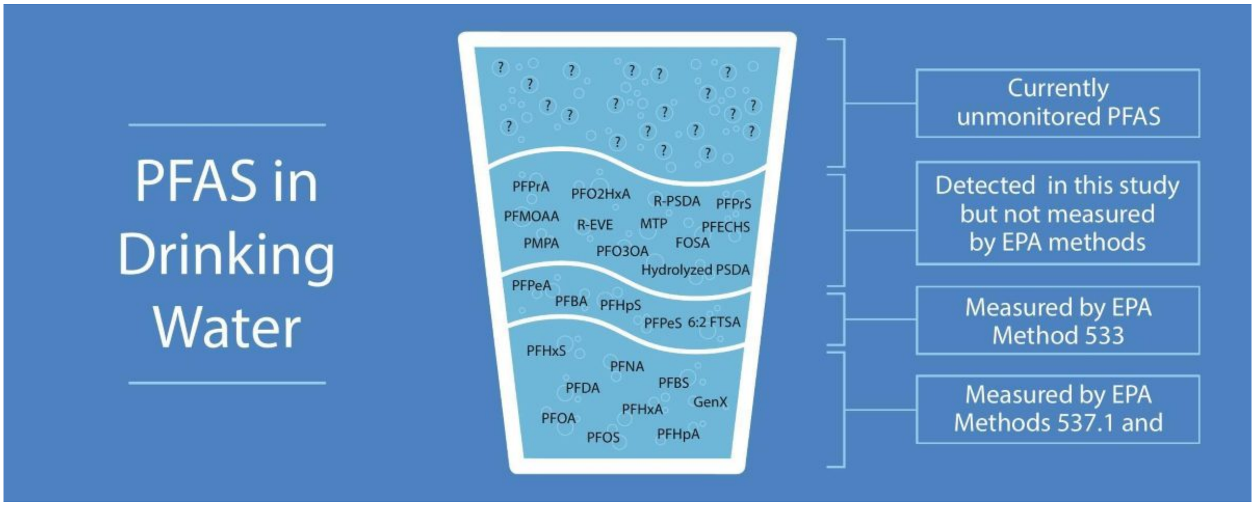

Figure 4. PFAS in Drinking Water (Pelch et al., 2023)

Figure 4 provides a visual on which PFAS are measured by which EPA methods. The study by Pelch et al. found other PFAS in drinking water by other methods and emphasizes that there are many more PFAS which are not monitored or tested for.

The EPA has listed three treatment technologies that are well known to be effective for PFAS remediation, which are granular activated carbon (GAC), ion exchange resins, and high-pressure membranes systems. According to the EPA, activated carbon is the “most studied treatment for PFAS removal” (U.S. EPA, 2022a). GAC consists of organic materials high in carbon, such as wood lignite, and coal in granular forms to adsorb substances like PFAS during the interface between solid and liquid phases. These materials are porous and have a large surface which helps with adsorption of PFAS. However, treatment is not as successful with short-chain PFAS. Anion exchange resins are made up of small beads of hydrocarbon. The positively charged resin works by attracting PFAS, which are negatively charged. This treatment can remove many types of PFAS, but is more costly than GAC (U.S. EPA, 2022a). The third treatment for PFAS is via high-pressure membrane systems. These treatments employ nanofiltration or reverse osmosis to remove PFAS. Membrane permeability affects the level of removal. The difference being that nanofiltration rejects substances with high degree of hardness, while reverse osmosis rejects all salts. Under the right conditions, GAC and ion exchange resins can remove 100% of PFAS for a period of time. Meanwhile over 90% of PFAS are removed in high-pressure membrane systems (U.S. EPA, 2022a).

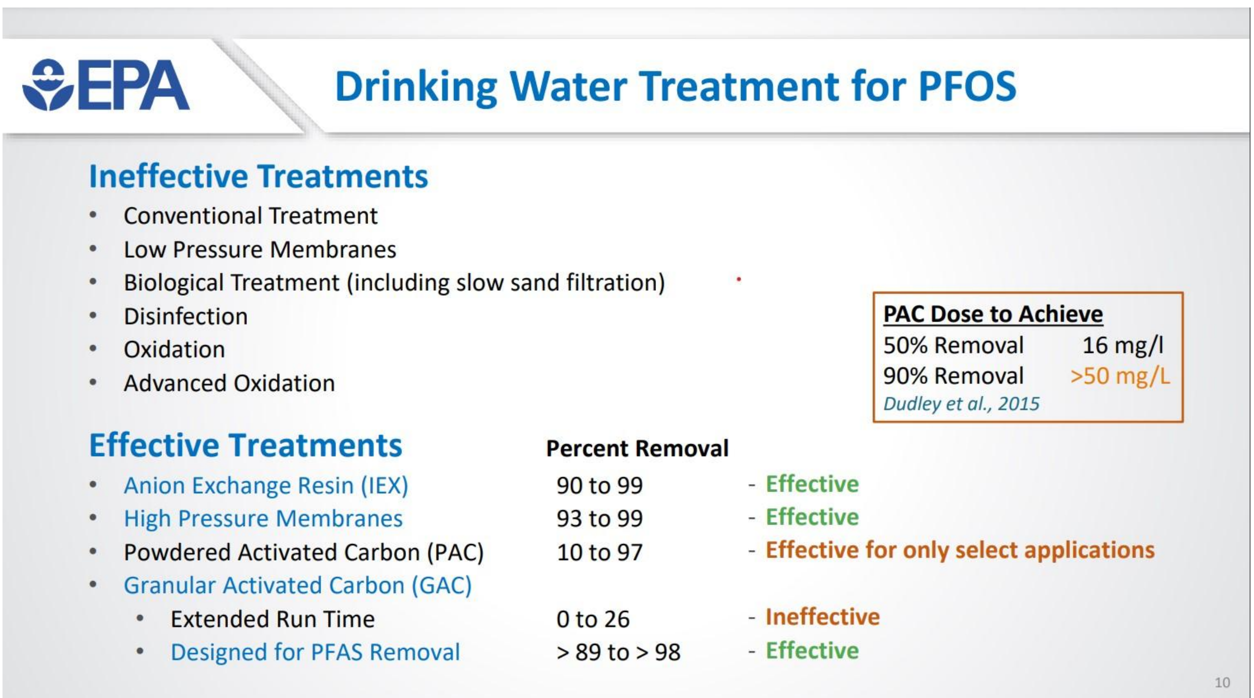

Figure 5. EPA Drinking Water Treatment for PFOS (U.S. EPA, 2022a)

1.8 Septic System Design & Regulations

Septic systems are an onsite, underground wastewater treatment technology for rural and suburban areas which are not serviced by a centralized wastewater treatment plant. More than 20% of U.S. households use septic systems instead of sewer (U.S. EPA, 2022b). Septic systems can serve a single house or a small cluster of houses or apartments. There are many benefits to using septic systems, including lower infrastructure and energy costs than a treatment plant. Septic systems also help to replenish aquifers and recharge groundwater. Some maintenance is required to keep the system working smoothly. Solids need to be pumped out of the septic tank about every 3 years, depending on size of the tank and number of people in the household.

Septic systems collect water from toilets, showers, kitchen and bathroom sinks, and clothing washing machines for treatment. A conventional septic system has a tank where solids settle and greases rise to the top. Wastewater exits the tank and is split into rows to drain into the drainfield. Gravel may be placed under the perforated drain pipes to increase treatment efficiency. Microbes in the soil naturally remove some of the nutrients, viruses, and bacteria from the effluent before it reaches groundwater. Note that the effluent of the septic system discharges downstream from the groundwater well.

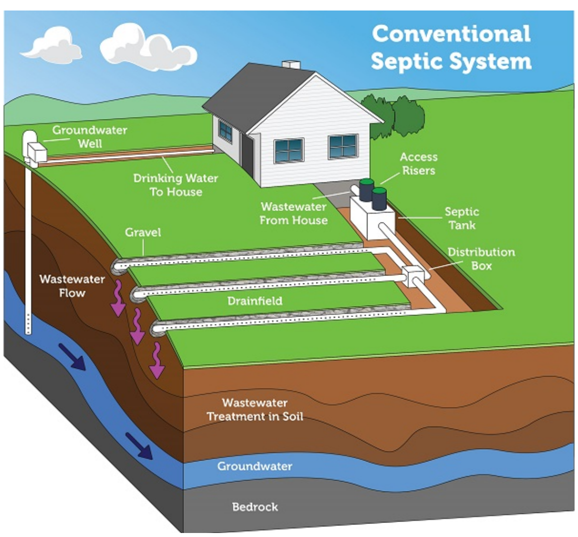

Figure 6. Conventional Septic System (U.S. EPA, 2022c)

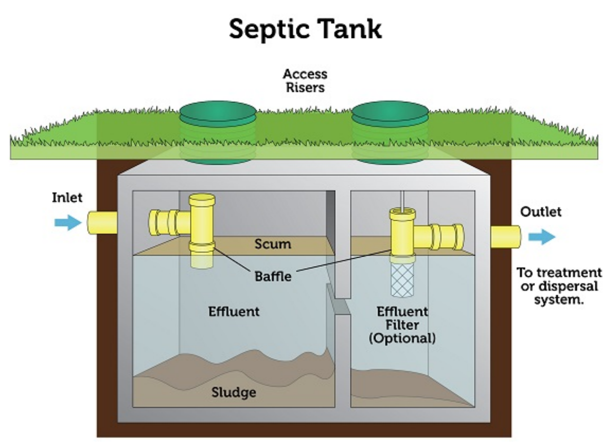

Figure 7. Septic Tank (U.S. EPA, 2022c)

Advancements in septic system technology can further remove nutrients, including nitrogen and phosphorus, in areas where nutrient pollution is of concern such as near bodies of surface water. These are called Innovative/Alternative (I/A) Systems.

Aerobic Treatment Units function similarly to a municipal sewer plant in that they pump oxygen into the septic tank to increase bacterial activity and nutrient removal. Some even have a disinfection step between the tank and the drainfield. Recirculating Sand Filters are another newer septic upgrade that pumps effluent from the tank through a sand filter before discharging to the drain field. Both of these are more expensive than conventional septic systems and require active pumping of water or air instead of simple gravity draining. Constructed Wetlands are also useful for additional nutrient and pathogen removal by plants and can be gravity fed.

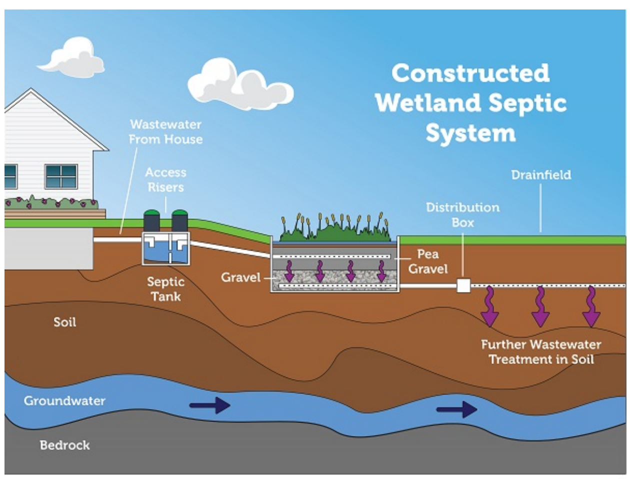

Figure 8. Constructed Wetland Septic System (US EPA, 2022c)

Cesspools, the predecessor to septic systems, date back to Ancient Rome or Babylonia and collect waste but do not treat it or distribute it to a drainage field. Title 5 is the set of laws in MA that regulate septic systems. Some MA homes still have functional cesspools. They do not need to be upgraded unless they are deemed a threat to public health or are too close to a well (Wind River Environmental, 2017).

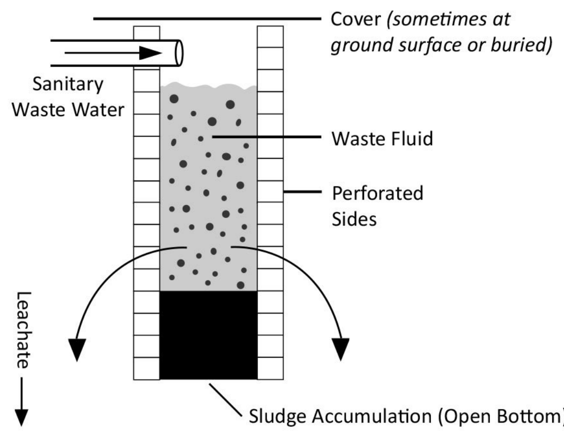

Figure 9. Cesspools. (Wind River Environmental, 2017)

Most of the septic systems in Massachusetts are conventional septic systems and have no additional nutrient removal technologies.

It is the homeowner's responsibility to maintain septic systems to meet state performance standards. Maintenance includes pumping every 3 to 5 years depending on tank size and number of people in the house. It is required that septic systems are inspected for functionality upon transfer of property, and it is recommended that routine inspections are conducted every 1-3 years. Septic systems are regulated by states. In Massachusetts, Title 5 is the set of laws governing septic systems. If a system is deemed failing, it must be repaired or replaced. Homes near public drinking water wells or in areas near nitrogen sensitive bodies of surface water might be subject to more stringent regulations (EPA, 2022c).

2. Objectives and Hypothesis

This project investigated domestic septic systems as a possible infiltration point for PFAS into groundwater (see Figure 10). Additionally, the project aims to explore which household products could be a source of PFAS. The hypothesis of this project is that residential septic systems will contain higher concentrations of PFAS than the tap water servicing the residence due to the use of PFAS-containing products in the home. Preliminary data on products used in these houses was also collected.

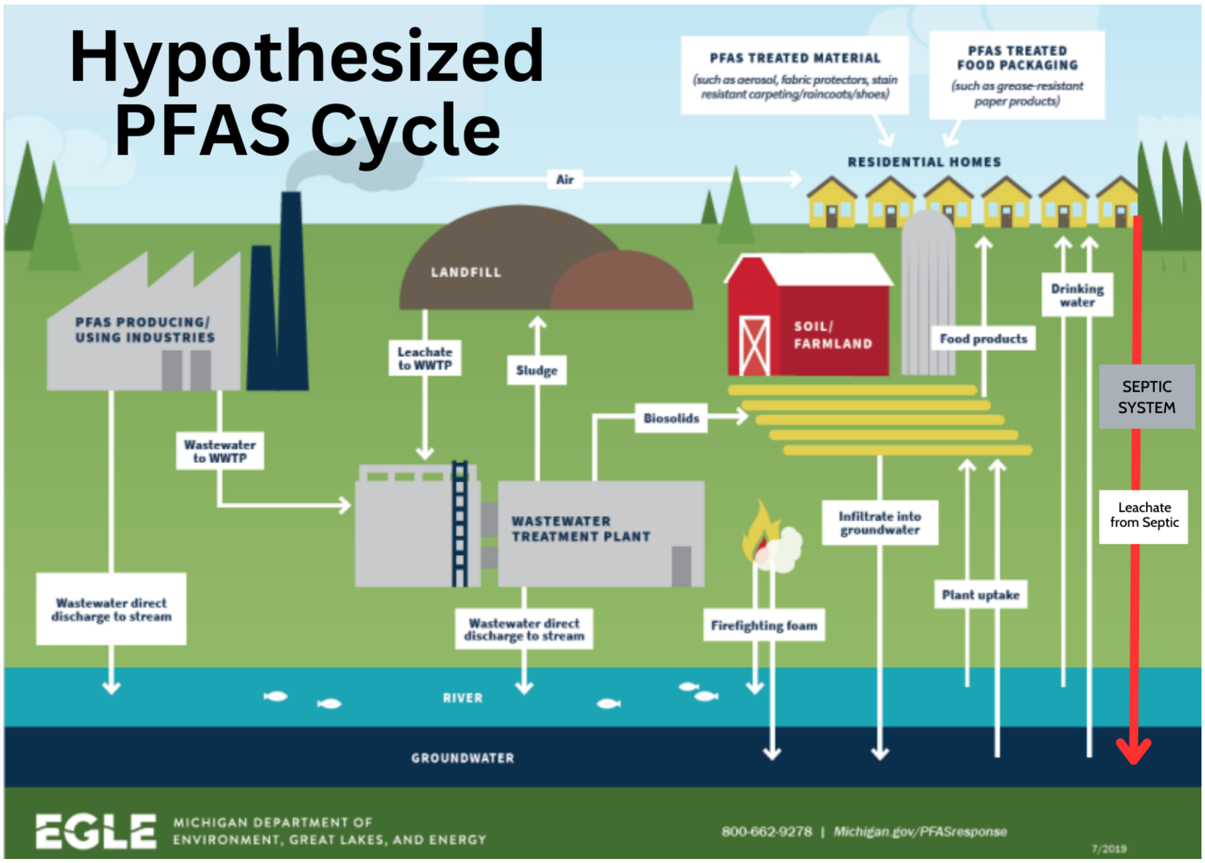

Figure 10. Hypothesized PFAS Cycle (Adapted from Michigan Dept. of Environment, Great Lakes, and Energy, 2019)

3. Methodology

3.1 Location Selection

The selection of towns and neighborhoods required extensive research into public water and sewer systems. Using the data portal from the Massachusetts Executive Office of Energy and Environmental Affairs, towns that showed non-detectable levels of PFAS contamination were identified. Areas with no detectable PFAS in the drinking water entering homes were targeted so that if PFAS are found in the septic, they are known to come from within the household. Locations with public water supply were chosen for the convenience of pre-existing incoming water data, and so that if PFAS are found in the septic, there are no concerns about them leaching into the homeowner's well. With this information and the suggestions from the Massachusetts DEP team, the towns selected were Groton, Pepperell, Rutland, and West Boylston. The other selection criteria for sites to sample from was the use of a septic system by the property. To assess this, each town was cross-referenced with sewer line district maps found online or through ArcGIS. A sewer district map of Groton is shown in Figure 11. Everywhere outside of the sewer district is on septic.

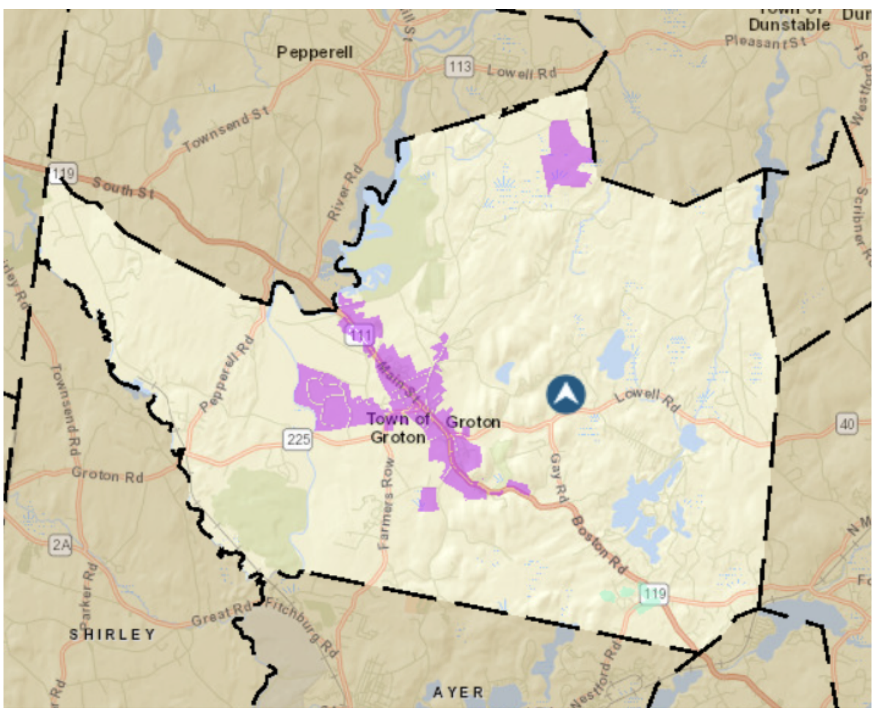

Figure 11. Sewer District Map of Groton (ARCGIS, 2022)

However, some maps were either not updated or unspecific, in which case the respective town's Department of Public Works (DPW) was contacted to confirm whether the neighborhoods were on septic. Once the homes were selected, the property owner's information was obtained through the Massachusetts Interactive Property Map and recorded for the surveys..

3.2 Survey Part 1

In the first stage of this research, homeowners received a cover letter with the project description (Appendix C) and completed a screening survey to determine the suitability of their property for further investigation (Appendix D). The screening survey asked for information about the homeowner's septic system including age, when it was last pumped, when they plan to have it pumped next, and what type of system it is. The survey also asks to confirm the address and provide contact information to stay in touch. Homeowners were asked when they plan to have their septic pumped next because, if sampling can be done during the septic pumping, the access point would already be exposed and sampling would be minimally disruptive to the homeowner's schedule and existing maintenance plans. Finally, the survey asks whether the homeowner would be interested in allowing their home to be sampled. This method was submitted to the WPI Institutional Review Board (IRB), who approved it under a Category 2 exemption. This category is reserved for studies which do not record identifying information or where the release of survey results "would not reasonably place the subjects at risk of criminal or civil liability" (Worcester Polytechnic Institute).

3.3 Survey Part 2

The second survey (Appendix E) was sent to households who participated in sampling and focused on household product usage to identify potential sources of PFAS if they are detected in the wastewater sample. Potential sources were split into several categories, and if a product was used, brand details were also requested. First the participants were asked if they used and washed moisture-wicking, stain-resistant, water-resistant, or dirt-repellent clothing, as research indicated these items have been shown to contain PFAS. In the kitchen, the survey asked about the use of non-stick cookware, certain types of food wrappers and packaging, and paper plates and bowls. In the bathroom, shower and cosmetic products were of interest. Shampoo, conditioner, shower gel, shaving cream, mascara - particularly waterproof mascara - lip gloss, etc. have all been found to contain PFAS, so the survey asked about these in particular. For the house and yard, questions about pesticides, fertilizers, insect sprays, plastic piping, floor wax, non-metal roofs, and plastic outdoor furniture were included. This survey and the research into PFAS in household products outlined in section 1.4 are anticipated to be of more use in future phases of this study, which could have a large enough sample size to link PFAS in a septic system to specific products used in that household.

3.4 Testing Procedure

Sampling Safety Protocol

A wastewater sampling requires the sampler to wear protection from these three forms of exposure: respiratory, dermal, and surface. As the students were only at the site for observation, the DEP stated that it was not necessary for them to wear any PPE other than disposable gloves and masks as long as the immediate sampling area was avoided.

If there are multiple sites to sample from, expected contamination of samples is graded from slightly contaminated to more contaminated. Slightly contaminated samples are collected first. Tap water samples - those were collected before the septic samples.

Containers for highly contaminated samples must be stored separately from other containers. Highly contaminated samples must not be placed in the same ice chest as other samples. Once the sample is collected, it will remain in the custody of the sampler and properly secured until it can be transferred for lab analysis.

As the homeowners have already exposed their access points, there will be no need for digging. Shovels and possibly backhoes require the use of safety glasses and closed toed shoes or possibly work boots and hard hats.

EPA Wastewater Sampling Operating Procedures, 2017

> "Proper safety precautions must be observed when collecting wastewater samples. Wastewater can contain microbiological disease agents (pathogens), chemical poisons (toxins), and other biological, chemical, and physical components that may cause human health problems or disturb natural aquatic ecosystems. Waterborne pathogens in the sewer collection system are different, and potentially more antibiotic resistant, than decades ago. Wastewater workers can be exposed to wastewater pathogens and toxins through several pathways:
> • respiratory exposure -face shield and masks protect from droplets and aerosols
> • dermal exposure -gloves and hand hygiene protect from direct contact
> • surface (fomite) exposure - barriers between skin and surfaces protect from wastewater and plant equipment contact"

There are three main places in which it is important to test within a septic system. The first place to test in the Scum layer of the septic tank. Scum layers in septic tanks tend to form when the majority of the oils and grease contained within the tank settle up to the top. This area is important to test as the PFAS found would be less dense and more soluble with grease and oil. There are a lot of PFAS that are known to be used for their ability to make materials grease and oil resistant. Knowing this, there maybe no PFAS present at all. If any are found, it can be certain it is not the PFAS used in these applications. However, if and at what level the PFAS are present will tell important information about if certain products are present in the house. Cosmetics and other products often contain oil and such that may be found within this layer, which could cause the PFAS used in them to also be found here.

The second layer that would require testing is the water/liquid within the septic tank. While this will not give much insight into the products used, it will be a good baseline of how many PFAS are being put into the tank from product usage within the household. It is also very important as, with water constantly leaving the septic systems via leach fields, it would likely be the biggest contributor of PFAS contamination in the local environment near the septic.

The final section of the tank that must be tested is the solids within the bottom of the tank. This will specifically reveal products consumed by the residents of the house. This area is believed to most likely have more PFAS within it than the other two layers as over time most contaminants within septic systems settle towards the bottom and would be found within the solids.

Finally, to begin the testing of a septic tank at a location, there must first be a baseline for the amount of PFAS within each testing site. This can be done by sampling from the faucet within the kitchen sick of each testing location.

Two locations were sampled from each site. To get the first sample the faucet that was being sampled was let to run for 5 minutes to ensure that any contaminants from the faucet and sink were washed out. While the faucet was running, both the sampling containers and the chain of custody were labeled to reflect when, where, and what sample was being taken. For the tap water sample, two sample containers were used. This was done as the more tests in a location the more accurate the measurements of PFAS can be. Once containers and chain of custody had been filled out, the EPA Method 1633 Sample Containers (Figure 12) were filled up to the shoulder. This sample was then placed into a cooler and kept cold until all samples had been collected from this location.

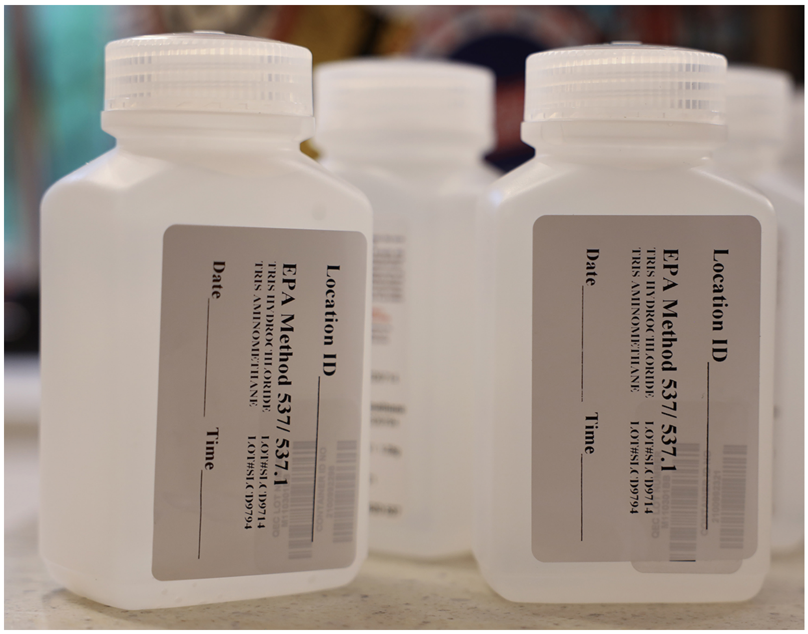

Figure 12. Sample Collection Bottles (WPI MQP Team, 2023)

This sample is taken mainly to provide a baseline PFAS level to compare the other samples too. All of the water which enters the septic tank must go through the same pipes as the water that exits the faucet. Therefore, the only additional PFAS that could be added would come exclusively from the products used in the house. This sample can also test for any contamination may be coming from the pipes within the house. Although this is an unexpected result if there is an observed jump in PFAS levels between what is tested here and what is found from EPA watershed data, pipes could be a contributing contaminate.

After this baseline sample was collected, the collection of the Septic liquid sample was next. Before collection could be completed the tank cover needed to be dug up and removed.

Students were not able to do this for liability reasons, so a qualified professional or the homeowner themselves conducted this step. Therefore, for both sampling locations, the homeowner removed the septic cover. After that was removed, the septic samples were collected. To begin the collection, each container was labeled. For the observed location, only one sample was able to be collected, and the chain of custody was filled out. The person collecting the sample then puts on all the required PPE: gloves, a respirator, and safety glasses. The bailer was then slowly lowered into the septic tank as pictured below.

Figure 13. Sample Collection Process (WPI MQP Team, 2023)

Once the bailer had been filled with septic liquid it was lifted out. The collected sample was then carefully poured into the pre-labeled container. This container was then placed in a cooler, separate from the first cooler, and kept cold. Both this and the initial coller were then sent to the lab for analysis.

4. Results and Discussion

4.1 Initial Survey Response

About 4% of surveys were returned to sender. Mass Interactive Property Mapper is a great resource, but is not entirely up to date. More people responded digitally (2.5%) than on paper (1.3%), though some people seemed to prefer paper so it is worth including the paper copies of the surveys and return envelopes. The overall response rate was about 4.3%, disregarding any return to sender addresses. The vast majority (about 92%) of people did not respond at all. This is likely due to busy lives or hesitance to let people onto their property and to share personal information for privacy concerns.

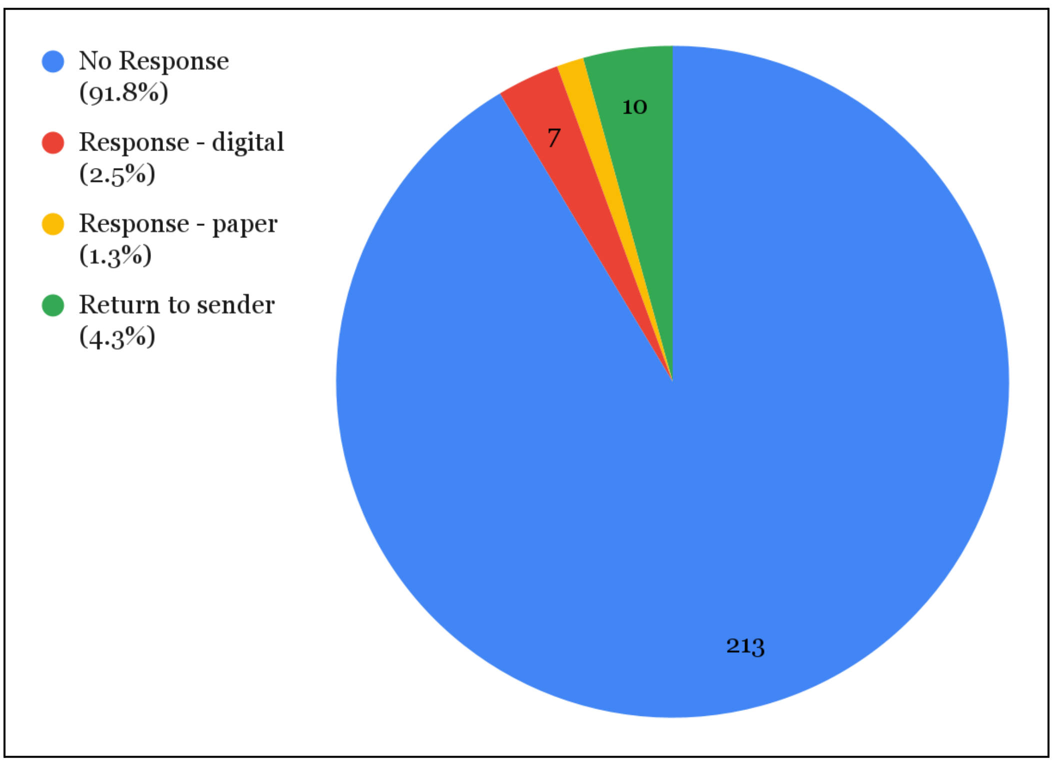

Figure 14: Survey Responses

Response rate varied significantly by town as seen in Table 3. West Boylston had the highest response rate, about 7%, followed by Groton (5.5%), Rutland (1.8%). No responses were received from Pepperell. Town demographic data could be speculated to correspond to likeliness of response if more towns are chosen for future surveying, but it is unclear what factors would apply. Educational information would be interesting to collect to see if people were more willing to participate in educational research surveys if they themselves had gone to college.

Table 3. Response Rate by Town

Town	Surveys Mailed	Responses Received	Response Rate (%)
Rutland	56	1	1.8
Groton	73	4	5.5
West Boylston	70	5	7.1
Pepperell	34	0	0.0
Total	233	10	4.3

4.2 Data and Analysis

At both sites, at least half of the samples with positive results were qualified as J (estimated, result is between RL and MDL) and/or F (estimated maximum concentration), as can be seen in Tables 4 and 5. For the septic samples, the lab results noted that the MDLs for those results were high due to low provided sample volume. In this analysis, all data will be examined regardless of qualifier. However, it should be noted that much of the data is estimated, and therefore quantitative conclusions will not be drawn. In addition, because the sample size in this study is two, the data gathered are not statistically significant and will be examined as a case study only. Due to the high MDLs in the septic samples as compared to the tap samples, the ND concentration will be assumed to be 0.5(MDL) in cases where one sampling location showed a detectable concentration but the other did not.

Table 4. Results of PFAS Sampling at Site 1.

	Site 1 Kitchen Tap				Site 1 Septic Liquid			
Acronym	Result (ng/L)	Qualifier	RL	MDL	Result (ng/L)	Qualifier	RL	MDL
PFOA	2.71		1.6	0.694	16.5		6.58	2.86
PFOS	1.44	J	1.6	0.726	ND		6.58	3.00
PFHpA	0.399	J	1.6	0.319	2.3	J	6.58	1.32
PFBS	2	-	1.6	0.535	3.29	J	6.58	2.20
PFPeA	ND	-	3.19	0.854	5.27	J	13.2	3.52
PFHxA	0.479	JF	1.6	0.471	10.2	-	6.58	1.94
PFHxS	0.718	J	1.6	0.383	ND	-	6.58	1.58
Total	7.746	-	-	-	37.56	-	-	-

Table 5. Results of PFAS Sampling at Site 2.

	Site 2 Kitchen Tap				Site 2 Septic Liquid			
Acronym	Result (ng/L)	Qualifier	RL	MDL	Result (ng/L)	Qualifier	RL	MDL
PFOA	1.58	-	1.51	0.657	3.38	J	6.77	2.94
PFOS	1.21	J	1.51	0.687	11.5	F	6.77	3.08
PFHpA	0.982	J	1.51	0.302	1.69	J	6.77	1.35
PFBS	0.755	J	1.51	0.506	ND	-	6.77	2.27
PFPeA	2.72	J	3.02	0.808	5.08	J	13.5	3.62
PFHxA	2.19	-	1.51	0.445	5.41	JF	6.77	2.00
PFHxS	0.528	J	1.51	0.362	ND	-	6.77	1.62
Total	9.965	-	-	-	29.01	-	-	-

For all PFAS compounds with a detectable amount in both the tap water and the septic liquid at the same site, the concentration was greater in the septic liquid than the tap water as shown in Figures 15 and 16. Two compounds from each site showed a detectable amount in the tap water but a non-detectable amount in the septic liquid. However, in these cases, the tap water concentration was lower than the MDL of the septic sample, so it is possible that there was a similar level of PFAS present in the septic liquid that could not be detected. This indicates that one or multiple products or other sources within the home have PFAS that have been released into the septic system.

While both sites showed more total PFAS contamination in the septic system liquid than the tap water, different PFAS were the primary causes of that at the different sites. The highest contributor at Site 1 was PFOA, at 16.5 ng/L, while Site 2 showed only an estimated 3.38 ng/L. Conversely, Site 1 did not show a detectable amount of PFOS (MDL was 3.00 ng/L, as compared to an estimated result of 1.44 ng/L in the tap water), while PFOS was the largest contributor in Site 2, at an estimated maximum of 11.5 ng/L. The second and third most concentrated PFAS were the same at both sites, being PFHxA and PFPeA respectively. This indicates that while there is evidence that PFAS contamination in a home septic system is at times higher than in the tap water entering that home, the PFAS compound(s) predominantly causing that increase will vary between homes.

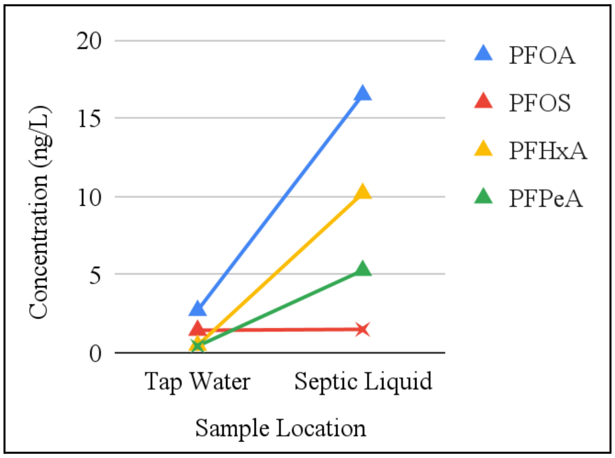

Figure 15: Site 1 PFAS Concentrations Between Septic and Tap. Values where ND=0.5(MDL) is assumed have been marked with x symbols. PFOA and PFHxA showed concentrations higher than 10 ng/L in the septic samples - an increase of 13.79 ng/L and 9.72 ng/L respectively.

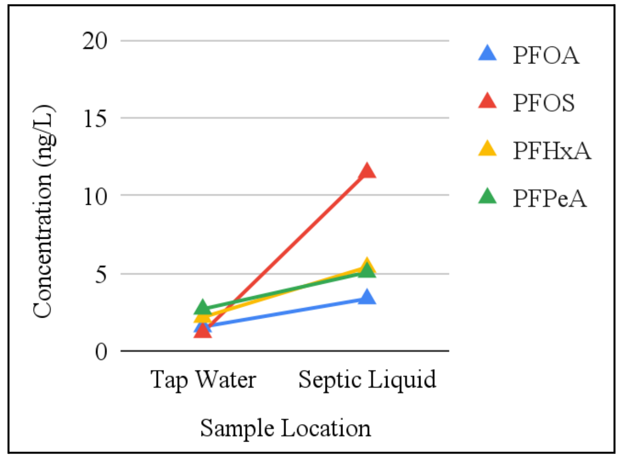

Figure 16: Site 2 PFAS Concentrations Between Septic and Tap. Values where ND=0.5(MDL) is assumed have been marked with x symbols. PFOS had the largest increase from tap water to drinking water at 10.29 ng/L.

Assuming 70 gallons / person / day, average household size of 2.5 people (U.S. EPA, 2002), and ½ MDL, a septic system could leach about 1.0 g of PFAS into groundwater from just the liquid. The calculations for mass of PFAS in grams over a 30 year lifetime of a septic system are shown in Appendix G. More PFAS could be stored in the solids, which end up pumped out and transported for treatment elsewhere.

4.3 Follow-up Survey Response

Both homeowners involved in Phase I completed the follow-up survey included in Appendix E, and their responses are included in Appendix H. Both homeowners reported using products in their home that have been shown to contain PFAS. A summary of their responses can be seen in Table 6. Of the products listed, Site 1 used more types of products than Site 2. While Site 1 also contained more total PFAS than Site 2, the sample size is not large enough to imply causation. Additionally, only the questions regarding disposable dishware and seafood intake asked about frequency of usage, which would impact flow rate into the septic system if those products contain PFAS. Still, it is possible that these products contributed to the increased PFAS concentration measured in the septic liquid.

Table 6: Summary of Responses to Follow-up Survey. ‘Yes’ and ‘No’ responses have been represented as green and red respectively, while questions in which the respondents answered on a scale or selected from a list of products have been represented as a scale from green to red, where green is ‘always’ or all products in the list and red is ‘never’ or no products on the list.

	Specialized clothing	Non-stick cookware	Disposable dishware	Seafood	Bathing products	Cosmetics	Yard products	Other
Site 1								
Site 2								

5. Recommendations

5.1 Ideal Testing Methodology

During testing there was only the ability to collect three containers, across two different sample locations; this however is not the ideal way to test in this study. If these tests were to be repeated, testing 3-4 locations with two sample bottles each would be the optimal testing method. When testing a septic tank the best way to fully understand what is being brought into it is to test the three main internal layers, the scum, sludge, and effluent, as well as getting a baseline from the house tap. These will give everything needed to fully analyze how much PFAS is being brought into the tank. Testing just the effluent is insufficient because there are quite a few products and PFAS sources that would likely be found in the solid layer. The reasoning for duplicate testing in each location is to ensure accurate results. As can be seen within Appendix F, the MDL of the analysis done on the tap water is much lower than that done on the septic samples. This discrepancy in MDL was because of having more sample volume from the tap than the septic.

In an expanded sampling plan, the tap water and septic effluent samples will be collected in the same way as they were within the original methodology. The first difference will come with the collection of the scum samples. The scum sampling will be done before the effluent sample is taken. First, labels on both sample containers and chain of custody should be filled out. The scum will then be removed from the tank via a stainless steel scoop or spoon. This spoon will be used to scrape the scum off the wall of the tank or to collect scum floated on the effluent if a wall cannot be reached. When collected the scum will be placed in a cooler separate from that of the tap water but can be the same as the effluent container.

Once both the scum and the effluent have been collected a sample can be taken from the sludge. Once again, the containers and chain of custody will be filled out prior to sampling. To begin taking a sludge sample first there must be a hole or opening created in the scum layer. This can either be done when the scum is collected or can be done using a stainless steel spoon right before sludge is collected. This will prevent scum samples from becoming mixed with the sludge sample. Once an opening has been made a core sampling device will then be lowered and pressed down into the sludge. It will then be brought back up out of the tank and the device will contain sludge and effluent. The effluent within the core sampling device can then be removed and returned to the tank and the solid sludge sample will be placed in its container and cooler before being shipped off for testing. Both the sludge and the scum samples taken from the septic tank can be analyzed using the EPA-1633 method as it is made for both solid and liquid samples.

After doing these additional tests there will be many ways to analyze data that were not available given the original methods. The most prominent of these is the ability to trace certain PFAS compounds and sources to certain layers. If trends can be found between product usage and PFAS existence in certain layers then contamination can be more easily addressed. It would also provide the ability to estimate where and what PFAS can be found in a septic tank by looking only at the products used in a house given enough data and strong trends. Checking the scum and sludge would also give us much more insight on how PFAS accumulates within a septic tank. With the Phase I testing methods, there is no way to know if all PFAS exiting the house through septic are being accounted for, or how much of the PFAS entering the septic system exits into the groundwater rather than being pumped out with the solids. Accumulation of PFAS over time within the other layers could also leach back into the effluent, leading to higher concentrations there. This would then cause more and more PFAS to be discharged into the local ecosystem via the leach field the longer between pumps of the septic.

This new testing method will give a much stronger ability to draw connections between the products and the contamination and more information on how the septic tank could affect the environment. However, this testing method would be much more expensive as it requires double the samples originally analyzed in Phase I.

5.2 Phase II Project Continuation

With this project moving on to a possible Phase II, more funding will need to be secured so that wider-scale testing can be accomplished and statistically significant results can be obtained. The two large costs that this project incurred were printing and mailing surveys and testing of samples. For this project 233 surveys were mailed out with a response rate of approximately 4%. Each survey cost $1.20 to mail and around the same to print, costing a total of $559.20. Two samples each from two sites were tested, with each sample costing $450 to analyze at the lab, totalling $1800. These, plus the cost of printing of surveys, means the total Phase I project cost was approximately $2,400.

A future trial should sample more houses in order to get statistically significant data. As there is only a small amount of data so far it is unknown how much would be needed to reach statistical significance. 10-20 homes are recommended as a starting point. With the response rate observed in this pilot, 250-500 initial surveys would need to be mailed to homeowners to get enough willing candidates. Given that 10 willing participants have already been gathered, no additional mail would be required for a 10 house Phase II. However, if additional participants were required and surveys were sent, this would cost approximately $300 for every additional 5 participants gained.

For sampling cost estimation there are two options. The first option would be to stick with the sampling method that was used in Phase I, but have a larger sample volume for both tap and septic to avoid the low MDLs that Phase I saw. This would mean each of the 10-20 locations would need 2 samples. Using 10 locations, that would cost $9,000. However, a more robust plan to sample more locations within the septic system was made in order to do a deeper analysis. This testing method would require 4 samples per location. Using the estimated 10 locations it would cost $18,000. Using these calculations a full scale trial would involve around between $10-20,000 of funding depending on changes in testing methodology.

Phase II of this project could also benefit from taking steps to anticipate the bureaucratic and logistical obstacles that were encountered this year. Obtaining an access agreement with the homeowners interested in having their system sampled will be a months-long process, and it should therefore be started at the very beginning of the school year. Once that process is complete, it will also take a few weeks to a month to work with the homeowners and samplers to set a date to take the samples. Additional difficulties faced during this time will depend on whether samples are being taken during regular pumping, which would remove the need to locate and remove the access cover but add another layer of scheduling difficulty and potentially the need for a liability waiver with the septic company, or at a separate time, which would require the sample takers to uncover the access point themselves. After the samples are obtained and sent to the lab, they will take roughly 3-6 weeks to get results, which the team should budget into their overall timeline. Overall, the project team that takes up this project next year should consider beginning this process as soon as possible, and once it is moving along, then dive into background research and other early-MQP tasks.

5.3 How to Reduce PFAS in Groundwater

It is not practical to treat every household's septic system to remove PFAS before effluent is discharged into groundwater. The hierarchy of engineering controls says that the first and simplest step before treatment is prevention. In order to prevent or reduce PFAS going into septic systems, there are a couple of possible routes. Governmental regulations banning PFAS in products are emerging and could eliminate the problem. In the meantime, consumers can do research and make informed decisions about which products they use contain PFAS. However, that would require a lot of public education and effort while shopping. Unfortunately, products that have been tested and brands that commit to not using PFAS tend to run on the expensive side, and to the average homeowner buying household products, the priority is price and not contents. Limited information on labels and the fact that manufacturers are not required to list PFAS as ingredients makes shopping to avoid them difficult.

6. Conclusions

PFAS are highly concerning substances that are ubiquitous in various consumer products. Therefore, the EPA has introduced new, stricter regulations of the compounds because of their damaging effects on human health and groundwater sources. This study has indicated a possible source of groundwater PFAS contamination is via leaching of septic systems, which may be transferred from household items. The data collected demonstrate that some species of PFAS in septic samples exceed the levels of tap water in the homes. However, due to the limited number of samples, it is not possible to assume that this is the case with every household. A future Phase II study, drawing from the pool of pre-screened homeowners who have approved sampling, will be able to draw more conclusive data using a wider scope of testing. The data gathered in this project indicate that further research is warranted into the transportation pathway of PFAS from household products into septic systems, and from there into groundwater.

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Appendices

Appendix A. Total Fluorine in Outdoor Apparel

(Adapted from Schreder & Goldberg, 2022)

Item	Total Fluorine
Alpine Design Men's Altitude 2.0 2L Rain Jacket	424 ppm
Canis Cute Kids Girls' New Flowers Hooded Raincoat	11 ppm
Columbia Rainy Trails Fleece Lined Jacket, Girls'	760 ppm
Dakine Women's Noella Tech Flannel Button Down Shirt	288 ppm
DSG Girls' Insulated Jacket	330 ppm
DSG Boy's Rain Jacket	743 ppm
DSG Men's Wind Jacket	<10 ppm
Lelinta Men's Casual Trousers	441 ppm
Mammut Kento HS Hooded Jacket, Men's	61 ppm
The North Face Women's Resolve 2 Rain Jacket	13 ppm
Patagonia Torrentshell Jacket, Women's	956 ppm
REI Co-op Drypoint GTX Jacket, Men's	82,000 ppm
Rei Co-op Westwinds GTX Jacket, Women's	83,300 ppm
REI Rainwall Jacket, Kids	1486 ppm
REI Co-op Sahara Convertible Pant, Women's	<9 ppm
REI Co-op Savanna Trails Pant, Men's	698 ppm
Rothco Tactical Duty Pants	1337 ppm
5.11 Tactical Women's Stain Resistant Shirt	1832 ppm
Under Armour Women's Woven Anorak Jacket	6465 ppm

Appendix B. Fast Food Restaurant Packaging with Fluorine

(Adapted from Schaider et al., 2017)

Restaurant	Food contact paper items tested	Percent of items testing positive for fluorine
Arby's	16	19%
Burger King	37	27%
Carl's Jr.	5	0%
Checkers	2	0%
Chick-fil-A	5	80%
Chipotle	17	65%
Church's Chicken	2	50%
Culver's	2	0%
Dairy Queen	5	20%
Domino's	2	0%
Dunkin Donuts	12	33%
Five Guys	1	0%
Jack in the Box	7	14%
Jimmy John's	9	100%
KFC	20	25%
Krispy Kreme	4	50%
Local restaurants	7	43%
McDonald's	31	19%
Panera	23	43%
Pizza Hut	3	33%
Quiznos	9	100%
Round Table Pizza	1	0%
Starbucks	21	76%

Steak ‘n Shake	3	67%
Subway	19	42%
Taco Bell	28	43%
Taco Time	5	100%
Wendy’s	31	23%
Total	327	40%

Appendix C. Cover Letter

Dear Homeowner,

We are a group of students from Worcester Polytechnic Institute (WPI) working with the Massachusetts Department of Environmental Protection on a project investigating the potential presence and sources of PFAS chemicals in groundwater.

PFAS (per- and polyfluoroalkyl substances) are a category of chemicals used for their stain-resistant, water-resistant, and non-stick properties. PFAS are water-soluble and travel readily through the environment. They do not degrade naturally in the environment. High levels of PFAS exposure may have adverse health effects. Your town is on a public water system which has been tested for PFAS and found to be under the EPA's acceptable limit.

Previous studies have shown that chemicals originating from domestic septic systems can leach into groundwater. We are looking to determine whether PFAS are present in septic systems, likely coming from consumer products such as laundry detergents, shampoos, non-stick cookware coatings, etc. We are conducting a survey of homeowners in order to help our research.

If you are interested in participating in this project, please scan the QR code below to complete the survey digitally, or fill out the attached paper survey and mail it back using the enclosed envelope.

Disclaimer: this survey is completely voluntary and identifying information will not be released.

Thank you for your time,

WPI Residential PFAS team and Massachusetts DEP

Appendix D. Screening Survey

Survey Questions

1. What is the address of your property?

2. How old is your septic system?
    - 0-4 years
    - 5-9 years
    - 10-14 years
    - 15-29 years
    - 20-29 years
    - 30+ years
    - Unsure/I don't know
    - Other:
3. When was your system last pumped? (Month,Year)

4. When are you planning to have your septic system pumped next? (Month, Year)

5. Would you be interested in allowing the team to take samples from your septic system, either while it is being pumped or at a separate date?
    - Yes
    - No
    - Maybe
    - Other:
6. What type of septic system do you have, if you know?

7. What is your email or phone number, so that we can contact you with more information?

Link to Actual Survey: https://forms.gle/rfrKKxDnkWkwcsz6A

Appendix E. Follow-up Survey

1. Do you own and wash clothing characterized as moisture-wicking, stain-resistant, water-resistant, or dirt-repellent?
    - Yes
    - No
    - Unsure
2. If yes, which articles of clothing?
    - Leggings/yoga pants
    - Rain jackets
    - Sportswear advertised as "moisture-wicking"
    - Winter coats or down jackets
3. If yes, which brands?
4. Do you use non-stick cookware?
    - Yes
    - No
5. If yes, which brands?
6. Have you purchased food or liquids packaged in any of the following items in the past? (Select all that apply)
    - Sandwich/burger wrappers
    - Paper bags/sleeves
    - Paperboard/cardboard box
    - Pet food bags
    - Plastic bottles
7. How often do you use paper plates, cups, or bowls for dining?
    - Very Often (daily)
    - Sometimes (a few times a week)
    - Rarely (a few times a month)
    - Never
8. Do you eat seafood?
    - Very Often (daily)
    - Sometimes (a few times a week)
    - Rarely (a few times a month)
    - Never
9. Do you use any of the following bathing products?
    - Shampoo
    - Conditioner
    - Shower gels
    - Bar soaps
    - Shaving cream /gel
10. If yes, which brand(s) do you commonly use?
11. Do you use any of the following cosmetic products? (Select all that apply)*
    - Mascara
    - Lip Stick/Gloss
    - Foundation
    - Cleanser
    - Moisturizer

- Shaving Creams

12. If yes, which brand(s) do you commonly use?
    - MAC
    - e.l.f.
    - Maybelline
    - Other:
13. Do you use any of the following?*
    - Fertilizer
    - Pesticide
    - Insect Spraying Service
    - Herbicide/ Weed killer
14. If yes, which brand(s) do you commonly use?
    - Scotts
    - Miracle Grow
    - Safer
    - Ortho
    - Spectracide
    - Round Up
    - Other:
15. Do you have any of the following?*
    - Plastic piping in house
    - Plastic Outdoor Furniture
    - Non-metal Roof
    - Floor Wax

Appendix F. Sampling Results Raw Data

Site 1:

	Kitchen Tap					Septic Liquid				
Parameter	Result (ng/l)	Qualifier	RL	MDL	Dilution Factor	Result (ng/l)	Qualifier	RL	MDL	Dilution Factor
Perfluorobutanoic Acid (PFBA)	ND		6.38	1.02	1	ND		26.3	4.21	1
Perfluoropentanoic Acid (PFPeA)	ND		3.19	0.854	1	5.27	J	13.2	3.52	1
Perfluorobutanesulfonic Acid (PFBS)	2		1.6	0.535	1	3.29	J	6.58	2.20	1
1H,1H,2H,2H-Perfluorohexanesulfonic Acid (4:2FTS)	ND		6.38	1.67	1	ND		26.3	6.88	1
Perfluorohexanoic Acid (PFHxA)	0.479	JF	1.6	0.471	1	10.2		6.58	1.94	1
Perfluoropentanesulfonic Acid (PFPeS)	ND		1.6	0.279	1	ND		6.58	1.15	1
Perfluoroheptanoic Acid (PFHpA)	0.399	J	1.6	0.319	1	2.3	J	6.58	1.32	1
Perfluorohexanesulfonic Acid (PFHxS)	0.718	J	1.6	0.383	1	ND		6.58	1.58	1
Perfluorooctanoic Acid (PFOA)	2.71		1.6	0.694	1	16.5		6.58	2.86	1
1H,1H,2H,2H-Perfluorooctanesulfonic Acid (6:2FTS)	ND		6.38	2.15	1	ND		26.3	8.89	1
Perfluoroheptanesulfonic Acid (PFHpS)	ND		1.6	0.431	1	ND		6.58	1.78	1
Perfluorononanoic Acid (PFNA)	ND		1.6	0.503	1	ND		6.58	2.07	1
Perfluorooctanesulfonic Acid (PFOS)	1.44	J	1.6	0.726	1	ND		6.58	3.00	1
Perfluorodecanoic Acid (PFDA)	ND		1.6	0.646	1	ND		6.58	2.67	1
1H,1H,2H,2H-Perfluorodecanesulfonic Acid (8:2FTS)	ND		6.38	2.48	1	ND		26.3	10.20	1
Perfluorononanesulfonic Acid (PFNS)	ND		1.6	0.495	1	ND		6.58	2.04	1
N-Methyl Perfluorooctanesulfonamidoacetic Acid (NMeFOSAA)	ND		1.6	0.870	1	ND		6.58	3.59	1
Perfluoroundecanoic Acid (PFUnA)	ND		1.6	0.694	1	ND		6.58	2.86	1
Perfluorodecanesulfonic Acid (PFDS)	ND		1.6	0.367	1	ND		6.58	1.51	1
Perfluorooctanesulfonamide (PFOSA)	ND		1.6	0.431	1	ND		6.58	1.78	1
N-Ethyl Perfluorooctanesulfonamidoacetic Acid (NEtFOSAA)	ND		1.6	0.862	1	ND		6.58	3.56	1
Perfluorododecanoic Acid (PFDoA)	ND		1.6	0.734	1	ND		6.58	3.03	1
Perfluorotridecanoic Acid (PFTrDA)	ND		1.6	0.598	1	ND		6.58	2.47	1

Perfluorotetradecanoic Acid (PFTeDA)	ND		1.6	0.423	1	ND		6.58	1.74	1
Hexafluoropropylene Oxide Dimer Acid (HFPO-DA)	ND		6.38	0.894	1	ND		26.3	3.69	1
4,8-Dioxa-3h-Perfluorononanoic Acid (ADONA)	ND		6.38	1.00	1	ND		26.3	4.15	1
Perfluorododecanesulfonic Acid (PFDoS)	ND		1.6	0.606	1	ND		6.58	2.50	1
9-Chlorohexadecafluoro-3-Oxanone-1-Sulfonic Acid (9Cl-PF3ONS)	ND		6.38	1.32	1	ND		26.3	5.43	1
11-Chloroeicosafluoro-3-Oxaundecane-1-Sulfonic Acid (11Cl-PF3OUdS)	ND		6.38	1.32	1	ND		26.3	5.43	1
N-Methyl Perfluorooctane Sulfonamide (NMeFOSA)	ND		1.6	0.694	1	ND		6.58	2.86	1
N-Ethyl Perfluorooctane Sulfonamide (NEtFOSA)	ND		1.6	0.734	1	ND		6.58	3.03	1
N-Methyl Perfluorooctanesulfonamido Ethanol (NMeFOSE)	ND		16	3.75	1	ND		65.8	15.50	1
N-Ethyl Perfluorooctanesulfonamido Ethanol (NEtFOSE)	ND		16	1.96	1	ND		65.8	8.07	1
Perfluoro-3-Methoxypropanoic Acid (PFMPA)	ND		3.19	0.455	1	ND		13.2	1.88	1
Perfluoro-4-Methoxybutanoic Acid (PFMBA)	ND		3.19	0.423	1	ND		13.2	1.74	1
Perfluoro(2-Ethoxyethane)Sulfonic Acid (PFEESA)	ND		3.19	0.351	1	ND		13.2	1.45	1
Nonafluoro-3,6-Dioxaheptanoic Acid (NFDHA)	ND		3.19	1.88	1	ND		13.2	7.77	1
3-Perfluoropropyl Propanoic Acid (3:3FTCA)	ND		7.98	2.63	1	ND		32.9	10.90	1
2H,2H,3H,3H-Perfluorooctanoic Acid (5:3FTCA)	ND		39.9	9.34	1	ND		165	38.50	1
3-Perfluoroheptyl Propanoic Acid (7:3FTCA)	ND		39.9	6.30	1	ND		165	26.00	1

Site 2:

	Kitchen Tap					Septic Liquid				
Parameter	Result (ng/l)	Qualifier	RL	MDL	Dilution Factor	Result (ng/l)	Qualifier	RL	MDL	Dilution Factor
Perfluorobutanoic Acid (PFBA)	ND		6.04	0.966	1	ND		27.1	4.33	1
Perfluoropentanoic Acid (PFPeA)	2.72	J	3.02	0.808	1	5.08	J	13.5	3.62	1
Perfluorobutanesulfonic Acid (PFBS)	0.755	J	1.51	0.506	1	ND		6.77	2.27	1
1H,1H,2H,2H-Perfluorohexanesulfonic Acid (4:2FTS)	ND		6.04	1.58	1	ND		27.1	7.07	1
Perfluorohexanoic Acid (PFHxA)	2.19		1.51	0.445	1	5.41	JF	6.77	2.00	1
Perfluoropentanesulfonic Acid (PFPeS)	ND		1.51	0.264	1	ND		6.77	1.18	1
Perfluoroheptanoic Acid (PFHpA)	0.982	J	1.51	0.302	1	1.69	J	6.77	1.35	1
Perfluorohexanesulfonic Acid (PFHxS)	0.528	J	1.51	0.362	1	ND		6.77	1.62	1
Perfluorooctanoic Acid (PFOA)	1.58		1.51	0.657	1	3.38	J	6.77	2.94	1
1H,1H,2H,2H-Perfluorooctanesulfonic Acid (6:2FTS)	ND		6.04	2.04	1	ND		27.1	9.14	1
Perfluoroheptanesulfonic Acid (PFHpS)	ND		1.51	0.408	1	ND		6.77	1.83	1
Perfluorononanoic Acid (PFNA)	ND		1.51	0.476	1	ND		6.77	2.13	1
Perfluorooctanesulfonic Acid (PFOS)	1.21	J	1.51	0.687	1	11.5	F	6.77	3.08	1
Perfluorodecanoic Acid (PFDA)	ND		1.51	0.612	1	ND		6.77	2.74	1
1H,1H,2H,2H-Perfluorodecanesulfonic Acid (8:2FTS)	ND		6.04	2.35	1	ND		27.1	10.50	1
Perfluorononanesulfonic Acid (PFNS)	ND		1.51	0.468	1	ND		6.77	2.10	1
N-Methyl Perfluorooctanesulfonamidoacetic Acid (NMeFOSAA)	ND		1.51	0.823	1	ND		6.77	3.69	1
Perfluoroundecanoic Acid (PFUnA)	ND		1.51	0.657	1	ND		6.77	2.94	1
Perfluorodecanesulfonic Acid (PFDS)	ND		1.51	0.347	1	ND		6.77	1.56	1
Perfluorooctanesulfonamide (PFOSA)	ND		1.51	0.408	1	ND		6.77	1.83	1
N-Ethyl Perfluorooctanesulfonamidoacetic Acid (NEtFOSAA)	ND		1.51	0.815	1	ND		6.77	3.65	1
Perfluorododecanoic Acid (PFDoA)	ND		1.51	0.695	1	ND		6.77	3.11	1
Perfluorotridecanoic Acid (PFTrDA)	ND		1.51	0.566	1	ND		6.77	2.54	1
Perfluorotetradecanoic Acid (PFTeDA)	ND		1.51	0.4	1	ND		6.77	1.79	1
Hexafluoropropylene Oxide Dimer Acid (HFPO-DA)	ND		6.04	0.846	1	ND		27.1	3.79	1

4,8-Dioxa-3h-Perfluorononanoic Acid (ADONA)	ND		6.04	0.95	1	ND		27.1	4.26	1
Perfluorododecanesulfonic Acid (PFDoS)	ND		1.51	0.574	1	ND		6.77	2.57	1
9-Chlorohexadecafluoro-3-Oxanone-1-Sulfonic Acid (9Cl-PF3ONS)	ND		6.04	1.24	1	ND		27.1	5.58	1
11-Chloroeicosafluoro-3-Oxaundecane-1-Sulfonic Acid (11Cl-PF3OUdS)	ND		6.04	1.24	1	ND		27.1	5.58	1
N-Methyl Perfluorooctane Sulfonamide (NMeFOSA)	ND		1.51	0.657	1	ND		6.77	2.94	1
N-Ethyl Perfluorooctane Sulfonamide (NEtFOSA)	ND		1.51	0.695	1	ND		6.77	3.11	1
N-Methyl Perfluorooctanesulfonamido Ethanol (NMeFOSE)	ND		15.1	3.55	1	ND		67.7	15.90	1
N-Ethyl Perfluorooctanesulfonamido Ethanol (NEtFOSE)	ND		15.1	1.85	1	ND		67.7	8.29	1
Perfluoro-3-Methoxypropanoic Acid (PFMPA)	ND		3.02	0.43	1	ND		13.5	1.93	1
Perfluoro-4-Methoxybutanoic Acid (PFMBA)	ND		3.02	0.4	1	ND		13.5	1.79	1
Perfluoro(2-Ethoxyethane)Sulfonic Acid (PFEESA)	ND		3.02	0.332	1	ND		13.5	1.49	1
Nonafluoro-3,6-Dioxaheptanoic Acid (NFDHA)	ND		3.02	1.78	1	ND		13.5	7.99	1
3-Perfluoropropyl Propanoic Acid (3:3FTCA)	ND		7.55	2.49	1	ND		33.8	11.20	1
2H,2H,3H,3H-Perfluorooctanoic Acid (5:3FTCA)	ND		37.8	8.83	1	ND		169	39.60	1
3-Perfluoroheptyl Propanoic Acid (7:3FTCA)	ND		37.8	5.96	1	ND		169	26.70	1

Appendix G. Calculation of PFAS Loading over Septic Lifetime

$$[PFAS]\ (\frac{ng}{L})\ x\ \frac{1\ g}{10^{9}\ ng}\ x\ \frac{70\ gal}{person \bullet day}\ x\ \frac{2.5\ people}{household}\ x\ \frac{3.79\ L}{gal}\ x\ \frac{365\ day}{year}\ x\ 30\ years$$

$$= \frac{g\ PFAS}{septic\ lifetime \bullet household}$$

Appendix H. Follow-up Survey Responses

	Site 1	Site 2
Do you own and wash clothing characterized as moisture-wicking, stain-resistant, water-resistant, or dirt-repellent?	Yes	No
If yes, what articles of clothing?	Leggings/yoga pants, Rain jackets, Sportswear advertised as "moisture-wicking"	
If yes, what brands?		
Do you use non-stick cookware?	Yes	Yes
If yes, what brands?		Volrath
Have you purchased food or liquids packaged in any of the following items in the past? (Select all that apply)	Sandwich/burger wrappers, Paper bags/sleeves, Paperboard/cardboard box, Pet food bags, Plastic bottles	Sandwich/burger wrappers, Paper bags/sleeves, Paperboard/cardboard box, Pet food bags, Plastic bottles
How often have you used paper plates, cups, or bowls for dining?	Rarely	Sometimes
Do you eat seafood?	Sometimes	Sometimes
Do you use any of the following bathing products?	Shampoo, Conditioner, Shower gels, Bar soaps, Shaving cream/gel	Shampoo, Bar soaps
If yes, which brand(s) do you commonly use?	Edge Gel, Equate, Axe, Dove	
Do you use any of the following cosmetic products? (Select all that apply)	Mascara, Lip Stick/Gloss, Cleanser, Moisturizer, Shaving Creams	
If yes, which brand(s) do you commonly use?	Maybelline	
Do you use any of the following?	Fertilizer, Herbicide/ Weed killer	
If yes, which brand(s) do you commonly use?	Scotts	
Do you have any of the following?	Plastic Outdoor Furniture, Non-metal Roof	Plastic piping in house, Non-metal Roof