ASSESSMENT OF HEALTH RISKS FROM PER- AND POLYFLUOROALKYL SUBSTANCES (PFAS, PFOA) EXPOSURE IN CONTAMINATED WATER SOURCES IN WEST VIRGINIA AND RECOMMENDATIONS FOR ADVANCED TECHNOLOGICAL TREATMENTS

by

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A professional paper submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Land Resources and Environmental Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

May 2025

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ACKNOWLEDGEMENTS

I wish to acknowledge several key supporters who have played a vital role in this journey. First and foremost, I am sincerely thankful to my colleagues at work, whose unwavering support and encouragement provided a solid foundation throughout this project. Your collaboration, camaraderie, and understanding allowed me to pursue my studies with the dedication required to bring this paper to fruition.

I extend a heartfelt thank you to my wife. Your love, patience, and belief in my abilities were essential to my success. You have been my anchor, offering encouragement and reminding me to maintain balance during this demanding time. Without your constant support and kindness, I would not have made it through this program.

I must also express my profound appreciation for Dr. Miranda Margetts, whose proactive guidance and support were instrumental at every stage of this project. Your classes sparked my passion for this subject, and your mentorship has been invaluable in navigating challenges along the way. Thank you for believing in me and for your thoughtful feedback that helped shape this paper.

Lastly, my gratitude extends to the graduate committee, Drs. Robert Peterson and Tracy Sterling, for their thorough review and insightful feedback on this paper. Your guidance has enhanced its quality and rigor.

Thank you all for being integral parts of this journey.

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ABSTRACT

The Parkersburg, West Virginia area has faced significant contamination of per- and polyfluoroalkyl substances due to heavy industrial releases from DuPont and Chemours facilities. These so called "forever chemicals" have infiltrated local groundwater and surface water sources which has posed a substantial health risk to residents who mainly rely on private wells for drinking water. Therefore, my paper assesses the extent of PFAS contamination in Parkersburg, evaluates the associated health risks, and identifies cost-effective remediation strategies. I conducted a human health risk assessment using groundwater contamination from the U.S. Geological Survey (USGS) and blood serum concentrations from the C8 Health Project. Risk quotients (RQ) are a metric used in conducting human risk assessments that evaluates the potential hazard of a contaminant. They were calculated based on the given exposure levels, which had revealed that all sampled locations exceeded safe thresholds, with Wood County having the highest RQ values (Child RQ = 161.21, Adult RQ = 86.28). Blood concentration data further confirmed the elevated exposure, which reinforces the urgency for intervention. I also examined the 'probable link' between PFAS exposure and adverse health outcomes as was determined by the C8 Science Panel. Testicular cancer (Relative Risk p to 3.0), autoimmune diseases (RR up to 3.2) and heart disease (RR up to 1.38) showed the strongest associations which highlights the long-term public health implications of PFAS contamination. In addressing contamination levels, the U.S. Environmental Protection Agency's (EPA) Best Available Technologies were evaluated, which included granular activated carbon, anion exchange, and reverse osmosis/nanofiltration. While reverse osmosis/nanofiltration demonstrates the highest removal efficiency of 99.9%, the evaluated high costs, reaching up to 84 million USD, presented financial challenges for local municipalities. Granular activated carbon offer more cost-effective solutions but would require supplemental treatments that would meet EPA's newly updated stringent standards. Given Parkersburg's ongoing efforts to upgrade water treatment infrastructure, this study recommends a hybrid approach that combines granular activated carbon and reverse osmosis/nanofiltration to balance efficacy as well as affordability. My findings underscore the need for immediate regulatory action and continued monitoring to help mitigate PFAS exposure, ultimately protecting public health.

CHAPTER ONE

INTRODUCTION

Background

The Parkersburg area, which is in West Virginia, is approximately 3000 hectares and is characterized by a rich tapestry of land uses. These include agriculture, industrial developments, wetlands, and rivers. The area is situated along the Ohio River, and the region mainly benefits from its strategic location near major transportation corridors, such as Interstate 77, which ultimately facilitates economic activity and connectivity (West Virginia GIS Technical Center, 2021). Parkersburg, West Virginia, is a city located at the junction of the Ohio and Little Kanawha Rivers that has a rich history dating back to the late 18th century. According to the last 2020 census, the population of this city is approximately 30,000, which represents a decline compared to previous years, mainly due to economic changes (U.S. Census Bureau, 2020). Parkersburg is characterized by a blend of urban and rural settings.

The region is surrounded by various types of wetlands and is marked by the Little Kanawha River. Wetlands act as natural filters that improve the overall quality of water by trapping sediments and absorbing pollutants before they reach the Ohio River. The ecological importance of the Parkersburg area has diverse habitats that encompass wetlands and riverside ecosystems which also play a major role in maintaining biodiversity. These natural areas support a variety of plant and animal species while providing essential ecosystem services including water purification, flood control, and habitat for wildlife (EPA, 2015). The waterways provide a vital and essential habitat for wildlife, which contributes to the ecological health of the area. The surface water sources include the Ohio River and its tributaries, while groundwater mainly comes from different aquifers that supply drinking water for local residents (West Virginia

Department of Environmental Protection, 2021). However, residents have raised concerns throughout the early 2000s about contamination-related issues that arose due to industrial activities, resulting in extensive monitoring and research studies conducted to fully understand the extent of the impact from anthropogenic actions (Shin et al., 2018).

The Parkersburg area is greatly supplied with significant groundwater resources, which are essential for both public water supply and private use. Groundwater in this region primarily exists in aquifers, with the most productive sources located in karst and alluvial formations (U.S. Geological Survey, 2022). The alluvial aquifers are formed by sediment deposited by rivers and streams and are mainly characterized by a high permeability, allowing for significant recharge from surface water, particularly during periods of heavy rainfall or snowmelt (U.S. Geological Survey, 2022). The alluvial aquifers in the Parkersburg region are essential for local water supply, mainly in municipal systems and private wells. These aquifers supply about 189.3 billion liters of groundwater. Furthermore, the Ohio River alluvium is mainly situated in the floodplains of the Ohio River Valley that reaches about 450 kilometers of a gradient between West Virginia and Ohio’s borders (U.S. Geological Survey, 2022).

Approximately 44 million individuals in the United States, representing about 13% of households, depend on domestic wells as their primary source of drinking water (U.S. Geological Survey, 2016a, b). This reliance on private wells highlights a significant aspect of America’s water supply landscape. Although the Environmental Protection Agency (EPA) plays a crucial role in regulating water quality from public sources and municipal water systems, it does not extend its oversight to private wells. As a result, responsibility falls on the owners of private wells to ensure the safety and quality of their drinking water. This lack of regulation can pose substantial risks, as various contaminants—including those that occur naturally in groundwater—may be present in these wells. Common contaminants in groundwater can include heavy metals, nitrates, and naturally occurring minerals, all of which can adversely affect human health if ingested at harmful levels (CDC, 2019). Specifically, about 23% of West Virginia relies on private wells for drinking water, and as was mentioned earlier, EPA does not regulate this, and they are outside of the West Virginia Department of Environmental Protection jurisdiction (West Virginia University, 2024).

The Dupont and Chemours facilities, which are located near Parkersburg, West Virginia, were known to be the major source of PFAS contamination in local water systems. These facilities were involved in the production of Teflon and other fluoropolymer products that had used per- and polyfluoroalkyl substances (PFAS) such as perfluorooctanoic acid (PFOA). It has been determined through a lawsuit that more than 7,100 tons of sludge containing PFOA were dumped on the Plaintiff Tenant's property as well as into the Ohio River (Hoffman, 2023). The chemicals entered the ground and local water sources. Clear evidence regarding the impact on the environment and health since 1976 was uncovered during the legal investigations of the Tennant vs. E.I. du Pont de Nemours & Company lawsuit. (Bilott, 2020). This trial led to the EPA charging DuPont for violating the Toxic Substances Control Act (TSCA). Section 8 (e) requires companies to report potential risks of the chemicals they use within their production (Hoffman, 2023). Furthermore, evidence has suggested that DuPont was fully aware of the dangers of PFAS, particularly PFOA; however, they continued to release the chemicals into the environment. Some of the key pieces of evidence that indicated DuPont were aware of PFOA's toxicity and persistence in the environment, were the internal studies that were conducted in 1960s and 70s, demonstrating that PFOA caused health issues in animals at specific dosages, including liver damage and reproductive harm (Rich, 2016). Even when DuPont knew about this they did disclose these risks to regulators, or the public, for several decades (Lerner, 2015). A settlement of $670 million USD was reached in 2017 due to PFAS contamination (Rich, 2016). In response to public health concerns, legal actions, and regulatory pressures, DuPont and Chemours have taken steps to reduce emissions and provide remediation efforts, which include improving wastewater treatment processes and environmental restoration projects which are aimed at mitigating the previous releases (Rich, 2016).

Per- and polyfluoroalkyl substances (PFAS) are a large group of synthetic chemicals which are characterized by a carbon-fluorine (C-F) bond, which is one of the strongest chemical bonds in organic chemistry. This type of bond makes PFAS very stable and resistant to degradation which is why it had earned their nickname of being "forever chemicals". One of the more well-known PFAS compounds includes perfluorooctanoic acid (PFOA); this compound is a fully fluorinated, eight-carbon chain with a carboxylic acid group (C8HF15O2). The carbon-fluorine bond mainly gives PFAS their unique properties, such as being water and oil-repellent, as well as thermally stable and chemically resistant (Buck et al., 2011). The chemicals are commonly used in industrial and consumer products due to their unique properties. Examples include non-stick cookware where PFOA was historically used in the production of polytetrafluoroethylene (PTFE), this coating is used in non-stick cookware like Teflon (NRDC, 2023).

PFAS has been linked to several adverse health effects as research has indicated that the chemicals disrupt endocrine function which leads to hormone imbalances and reproductive issues (Verner et al., 2020). Epidemiological studies have also associated PFAS exposure with elevated cholesterol levels, immune system dysfunction, and increased risk of cancers including kidney and testicular cancer (Verner et al., 2020). They have also shown to impact fetal development, which contributes to low birth weight and development delays (Verner et al., 2020). The persistence of PFAS in our human bodies further increases these health risks as they accumulate over time which lead to chronic exposure scenarios (Lindström et al., 2011).

Remediation methods for these wetlands include physical approaches like sediment dredging and activated carbon filtration, chemical techniques such as in situ chemical oxidation and sorbent amendments, and biological strategies like phytoremediation and microbial degradation (Interstate Technology and Regulatory Council [ITRC], 2020). However, the main challenges persist due to the strong carbon-fluorine bonds in PFAS, which make them resistant to degradation and their high tendency to bioaccumulate in wetland biota (Anderson et al., 2016).

Objectives

I have undertaken several objectives that are aimed at understanding the impacts of PFAS contamination in the Parkersburg area. First, I have conducted two human risk assessments based on blood concentrations and groundwater concentration measurements, given many residents depend on wells sourced from groundwater in Parkersburg, West Virginia. Secondly, I analyzed research from the C8 Science Panel (C8 Science Panel, 2012) to explore the probable link between specific diseases and PFAS exposure, particularly focusing on the releases of PFOA from the Washington Works plant. Finally, I reviewed and identified advanced technological treatments capable of degrading or filtering PFOA and PFAS while also evaluating their efficacy and conducting a cost analysis, and recommending the most cost-effective treatment for Parkersburg, West Virginia.

CHAPTER TWO

HUMAN RISK ASSESSMENT

Problem Formulation

The Parkersburg area, which is situated in West Virginia, has been affected significantly by per- and polyfluoroalkyl substances (PFAS) due to the historical releases from the DuPont and Chemours facilities. These facilities used PFAS-containing substances in their manufacturing processes (Figure 1), resulting in widespread contamination of local groundwater and surface water sources (C8 Science Panel, 2012). As many residents in Parkersburg rely on private wells sources from this compromised groundwater, there is a legitimate concern regarding the potential health risks associated with PFAS exposure (Vineis et al., 2011). Exposure to PFAS is linked to various health outcomes, including hormonal disruption as well as increased risk of certain cancers (Verner et al., 2020). Therefore, I hypothesize that residents in the Parkersburg area are exposed to concerning levels of PFAS through their drinking water, posing significant public health risks. To investigate the potential health impacts and associated risks of PFAS exposure in Parkersburg, I reviewed existing blood concentration data, groundwater contamination levels, and relevant health studies related to PFAS exposure.

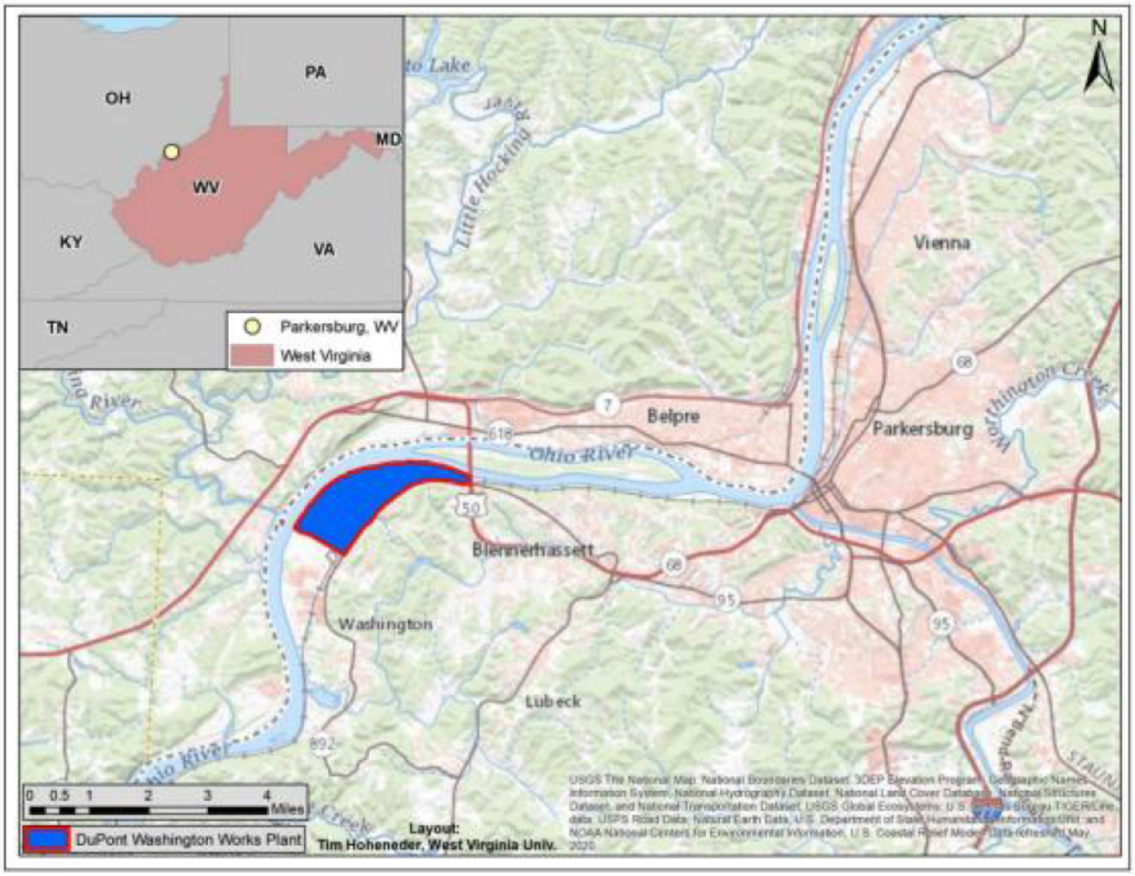


Figure 1: Dupont Washington Works Plant in relation to Parkersburg, WV and the surrounding areas. (Adams, 2021).

Hazard Identification

Because PFAS are highly resistant to degradation and bioaccumulate in living organisms, exposure to these chemicals can magnify through the food web, posing significant health risks to both wildlife and humans. In the Parkersburg area, many residents rely on groundwater sourced from private wells, making them potentially vulnerable to PFAS contamination (Vineis et al., 2011). As individuals consume water and food from these affected areas, they may experience exposure to PFAS through dietary ingestion, water ingestion, air exposure, and dermal contact.

PFAS exposure can lead to numerous health issues, including hormonal disruptions, decreased reproductive health, and potential carcinogenic effects (Verner et al., 2020). These compounds can impair immune system function and are associated with increased cholesterol levels (Hoffman et al., 2021). The toxic effects of PFAS extend beyond just reproductive health, affecting thyroid functions and vital systems in the body, but the effects are still being researched (Lindström et al., 2011).

Dose Response

Most of the PFAS are efficiently absorbed upon ingestion and distributed to vital organs through the bloodstream (Pérez et al., 2013; Kudo, 2015), where they can persist and accumulate for extended periods due to their prolonged half-lives in the human body (Olsen and Zobel, 2007). This major finding resulted in further studies on the associations between PFAS exposure and a range of adverse health outcomes, such as kidney and testicular cancer, autoimmune disorders, immune suppression, neurodevelopmental impairments, thyroid dysfunction, preeclampsia, and reduced fertility, among others (Garg et al., 2020; Agency for Toxic Substances and Disease Registry, 2021). The primary routes of PFAS exposure for the general population include the consumption of contaminated drinking water and food, inhalation of indoor air and dust, and contact with consumer products (Sunderland et al., 2019) (Figure 2). However, no single exposure pathway is universally dominant across all populations or settings.

There is limited research that specifically addresses the impacts of PFAS on local populations and species, particularly concerning their exposure to contaminated water supplies. Therefore, I use the current literature and risk assessment models to establish health risk quotients for Parkersburg residents based on available data on PFAS contamination levels. My analysis includes findings from existing studies, concentrating on the most vulnerable populations affected by PFAS exposure. As part of my evaluation, I apply risk quotient calculations as recommended by the EPA to better understand potential health risks in this community, leveraging quantitative measures of PFAS contamination present in local groundwater and blood concentration levels.

Methods

Groundwater Data

The primary data for this assessment was sourced from the U.S. Geological Survey (USGS) publication titled "Occurrence of Per- and Polyfluoroalkyl Substances and Inorganic Analytes in Groundwater and Surface Water Used as Sources for Public Water Supply in West Virginia" (USGS, 2022). This publication provides comprehensive measurements of PFAS concentrations in groundwater, which served as the foundation for calculating exposure levels among residents relying on private wells in Parkersburg, West Virginia. The USGS report provides detailed groundwater quality data, including concentrations of various contaminants such as heavy metals, nitrates, and organic compounds, measured across multiple wells in the region.

Data were collected by USGS between 2019 and 2021 and represent the groundwater conditions in the study area. Raw source water was sampled for groundwater and surface-water sites at the public water system's first available tap before undergoing any treatment. Samples were taken from the public supply of water in West Virginia, which has geological conditions where groundwater sites have high-yield aquifers of karst and alluvium properties. A total of 173 samples were taken from groundwater, while 106 samples were taken from surface water. Each sample was analyzed for pH, specific conductance, water temperature, dissolved oxygen, turbidity, and alkalinity. Of all the samples analyzed, PFAS concentrations were detected across 24% of the sites. Out of the samples taken, most of the PFAS concentrations were higher in groundwater samples than in surface water. The method of sampling for potential PFAS contamination is taken from the NAWQA (McMahon et al., 2022), which consists of two, 250-ml high-density polyethylene (HDPE) bottles that were sent for lab analysis. Concentrations of PFOA and PFOS at the sites tested had exceeded the high threshold of 70 ng/liter (Table 1). High PFAS concentrations reflects 24% above the reporting level and the remaining 76% were under the reporting level (Figure 2).

Table 1: Five locations in Virginia that were greater than the Perfluorooctanoic Acid, Perfluorooctanesulfonic Acid reporting level of 70 ng/liter.

Site Name	**Location**	**PFOA + PFOS Concentration (nanograms per liter)**
Woo-0215	Wood County, Location 1	1,540
Woo-0216	Wood County, Location 2	156
Woo-0121	Wood County, Location 3	104
Mal-0410	Marshall County, Location 4	98
Ber-0468	Berkeley County, Location 5	71

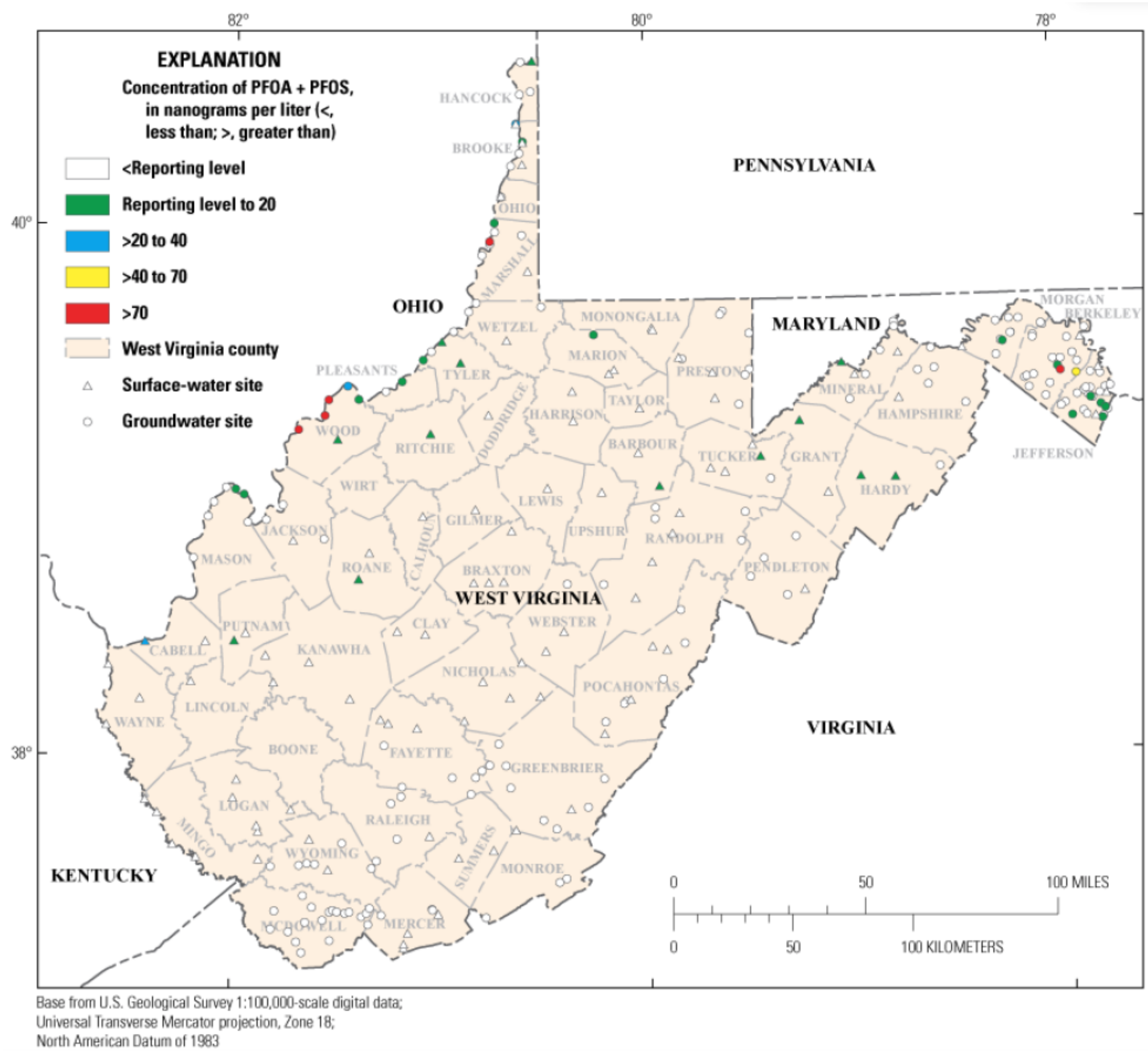


Figure 2: The locations where samples were taken from groundwater and surface water sources for detected perfluorooctanoate (PFOA) and perfluorooctanesulfonate (PFOS) concentrations. (USGS, 2022).

Blood Concentration Levels

The second primary data from this assessment are from the C8 Health project, which was the result of a settlement agreement case of Jack W. Leach. Jack Leach resided in Parkersburg who had raised a lawsuit against DuPont because of his claim that PFAS contamination was the cause of the cancer he developed (Bilott, 2020). The legal settlement involved DuPont funding the C8 Health Project, which was led by a group of scientists to study the relationship between health impacts and C8 exposure (Bilott, 2020). Within a period of 13 months between 2005 and 2006, a large amount of data were collected, which includes clinical laboratory testing. Blood samples of adults and children were taken and processed to detect PFAS levels. The entire C8 project surveyed a total of 69,030 people, with participants drawn from various water districts including: City of Belpre (Ohio), Tuppers Plains (Ohio), Little Hicking Water Association (Ohio), Lubeck Public Service District (West Virginia), Mason County (West Virginia), and Village of Pomeroy (Ohio), all of which surrounded the Parkersburg County of the PFAS contamination from Dupont and Chemours facilities. Serum concentrations were collected from various age and sex groups to compare concentration levels (Perera et al., 2009). For this assessment, I extracted the mean levels of PFOA and PFOS for all genders under 12 years of age, categorizing this as ‘Child’ exposure, and determined the total mean for participants aged 20 and older as ‘Adult’ exposure (Table 2).

Table 2: Total Serum concentrations of Perfluorooctanoic Acid and Perfluorooctanesulfonic Acid for mean age and gender groups

Age Group	**Total mean PFOA Concentration for female and male (ng/mL)**	**Total mean PFOS Concentration for female and male (ng/mL)**
Child (Ages < 12 years)	77.6	23.6
Adult (Ages 20-39 years)	58.1	20.1
Adult (Ages 40-59 years)	99.4	23.6
Adult (Ages > 60 years)	113.8	29.2
Adult Mean (Ages > 20)	90.4	24.3

Exposure Assessment

For my exposure assessment, I used the following assumptions to estimate the threshold intake value of a child and adult, for the five geographic locations listed above:

a. Child's Age: 6-11 who drinks 95th percentile water per day = 1,316 ml/day
b. Adult's Age: 20 and above who drinks 95th percentile water per day = 2,958 ml/day
c. Child's weight = 20 kg
d. Adults weight = 84 kg (U.S. EPA, 2011)
e. Exposure to PFAS is through consumption of contaminated groundwater retrieved from private water wells.
f. Concentration of PFAS, 1 ppt = 1 ng/L

g. Risk Quotient of 1 or greater indicates that the measured concentration has exceeded the threshold value, equal to 1 is at threshold level, and less than 1 indicates that the concentration is below the threshold

The main exposure pathway for PFAS is via ingestion of contaminated water, which I assumed to be the only exposure to humans through groundwater retrieved from private wells and directly ingested without any type of purification. As a result of changes from regulatory bodies, the 95th percentile was assumed to refer as the amount of water consumed by the top 5% of the population to ensure that the risk assessment conservatively accounts for individuals consuming a high level of water.

Furthermore, I used the threshold value from the European Food Safety Authority (EFSA) which had established a tolerable weekly intake (TWI) for PFAS of 4.4 nanograms per kilogram of body weight per week (ng/kg bw/week) which is based on the cumulative effects on the immune system (EFSA, 2020). EPA's approach focused mainly on drinking water standards and health advisories instead of setting a TWI. EPA set a lifetime health advisory level of 4.0 ppt for PFOA and PFOS (EPA, 2022), which would not feasibly allow for the determination of the tolerable intakes for body weight per week.

The equations below were used to calculate the threshold values for PFAS exposure, which will assess the associated health risks by comparing estimated weekly exposure to established thresholds.

Equation 1: Threshold Value = $(kg\ body\ weight) * (4.4\ ng\ total\ PFAS\ kg\ body\ weight)$

Child Threshold: 20 kg body weight * 4.4 ng PFAS / kg body weight / week) = <u>88 ng/week</u>

Adult Threshold: 84 kg body weight * 4.4 ng PFAS / kg body weight / week) = <u>369.6 ng/week</u>

Equation 2: Risk Quotient Calculation

Risk Quotient = Weekly Estimated Exposure ÷ Weekly Intake Threshold

The location nearest to Parkersburg in Wood County had the highest RQs, calculated at 86 for adults and 161 for children.

Table 3: Perfluorooctanoic Acid and Perfluorooctanesulfonic Acid risk quotient calculations for Berkeley County site in Virginia.

PFOA + PFOS (PFAS) Consumption by Drinking Sourcewater	
Child	(1.316 L/day drinking source water) (71 ppt PFOA + PFOS) = 93.4 ng/day
Adult	(2.958 L/day drinking source water) (71 ppt PFOA + PFOS) = 210 ng/day
Weekly Consumption – Child & Adult	
Child	(93.436 ng/day) (7 days) = 654.1 ng/week
Adult	(210.018 ng/day) (7 days) = 1,470.1 ng/week
Risk Characterization – Child & Adult	
Child	RQ = Weekly Exposure / Max Weekly Intake = 654.1 ng/week /88 ng/week = **7.4**
Adult	RQ = Weekly Exposure / Max Weekly Intake = 1,470.1 ng /week/369.6 ng/week = **3.4**

Table 4: Perfluorooctanoic Acid and Perfluorooctanesulfonic Acid risk quotient calculations for Marshall County site in West Virginia.

PFOA + PFOS (PFAS) Consumption by Drinking Sourcewater	
Child	(1.316 lts/day drinking sourcewater) (98 ppt PFOA + PFOS) = 129.0 ng/day
Adult	(2.958 lts/day drinking sourcewater) (98 ppt PFOA + PFOS) = 289.9 ng/day
Weekly Consumption – Child & Adult	
Child	(128.968 ng/day) (7 days) = 902.8 ng / week
Adult	(289.884 ng/day) (7 days) = 2,029.2 ng / week
Risk Characterization – Child & Adult	
Child	RQ = Weekly Exposure / Max Weekly Intake = 902.8 ng / week / 88 ng / week = **10.3**
Adult	RQ = Weekly Exposure / Max Weekly Intake = 2,029.2 ng / week / 369.6 ng / week = **5.5**

Table 5: Perfluorooctanoic Acid and Perfluorooctanesulfonic Acid risk quotient calculations for Wood County site in West Virginia (Parkersburg Area).

PFOA + PFOS (PFAS) Consumption by Drinking Sourcewater	
Child	(1.316 lts/day drinking sourcewater) (104 ppt PFOA + PFOS) = 136.9 ng/day
Adult	(2.958 lts/day drinking sourcewater) (104 ppt PFOA + PFOS) = 307.6 ng/day
Weekly Consumption – Child & Adult	
Child	(136.864 ng/day) (7 days) = 958.1 ng / week
Adult	(289.884 ng/day) (7 days) = 2,153.4 ng / week
Risk Characterization – Child & Adult	
Child	RQ = Weekly Exposure / Max Weekly Intake = 958.0 ng / week / 88 ng / week = **10.9**
Adult	RQ = Weekly Exposure / Max Weekly Intake = 2,153.424 ng / week / 369.6 ng / week = **5.8**

Table 6: Perfluorooctanoic Acid and Perfluorooctanesulfonic Acid risk quotient calculations for Wood County site in West Virginia (Parkersburg Area).

PFOA + PFOS (PFAS) Consumption by Drinking Sourcewater	
Child	(1.316 lts/day drinking sourcewater) (156 ppt PFOA + PFOS) = 205.3 ng/day
Adult	(2.958 lts/day drinking sourcewater) (156 ppt PFOA + PFOS) = 461.4 ng/day
Weekly Consumption – Child & Adult	
Child	(205.3 ng/day) (7 days) = 1,437.1 ng / week
Adult	(461.5 ng/day) (7 days) = 3,230.1 ng / week
Risk Characterization – Child & Adult	
Child	RQ = Weekly Exposure / Max Weekly Intake = 1,437.1 ng / week / 88 ng / week = **16.3**
Adult	RQ = Weekly Exposure / Max Weekly Intake = 3,230.1 ng / week / 369.6 ng / week = **8.7**

Table 7: Perfluorooctanoic Acid and Perfluorooctanesulfonic Acid risk quotient calculations for Wood County site in West Virginia (Parkersburg Area).

PFOA + PFOS (PFAS) Consumption by Drinking Sourcewater	
Child	(1.316 lts/day drinking sourcewater) (1,540 ppt PFOA + PFOS) = 2,026.6 ng/day
Adult	(2.958 lts/day drinking sourcewater) (1,540 ppt PFOA + PFOS) = 4,555.3 ng/day
Weekly Consumption – Child & Adult	
Child	(2,026.6 ng/day) (7 days) = 14,186.5 ng / week
Adult	(4,555.3 ng/day) (7 days) = 31,887.2 ng / week
Risk Characterization – Child & Adult	
Child	RQ = Weekly Exposure / Max Weekly Intake = 14,186.5 ng / week / 88 ng / week = **161.2**
Adult	RQ = Weekly Exposure / Max Weekly Intake = 31,887.2 ng / week / 369.6 ng / week = **86.3**

Table 8: Perfluorooctanoic Acid and Perfluorooctanesulfonic Acid risk quotient calculations for Blood Concentrations based on the C8 Health Survey Project.

PFOA Concentration - Blood Absorption	
Child	(1.316 lts/day drinking water) (77.6 ppt PFOA) = 102.1 ng/day
Adult	(2.958 lts/day drinking water) (90.4 ppt PFOA) = 267.4 ng/day
PFOS Concentration - Blood Absorption	
Child	(1.316 lts/day drinking water) (23.6 ppt PFOS) = 31.1 ng/day
Adult	(2.958 lts/day drinking water) (24.3 ppt PFOS) = 71.9 ng/day
Weekly Consumption – Child	
PFOA	(102.122 ng/day) (7 days) = 714.9 ng / week
PFOS	(31.058 ng/day) (7 days) = 217.4 ng / week
PFAS Total	= **932.3 ng / week**
Weekly Consumption – Adult	
PFOA	(267.403 ng/day) (7 days) = 1871.8 ng / week
PFOS	(71.879 ng/day) (7 days) = 503.2 ng / week
PFAS Total	= **2375.0 ng / week**
Risk Characterization – Child & Adult	
Child	RQ = Weekly Exposure / Max Weekly Intake = 932.26 ng / week / 88 ng / week = **10.6**
Adult	RQ = Weekly Exposure / Max Weekly Intake = 2374.974 ng / week / 369.6 ng / week = **6.4**

Risk Characterization

First, I performed a risk characterization to show the risk of ingesting drinking water from groundwater and surface water samples. Five locations were picked based on the highest concentrations of PFOA and PFAS. The Risk Quotient (RQ) was calculated using the threshold value and risk quotient equation. Water consumption concentration was calculated based on a weekly basis for the combination of PFOS and PFAO. This value was then taken to divide by the maximum weekly intake for child and adult RQ (Tables 3-7). The second risk characterization was performed to show the risk of ingesting drinking water based on available blood concentration data in the Parkersburg area. PFOA and PFOS were calculated separately. The concentrations per day were first taken which was then multiplied by seven to calculate the weekly exposure. The PFOA and PFOS were then added for both adult and child and divided by the maximum weekly intake threshold (Table 8).

Table 9: Risk Quotients for all locations and blood concentrations from the C8 Project.

Location / BC	Child RQ	Adult RQ
Berkeley County	7.4	3.4
Marshall County	10.3	5.5
Wood County	10.9	5.8
Wood County	16.3	8.7
Wood County	161.2	86.3
Blood Concentrations (C8 Project)	10.6	6.4

The RQs calculated indicate the human health risks associated with PFOS/PFOA for both adults and children (Table 9). An RQ of 1.0 or more signifies that the maximum weekly intake exceeds the threshold limits set by the European Food Safety Authority (EFSA). The threshold values were given for both adult and child since children are in the vulnerable category indicating higher risk quotients.

The results showed that all the RQs exceeded the RQ value of 1, indicating a high risk of human health impacts for both children and adults. There was not a single category or site location where the RQ was ≤ 1.0, suggesting certainty that any exposure would lead to negative health effects. I observed that the highest RQs were in Wood County from all the groundwater and surface water samples taken in West and East Virginia. Wood County is where the Parkersburg contaminated site is located, so it is plausible to associate the high quotients with the DuPont contamination. One of the locations in Wood County, which had the highest RQ, is specifically at the contamination point. The blood concentration health study also showed significant RQ values that exceeded the thresholds, further strengthening the findings from the groundwater samples and their association with exposures and health impacts on local residents.

It's also important to note that the RQs calculated indicated significantly elevated levels of PFAS/PFOS exposure among residents in the study area, with values far exceeding the thresholds. These RQs highlight the urgent need to implement mitigation measures to reduce this exposure and protect public health. Access to uncontaminated drinking water is critically important since prolonged exposure has been linked to adverse health outcomes (Bilott 2020).

The significant limitation of the groundwater studies arises from the source of the water samples analyzed for RQs. These samples were taken from sources intended for drinking, which undergo different processes compared to water that comes directly from treatment plants. This is crucial since drinking water typically includes additional treatments and filtration processes designed to ensure safety and compliance with PFOS and PFAS limits before reaching the consumer. Ultimately, this skews the findings of this study, leaving a major gap in actual RQ levels. I suggest further research is required that uses direct samples from treatment facilities and is more comprehensive and accurate in defining RQs.

CHAPTER THREE

PROBABLE LINK TO ILLNESSES

The C8 Science Panel determined the health effects of PFAS exposure using data from the C8 Health Survey Project, which included approximately 70,000 participants from the Parkersburg, West Virginia area. This project, together with various epidemiological studies and toxicological research, helped establish a 'probable link' between PFOA exposure and numerous diseases, as will be elaborated on further (C8 Science Panel, n.d.). This underscores the potential risks posed by PFAS exposure to the public, primarily through ingestion, which is one of the main pathways of exposure (C8 Science Panel, n.d.).

Methods

Over a period of 10 months, summaries of probable link evaluation reports were prepared by three epidemiologists and subsequently submitted to the Wood County Court (C8 Science Panel, n.d.). These substantive reports aimed to assess various health-related concerns and their potential connections to PFAS. The term “probable link” has been defined in this settlement agreement to mean that it’s more likely than not that there is a link between PFOA exposure and human diseases (C8 Science Panel, n.d.). The submission dates for these evaluations and link evaluation report names are as follows, which designate the specific health conditions evaluated by the C8 Science Panel for their potential link to PFOA exposure.

- **December 5, 2011** – Probable Link Evaluation of (1) Birth Defects, (2) Pregnancy-Induced Hypertension and Preeclampsia, (3) Miscarriage and Stillbirths, (4) Preterm Birth and Low Birth Weight.
- **April 16, 2012** – Probable Link Evaluation of (5) Cancer, (6) Diabetes.

- **July 30, 2012 –** Probable Link Evaluation of (7) Autoimmune Disease, (8) Infectious Disease, (9) Neurodevelopmental Disorders in Children, (10) Respiratory Disease, (11) Stroke, (12) Thyroid Disease.
- **October 29, 2012** – Probable Link Evaluation of (13) Heart Disease, (14) Kidney Disease, (15) Liver Disease, (16) Osteoarthritis, and (17) Parkinson's Disease

The Science Panel used specific criteria to establish a 'probable link' as is outlined below:

1. <u>Consistency:</u> Evidence from several other studies showing that there is a consistent association between PFOA exposure and the linked diseases.
2. <u>Strength of Association:</u> This is quantified using **Relative Risk (RR)**, which compares the disease risk in individuals exposed, to those who are unexposed or minimally exposed. RR greater than 1.0 would indicate an increased risk of exposure, RR less than 1.0 indicates a decreased risk. This takes into consideration to demographic variables including age and gender. **Odds Ratio** was also another marker to measure the risk in exposed compared to the risk in the unexposed or low-exposed (1.0 = no association between exposure and outcome, >1 = evidence of increased risk with increased exposure, <1 = evidence of decreased risk with increased exposure.
3. <u>Dose-Response Relationship:</u> Evidence showing that the risk of disease increases with higher levels of PFOA exposure.
4. <u>Chance or Bias:</u> Potential for there to be a result of chance or bias, which is evaluated with the 95% Confidence Intervals that assess the RR's statistical precision. P-values were also used to determine likelihood of chance where $p < 0.05$ would indicate that the result was due to chance.

5. Biological Plausibility: Evidence showing animal studies demonstrating mechanism with which PFOA exposure would result in the associated disease (C8 Science Panel, n.d.).

The criteria outlined earlier was used to rank and highlight the ‘most likely’ links, arranged from highest to lowest, based on the Relative Risk (RR) values. Of the 17 evaluations conducted, the C8 Science Panel determined that only five demonstrated a probable link to C8 exposure. I examined these five evaluations and categorized them by the highest linked probability to the lowest based on the above criteria (Figure 3 and Table 10). The data on relative risks were derived from studies that measured the increase in serum levels.

Probable Link Evaluation of Heart Disease

There is a probable link between exposure to PFOA and high cholesterol that was diagnosed. Studies by the Science Panel to analyze probability levels had conducted a cross-sectional study of 46,000 adults, which showed an increase in cholesterol with an increase in PFOA, considering the adjustment of demographic values, including age, gender, education, smoking, BMI, alcohol, and exercise. The analysis of those who had high cholesterol of 240 mg/dL or greater, also showed to have an increased hypercholesterolemia and that was associated with high levels of PFOA in serum concentrations. The RR showed a linear trend with an increase in PFOA of 1.0, 1.21, 1.33, and 1.38 ($p<0.0001$). This evaluation concludes that most of the cross-sectional studies had positive evidence of the probability of exposure to PFOA. However, a few studies did not have the same results (C8 Science Panel, n.d.).

Probable Link Evaluation of Autoimmune Disease

This evaluation did not find any probable relation with PFOA and autoimmune diseases such as rheumatoid arthritis, lupus, type 1 diabetes, Crohn's disease, or multiple sclerosis. However, there was a probable link with only ulcerative colitis and PFOA exposure, which has a strong dose-response gradient. A separate analysis was conducted for 161 cases. An increasing exposure in RR value were as per the following: 1.0, 1.89, 2.58, and 3.18 with a p-value of <0.0001. Another analysis had a positive trend of increasing exposure for 30 cases which had the following RR values: 1.0, 1.49, 1.84, 2.18 and p-value of 0.28 (C8 Science Panel, n.d.).

Probable Link Evaluation of Thyroid Disease

The overall analysis with the probable link evaluation of thyroid disease showed there was not a large increase in trend for increasing PFOA in serum with RRs values of 1.0, 1.2, 1.2, 1.3 across the categories and a p-value of 0.09. However, the results had inconsistencies between men and women (C8 Science Panel, n.d.).

Probable Link Evaluation of Cancer

There were two types of cancers that had positive trends with increasing exposure based on the measured serum levels. Testicular cancer had a positive trend with increasing RR and exposure with 1.0, 1.2, 1.7 and 3.0 with a p-value=0.04. Thyroid cancer also showed positive correlation, however, the trend was inconsistent: 1.0, 2.2, 2.3, 1.7 with a p-value= 0.34. Therefore, it was not considered sufficient evidence to conclude a probable link. Kidney Cancer had a normal positive increase of 1.0, 1.0, 1.7, and 1.4 with a p-value=0.18 (C8 Science Panel, n.d.).

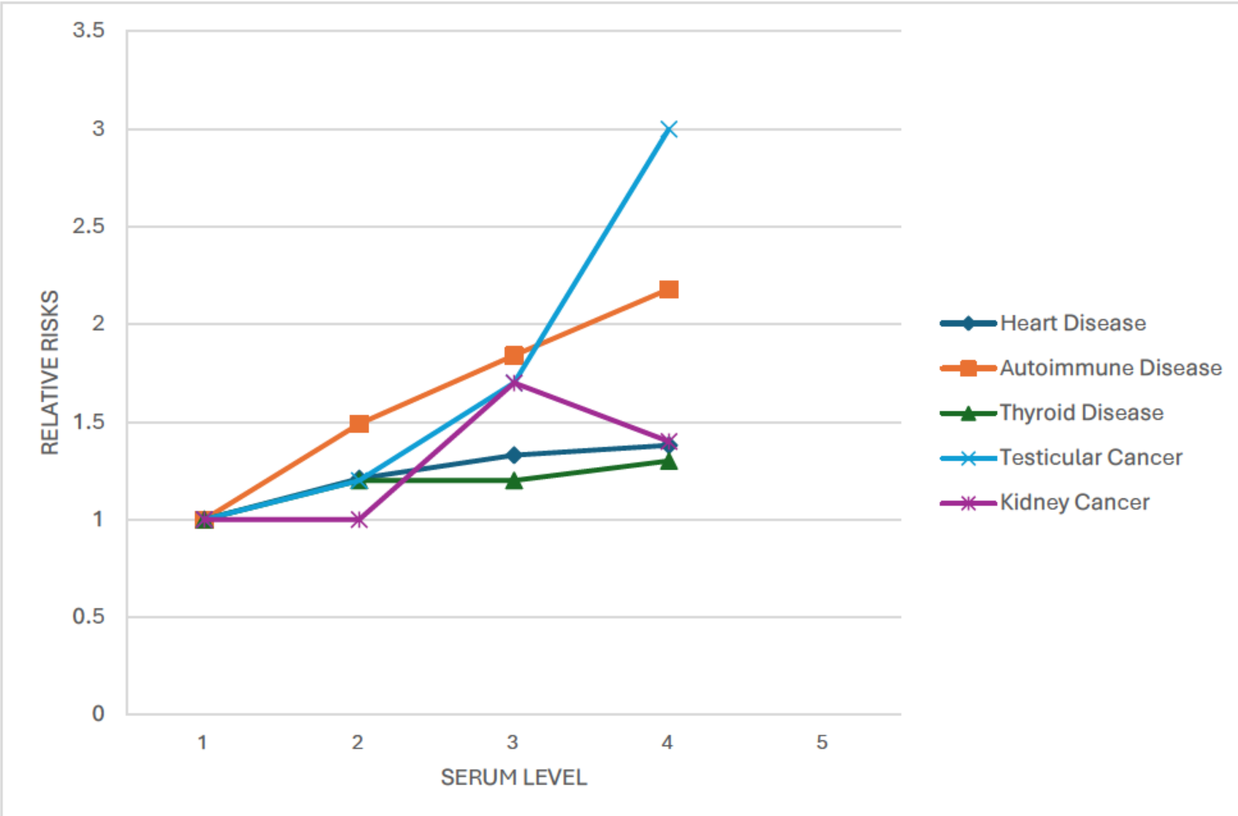


Figure 3: Relative risk of serum levels in Parkersburg residents for the five probable links to health-related illnesses or cancers.

Table 10: Rank of the highest probable link of exposure to Per- and Polyfluoroalkyl Substances with the specific illness or cancer.

	Relative Risk				Rank (From 1-5, 1 being highest, 5 lowest)
Heart Disease	1	1.21	1.33	1.38	3
Autoimmune Disease	1	1.49	1.84	2.18	2
Thyroid Disease	1	1.2	1.2	1.3	5
Testicular Cancer	1	1.2	1.7	3	1
Kidney Cancer	1	1	1.7	1.4	4

Discussion

The findings from the C8 Science Panel's evaluations provided important insights into the health risks due to PFOA and PFAS exposure. The panel's methodology included epidemiological studies, toxicological research, and a large-scale health survey, which had established a 'probable link' between PFOA exposure and diseases. I will discuss the results of the probable risks and the implications on human health as well as areas that are needed for further research.

The C8 Science Panel identified at least five health outcomes with a probable link to PFOA exposure, including heart disease, autoimmune disease, thyroid disease, testicular cancer, and kidney cancer. Among them, testicular cancer showed the strongest association with a relative risk increasing to 3.0 at the highest serum exposure levels (Table 10). This result is of considerable concern given the increase in testicular cancer at a global scale due to possible environmental toxins (Smith et al., 2011). However, further research is needed to understand this association, particularly from PFOS and PFAS exposure in the Parkersburg area.

Autoimmune diseases were ranked second as they also had high RR values, which provide evidence of association. However, there was a lack of links to other autoimmune conditions such as rheumatoid arthritis and lupus, which suggested that the effects of PFOA linkage is specific to the type of the disease. This opens further investigation to the immunological pathways influenced by PFAS exposure.

Heart disease ranked third in terms of probable link strength as it had a consistent statistically significant increase in risk with higher PFOA exposure. The linear trend in RR values (1.0, 1.21, 1.33, 1.38) with a strong p-value of (<0.0001) which underscore cardiovascular risks from PFOA.

Last, kidney and thyroid cancers had weaker associations with inconsistent trends across exposure categories. RR values for thyroid disease (1, 1.2, 1.2, 1.3) had a p-value of 0.09, which would indicate a small increase in risk, while kidney cancer had a positive trend in comparison, hence why it was ranked higher than thyroid disease. RR values for kidney cancer also has a disconnect where it decreases from 1.7 to 1.4.

Limitations

The C8 Science Panel's approach was considered methodologically robust as it had several criteria areas, including consistency, strength of association, dose-response relationship, and biological plausibility, which was used to evaluate the 'probable risk'. However, this is not without limitations, as these are merely 'probable' risks that do not align with specific correlations of health impacts. Furthermore, the cross-sectional design of some analyses limits the ability to establish causation since it captures data as a single point in time. This design complicates determining whether PFOA exposure happened before disease onset, or if other factors influenced the observed associations. Longitudinal studies can track participants over time and can provide more substantial evidence for causality by establishing relationships between exposure and health outcomes. Another limitation is the heterogeneity of the study designs where some studies in the C8 Science Panel's evaluations were conducted for populations in specific geographic areas that did not have high PFOA contamination. There were also inconsistencies between men and women in the results, which can suggest hormonal influences instead of a biological effect. Furthermore, it's noteworthy to point out the risk ratios were generally low which suggests that while PFOA exposure may contribute to adverse health outcomes, the strength of association with any specific condition is limited.

Conclusion

The C8 Science Panel's evaluation provides strong evidence of the association of health risks due to PFOA exposure, particularly for testicular cancer, heart disease, and autoimmune disease. The findings highlight the importance of further research to understand the mechanisms of PFAS toxicity and to identify strategies for reduced exposure. These findings serve as a foundation for informing policy decisions and safeguarding public health. The limitations of cross-sectional designs and heterogeneity in study designs highlight the need for further longitudinal research to establish causality, which can improve exposure assessment accuracy and have a more generalized result across the diverse populations.

CHAPTER FOUR

GROUNDWATER TREATMENT AND COST IMPACT

The U.S. EPA has identified and established the technologies that are listed as "Best Available Technologies" (BATs) to reduce the level of PFAS in water sources to support compliance with the EPA PFAS Maximum Contaminant Levels (MCLs) (U.S. Environmental Protection Agency [EPA], 2024). These were introduced in 2024 as part of the new compliance regulations the EPA set for six PFAS (PFOS, PFOA, PFNA, PFBS, PFHxS, and GenX) announced under the finalized National Drinking Water Standards. BATs are listed based on a **set of criteria** that EPA has defined, which include the following (EPA, 2024):

1. **Removal Efficiency** – This assesses the treatment technology's capability of effectively removing PFAS from water, it directly impacts the levels of PFAS left in treated water as well as determining compliance with regulatory standards.

2. **Full Scale Operations** – This evaluates whether the technology was successful in full-scale operational setting which is studied through pilot studies or laboratory tests. This ultimately provides insights into how reliable, efficient, and practical the technologies are in terms of operational function.

3. **Geographic Applicability** – The effectiveness of technology varies across different geographic regions with unique environmental conditions and water quality issues. PFAS contamination can affect the geology and hydrology of a region, so technologies that are adaptable and effective in various environmental contexts are crucial.

4. **Compatibility with other treatment processes** – This assesses how easy it is for a treatment technology to work with the current and existing technologies, this essentially means smoother and cost-effective transitions in upgrading technologies.

5. **Compliance of the water system** – Compliance is the evaluation of whether the technology fulfills regulatory and federal standards in terms of water quality.

6. **Reasonable Costs** – Lastly, cost is crucial in selecting the best PFAS treatment methods, as these technologies are usually expensive to construct, operate, and maintain, making them often impractical and less likely to be approved by city councils.

I analyzed leading treatment technologies using the EPA's BAT criteria, to determine the most effective solutions for the drinking water needs of Parkersburg residents. Additionally, I performed a cost assessment to evaluate the expenses the city will incur for these technologies in conjunction with their current systems, identifying the most cost-effective option. EPA has identified that the "Best Available Technologies" include granular activated carbon, anion exchange, reverse osmosis, and nanofiltration.

Granular Activated Carbon

This treatment method works by passing contaminated water through a filter box that has granular activated carbon (GAC). The PFAS in the contaminated water attaches to the activated carbon, adsorbing the PFAS molecules before being released for consumption. This step occurs typically at the end of treatment plants. The effectiveness of this treatment method relies on the types of PFAS compounds present in the water and contact time with the carbon (EPA, 2024). Forrester and Bostardi (2019) show that removal efficiencies are 90% or greater for carboxylate and sulfonate PFAS compounds. As for PFOA and PFOS, the maximum removal efficiencies are greater than 99% ([EPA, 2024).

Cost Impact: The cost of having a GAC treatment technology varies on the design framework and purpose of mechanism. A small system with a design of 50,000 bed life can treat 0.5 million gallons per day. Bed life is the number of days between GAC replacements where the volume of water that is treated during the bed life is divided by the volume of the GAC bed. Accordingly, a higher number would indicate a longer bed life and efficient treatment (Table 10). The next bigger design framework has the same bed life but a higher million gallons per day (mgd) of 5.809. The highest design has a treatment quantity of 56.271 mgd, however, this is mainly focused on surface water treatment. The first two designs are only for groundwater.

Anion Exchange

Anion exchange mechanisms work by passing contaminated water through a vessel that has a media for anion exchange. The anions, which are usually chloride or hydroxide, are exchanged with the PFAS. The media is replaced once the exchange reaches its limit and does not function for its purpose. Removal of PFAS depends mainly on the pH of the contaminated water and efficiency increases when water is more acidic and has lower pH. Anion Exchange is also located at the end of treatment plants, which is similar to granular activated carbon (EPA, 2024). Removal efficiency of this treatment method shows that 90% or greater of carboxylate and sulfonate PFAS compounds are removed. Woodard (2017) also indicated that for PFOA and PFOS the removal efficiency was greater than 99%, which is again similar to GAC efficiencies (EPA, 2024).

Cost Impact

As for the Anion Exchange system, the design figures are the same as the GAC where the design for the low-cost groundwater treatment has a design of 0.500 mgd, however, the bed volumes is 120,000. The mid-cost components with the 5.809 mgd design has a bed volume of 160,000. The surface water with high-cost components has a design of 56.271 mgd and 120,000 bed volume.

Reverse Osmosis / Nanofiltration (RO/NF)

RO and NF are both membrane processes which work by separating the contaminants from the water being filtered and illustrated in Figure 4. The system effectively isolates solute compounds, specifically PFAS, by pushing a solvent through a membrane under pressure exceeding the standard osmotic pressure. Typically, this consists of a spiral-wound configuration that has many membrane envelopes which are also layered with the feed spacers and rolled together as illustrated in Figure 4 below. Studies (Boonya-Atichart, 2016; Lipp, 2010) showed that the maximum removal efficiencies, 99.9% was removed for PFOA and this treatment was for the carboxylate PFAS (EPA, 2024).

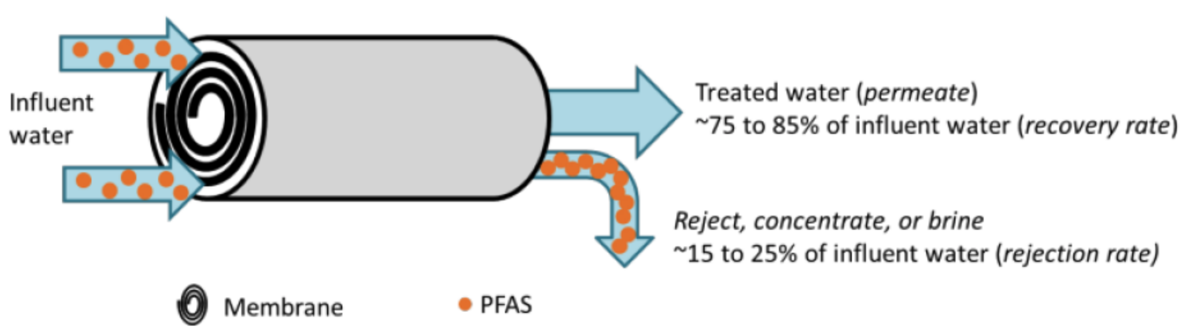


Figure 4: The Reverse Osmosis treatment process showing the spiral formations of the membrane (EPA, 2024).

Cost Impact

RO and NF cost again had similar design frameworks ranging from low cost to high-cost components. Cost figures are given in Tables 11 to 13 below.

Current Upgrade Plans in Parkersburg

In 2024, the Parkersburg Utility Board announced that it had almost completed the design of a water treatment facility. This facility would ensure that it aligns with the newly proposed federal PFAS standards of below four parts per trillion in drinking water. However, the Board has admitted that with the current technologies, it is not able to filter PFAS to these newly proposed levels and they're working currently working with design plans to design a new facility (WTAP, 2024).

Total Cost Results

The costs consist of several components in the treatment systems required to function as per the required standards. Examples for GAC treatment would include the pressure vessels, fiberglass tanks, process piping, backwash piping, influent and treated water piping, amongst other items. These are all the process costs excluding the indirect and add-on costs. Examples of indirect costs are the mobilization and demobilization, architectural fees for the treatment building, site work, land cost, and miscellaneous allowances. The operations and maintenance costs will also be included, which include the manpower salaries, building and HVAC maintenance, energy for lighting and ventilation, and the holding tanks solids disposal.

Table 11: Granular Activated Carbon Treatment costs from low cost to high design systems.

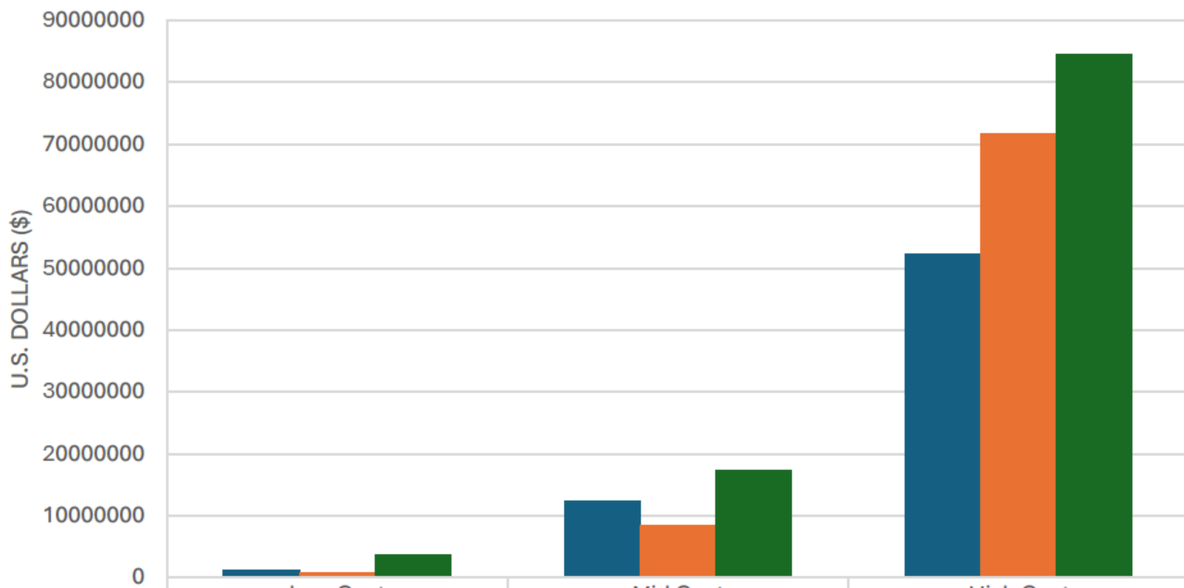
	GAC Treatment – Low-Cost Components	GAC Treatment – Mid-Cost Components	GAC Treatment – High-Cost Components
Process Cost	$448,246	$4,464,088	$19,314,431
System Cost	$781,542	$7,611,950	$30,459,582
O&M Cost	$29,459	$353,108	$2,522,462
Total Cost	$1,259,247	$12,429,146	$52,296,475

Table 12: Anion Exchange Treatment costs from low cost to high design systems.

	AE Treatment – Low-Cost Components	AE Treatment – Mid-Cost Components	AE Treatment – High-Cost Components
Process Cost	$305,996	$2,915,191	$26,211,376
System Cost	$553,898	$5,080,648	$40,709,867
O&M Cost	$36,008	$518,460	$4,888,971
Total Cost	$895,902	$8,514,299	$71,810,214

Table 13: Reverse Osmosis / Nanofiltration (RO/NF) Treatment costs from low cost to high design systems.

	RO/NO Treatment – Low-Cost Components	RO/NO Treatment – Mid-Cost Components	RO/NO Treatment – High-Cost Components
Process Cost	$1,317,693	$6,386,707	$30,494,099
System Cost	$2,272,755	$10,021,165	$45,989,212
O&M Cost	$117,342	$1,005,211	$7,976,137
Total Cost	$3,707,790	$17,413,083	$84,459,448



	Low Cost	Mid Cost	High Cost
GAC	1259247	12429146	52296475
AE	895902	8514299	71810214
RO / NF	3707790	17413083	84459448

Figure 5: Cost comparison analysis of BAT treatment technologies, which includes the total low, medium, and high-cost components associated with each treatment method.

Discussion

The findings of my analysis highlight the role of Best Available Technologies (BATs) which addresses PFAS contamination in drinking water, mainly in the context of Parkersburg's water treatment requirements. Using EPA's criteria for BATs which include removal efficiency, full-scale operations, geographic applicability, compatibility with existing systems, regulatory compliance and cost, I found they provide a thorough and fully comprehensive framework to help assess the suitability of treatment technologies and specific application to Parkersburg's contamination. My analysis involves effectiveness and economic feasibility, particularly considering the city of Parkersburg already faces financial challenges in water treatment infrastructure upgrades.

First, I found that granular activated carbon (GAC) is a treatment that is highly effective in removing PFAS, specifically for carboxylate and sulfonate compounds, which has efficiencies that exceed 90% and 99% for PFOA and PFOS alone. However, GAC systems for groundwater treatment will vary depending on the design framework and operational demands and that it is essential to consider long-term and maintenance costs, which may not be financially feasible for the city.

Anion exchange (AE) also demonstrated high removal efficiencies with similar percentage results to GAC. AE systems are positioned at the end of treatment plants which can be compatible for infrastructure that is already there. However, I noted that these systems need more frequent media replacement, which would increase operational costs in the long term. As for the cost assessment, AE systems are more expensive than GAC for small-scale applications, but the costs increase higher for larger systems, specifically for surface water treatment. Mid-cost treatments, however, are more expensive for GAC in comparison to AE. These comparisons can be visualized in Figure 5 and detailed in Tables 11-13.

Lastly, Reverse Osmosis (RO) and nanofiltration (NF) had the most effective technologies where the removal efficiencies reached 99.9% for PFOA and other carboxylate PFAS. I found that membrane-based processes are more reliable but, unfortunately, come at much greater upfront and operational costs in comparison to GAC and AE. In Figure 5, the cost is significantly greater in all levels of components cost (low-high). Regarding the applicability of this technology for Parkersburg, this treatment method would be more suitable for the city based on the high-risk quotient levels analyzed in Chapter 2. On the other hand, the high costs can be financially burdensome for cities with smaller municipalities that cannot afford to pay such high costs in the short and long term.

In my results of Parkersburg's current upgrade plans, I noted that the city is already working to design a new water treatment facility that will comply with EPA's newly proposed PFAS standards. I also determined that the existing technologies are not sufficient to meet the new regulatory requirements of below than four parts per trillion. This highlights the need for further research for Parkersburg to evaluate the trade-offs between treatment effectiveness and the costs of BAT selection. Based on the percentages of efficiency and costs, I believe that combining technologies such as GAC for initial treatment and RO/NF for final treatments can result in a balanced solution to meet EPA's regulatory requirements while reducing operational and maintenance costs.

Conclusion

My analysis of the EPA's Best Available Technologies presents viable solutions for addressing the PFAS issue in Parkersburg. Each has its strengths and limitations, and the treatment methods will depend on the PFAS compounds currently in the groundwater, the scale of treatment required, and the financial resources available in the city. I recommend conducting a thorough evaluation, considering budgetary constraints, to determine the most suitable treatment approach.

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