HOUSEHOLD WATER ACCESS AS AN ENVIRONMENTAL JUSTICE ISSUE: HOW RACE AND INCOME ARE ASSOCIATED WITH WATER ACCESS ACROSS SPACE

By

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ABSTRACT

HOUSEHOLD WATER ACCESS AS AN ENVIRONMENTAL JUSTICE ISSUE: HOW RACE AND INCOME ARE ASSOCIATED WITH WATER ACCESS ACROSS SPACE

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Equitable access to clean and affordable household water services has received increasing academic attention in the past decades. This dissertation addresses the effects of water costs and quality through an environmental justice lens in three chapters. The first two chapters use a novel survey titled the Survey of Water Innovation and Socioeconomic Status of Households (SWISSH), which includes questions related to a range of water issues for respondents in nine regions across the United States (US).

Chapter one identifies demographic characteristics of those most impacted by rising water bills, the industries that could subsequently be affected by systematic changes in household budgets, and at what bill increase levels these trends are most pronounced. A randomized water price-increase scenario was presented to each respondent, who was asked about the effect these price changes would have on household purchases. Systematic differences among social and demographic changes were found, with major budget changes occurring with a water bill increase of just $12 monthly. Chapter two also uses SWISSH, in this instance to better understand household perceptions of whether water bills are too high according to social, demographic, geographic, and water billing characteristics. Results suggest low-income, minority, and otherwise underrepresented groups were more likely to perceive their water bills as too high. In terms of policy implications, model results indicate utilities can favorably affect perceptions of water bills via the frequency of water billing and provision of payment assistance programs. Chapter three uses spatial cluster analysis to understand neighborhood characteristics

surrounding highly polluted ‘Superfund’ sites known to be contaminated with PFAS. Several indicators of vulnerability including poverty, ethnic and racial minorities, linguistic barriers, and single parent households were found to be elevated in communities within a six-mile distance from these PFAS-polluted sites.

For my husband Sean and my parents June and Barry –
in gratitude for your unwavering support and positivity.

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KEY TO ABBREVIATIONS

ACS… American Community Survey

AWWA… American Water Works Association

BEA… Bureau of Economic Analysis

BLS… Bureau of Labor Statistics

CAP… Customer Assistance Programs

CDC… Centers for Disease Control and Prevention

CRS… Congressional Research Service

CBO… Congressional Budget Office

CERCLA… Comprehensive Environmental Response, Compensation, and Liability Act

CWA… Clean Water Act

CWS… Community Water Systems

DOD… Department of Defense

EJ… Environmental Justice

EPA… Environmental Protection Agency

EPL… Percentile Percentage Ranking for Social Vulnerability Index Themes

EWG… Environmental Working Group

EQI…Environmental Quality Index

FAFH… Food Away from Home

GDP… Gross Domestic Product

HOA… Homeowners' Association

OMB… Office of Management and Budget

PFAS… Per- and Polyfluoroalkyl Substances

PFOS… Perfluorooctane Sulfonate or Perfluorooctane Sulfonic Acid

PFOA… Perfluorooctanoic Acid

RPL_Theme… Percentile Ranking for Social Vulnerability Index Themes

RUCA… Rural-Urban Commuting Area

SCEPW… Senate Committee on Environment and Public Works

SDWA… Safe Drinking Water Act

SDWIS… Safe Drinking Water Information System

SPL… Percentile ranking for Social Vulnerability Index Themes

SVI… Social Vulnerability Index

SWISSH… Survey of Water Innovation and Socioeconomic Status of Households

UCC… United Church of Christ Commission for Racial Justice

UN … United Nations

WBG… World Bank Group

1. INTRODUCTION

1.1 Research Context: Environmental Justice

Environmental justice gained broad recognition in 1982 in response to illegal PCB dumping in a landfill in Warren County, which had the highest proportion of Black individuals across the state of North Carolina (Mohai, 2018). The controversy surrounding the Warren County PCB landfill led to increased public awareness that low-income and racial and ethnic minorities are more likely to be exposed to chronically polluted land (Bullard, 1983). Studies such as those by Bullard (1983), Cutter (1995) and the Commission for Racial Justice of the United Church of Christ Commission for Racial Justice (UCC) (1987) established environmental justice as a unified subject of study in the academic literature. These foundational studies established the basis for what is now understood as the three pillars of environmental justice. The first pillar is the need for an equitable distribution of ecological benefits and hazards. This is the most referenced component of environmental justice is ensuring environmental benefits and harm are equally distributed, regardless of income or race/ethnicity (Banzhaf et al., 2019). The second pillar is the integration of contexts of oppression in environmental actions. Here, the context of racial oppression must be recognized by policymakers and academics in addressing concerns of present-day inequities (Fraser et al., 2003). This context may be historical or involve present-day cultural factors such as societal norms and language. Cultural factors may perpetuate disadvantage and injustice for marginalized groups. Low-income and minority groups face unique challenges based on systems and cultural mores that must be acknowledged. The third pillar of environmental justice is the need for political representation in environmental policy decisions (Schlosberg, 2007; Environmental Protection Agency (EPA), 2022). Participation in governance decisions, particularly in the form of laws, regulation and policies is fundamental for ensuring environmental justice (Schlosberg, 2004; Schlosberg, 2009).

Access to clean drinking water and water sanitation is recognized internationally as a human right and essential to life (Schlosberg, 2007; United Nations (U.N.), 2014). Since water access and quality are a necessity in everyday life and largely dependent on ecosystem health, water issues are an essential component of the environmental justice paradigm (Schlosberg, 2007). Environmental justice studies of disparities in clean water provision provide examples of low-income and racial minority communities experiencing drinking water contamination at higher rates in the form of elevated nitrate, lead, coliform, and arsenic levels (Delpla et al., 2009; Schaider et al., 2019). As an example, the Flint Water Crisis in Michigan resulted in lead-contaminated water delivered to households after the local tap water source was changed without necessary corrosion controls added (Mohai, 2018). The water crisis in the Navajo reservation in Arizona and New Mexico is another example of environmental harm disproportionately affecting a community of color. Household drinking water contamination was a result of uranium mines leaching radioactive discharge into local water supplies with nearly 26% of wells had concentrations exceeding EPA standards despite previous cessation of mining activities in the 1980's. (Corlin et al., 2016; Raymond-Whish et al., 2007). Environmental justice studies find low-income households are particularly vulnerable particularly because often rural water providers have fewer resources for water sanitation and water quality compliance testing (Delpla et al., 2009; Ranganathan & Balazs, 2015). Indeed, inequity in clean water access occurs in American cities due to inadequate water infrastructure such as lead piping (VanDerslice, 2011). This dissertation examines water provision as an environmental justice issue, which is important to understand given the historical development of America's physical water infrastructure network, the age of these systems, and current climatic pressures on water systems (Delpla et al., 2009).

This dissertation examines a series of water issues across three chapters through the lens of a distributional environmental justice framework. The first series of questions center on whether increasing costs of distributing water affect vulnerable households, the household perceptions of these experiences, and potential inequities in the exposure to harm from pollution in the local environment. From a theoretical perspective, the first chapter explores the distribution of burdens of increased water infrastructure costs. Particularly, this chapter provides information about the budgeting decisions households make when faced with increased household water costs, and whether these changes disproportionally affect racial/ethnic minorities and low-income individuals. The second chapter adds to the existing body of environmental justice research by providing information on whether the costs of water services are perceived as fair for respondents according to race, ethnicity, class, and other characteristics. Knowledge about this topic sheds light on the experiences of households participating in utility programs designed to ease financial hardship in paying for water services. The last chapter of this dissertation asks whether there are inequities in the distribution of burdens of PFAS pollution emanating from Superfund sites. An index approach is used to capture any additive and/or interactive effects of various forms of social vulnerability on Superfund site proximity, which remain unevaluated in the literature thus far. Until now, no studies have considered three or more dimensions of vulnerability simultaneously when looking at potential PFAS Superfund exposure (Mohai et al., 2009; Switzer & Teodoro, 2018). Secondly, this paper is the first to focus exclusively on Superfund sites found to be contaminated with PFAS.

1.2 Water Infrastructure and Legislation in the 19th and 20th Century

For several decades, most Americans have enjoyed uninterrupted and affordable household tap water and wastewater services without having to give water infrastructure much thought. More recently though, policy makers and academics are increasingly interested in questions of maintaining water provision and wastewater management as a vital resource, due to rapidly shifting economic, demographic, and environmental trends. Globally, many countries are experiencing water-related crises that pose national security risks and fuel conflict, with no end in sight (Eliasson, 2015). For instance, the Chad basin has shrunk by more than 90 percent compared to its size in the 1960s diminishing local agricultural production, affecting transportation networks, diminishing trade links, and creating hostile relations among neighboring countries (Neiland & Bene, 2003; Okpara et al., 2015). Many other examples are also ongoing including the competition for water resources from 11 states surrounding the Nile basin (Dinar et al., 2015) and in South Africa there are risks of civil war and impacts on internal economic growth due to water shortages (Arnell, 2004). Demand for water is projected to grow more than 40% by 2050 and by 2025 an estimated two thirds of the global population will face circumstances where their water demand surpasses their available access to clean water supply (Eliasson, 2015). As a rich nation, the United States (US) is in a comparatively better position to ensure water service needs are met for the population, especially due to massive federal spending in the post–World War II period.

Prior to this era, in the 1800s to the early 1900s, America's water infrastructure was comprised of rudimentary physical infrastructure including reservoirs, pumps, pipes, and treatment plants (Burian et al., 2000), with only remnants of this system remaining today (AWWA, 2012). The first public water works in America were established at the end of the 18th

century in Pennsylvania, Rhode Island, and New York City. In New York City, private wells were used as the main public water source yet it wasn't until 1842 that city officials built infrastructure to transport water from the Croton River (National Research Council, 2002). The majority of wastewater management first gained relevance in America in the mid-1850s however, as emerging scientific advancements provided evidence of disease spread by water, including typhoid and cholera (National Research Council (NRC), 2002). In the midst of population growth, the increasing focus on public health, and increased demand for water to extinguish residential and industrial fires, the number of public water supplies in the United States increased from 83 in 1950 to over 3,000 in the beginning of the 20th century (National Research Council, 2002). In this period advances in water treatment methods led to the use of slow sand filtration and rapid filtration with chemical coagulation and in 1914, water service drinking water standards were adopted (AWWA, 1981). These standards included regulatory requirements such as bacterial limits and mandatory approval of water supplies in cities that provided water for interstate carriers by the U.S. Public Health Service (National Research Council, 2002).

Unfortunately, growing cities fell into a pattern of waiting until water demand greatly exceeded the capacity of water suppliers, to then contribute large-scale financial investments toward the import of water from elsewhere (Sedlak, 2020). The increased water demand was not only due to improved standards of living in this period, but urbanization also involves landscape changes including land surface, building, and infrastructure characteristics leading not only linked to changes in runoff due to the removal of natural vegetation, compaction of the soil and introduction of impervious surfaces increasing drainage density of urban catchments (Burian et al., 2013). These factors lead water providers scrambling to develop treatment plants to manage the resulting sewage-contaminated waters, leading to billions of dollars invested in technology for water filtration and chlorination (Sedlak, 2020). Though water sanitation technologies advanced, the next major allotment of federal funds toward water infrastructure did not occur until the post-World War Two period. After over two decades of foul odors emanating from urban waterways, unchecked algal blooms and various instances of extreme water pollution events, significant federal water legislation was passed (Congressional Research Service (CRS), 2019; Sedlak, 2020; U.S. Congressional Budget Office (CBO), 2014). The CWA's objectives are to restore and maintain the chemical, physical and biological integrity of the nations' waters (Copeland et al., 1999). It was initially a federal grant program allocating $65 billion in the period between 1972 and 2016 (CRS, 2016). Similarly, the SDWA is the key federal law for protecting public water supplies from harmful contaminates, consisting of programs that establish standards and treatment requirements for public water supplies, provide technical assistance to small water systems, finance infrastructure projects, and protect sources of drinking water (Tiemann, 2014). In response to this sweeping legislation, the mid-1970s to the mid-1980s represented the era with the largest water infrastructure investments in U.S. history, much of which forms the water infrastructure network in use today. The benefits were clear, as Americans enjoyed an unprecedented decrease in waterborne disease in tandem with lengthened average lifespans (Sedlak, 2020). This infrastructure overhaul was followed by modern filtration and chlorination methods, which improved water safety and public health further (Sedlak, 2020).

However, federal water infrastructure investments have stagnated since the 1980s in part due to a 1987 amendment to the CWA relevant to wastewater treatment construction. The CWA initially ensured federal grants for wastewater treatment construction were provided to local communities according to state priorities and did not require repayment (CRS, 2016b). However, the entire financial responsibility for achieving these goals was transitioned from the federal government to the states and local municipalities in the form of a revolving loan program. This loan concept required funds used for wastewater treatment construction be repaid to the state and put toward ensuing projects. This worked for wealthier states and localities, yet some states fared better at maintaining wastewater management goals than others (CRS, 2016b). An array of other challenges beyond financial restructuring known to have contributed to previous national water crises are surfacing in America once again. Urbanization continues to intensify in the modern time with 83% of the U.S. population living in urban areas, up from 64% in 1950. By 2050, 89% of the U.S. population is projected to live in urban areas (United Nations (UN), 2018). This challenge and others are discussed in more detail in the following sections.

1.3 Research Context: How Rapid Urbanization and Agglomeration Influenced the Building of US Water Infrastructure

The history of water infrastructure booms demonstrates that throughout US history, funding for water infrastructure was and indeed continues to be a reaction to a rapidly urbanizing society rather than carefully considered urban planning efforts. Many effects of this initial process are still felt today, with modern water infrastructure issues mirroring past crises. To understand the state of modern water infrastructure issues in America, it is important to situate its development within the context of historical American events. In the 1800s, industrialization propelled America from largely an agrarian nation to one of business and industrial manufacturing (Cochran, 1981). The rapid industry expansion triggered agglomerative forces to the surge of populations across many city clusters in the nation whereby it was increasingly advantageous for firms, consumers, and public institutions to spatially co-locate in space (Hoover, 1937; MacKinnon & Cumbers, 2018; Weber, 1962). For firms, this means having access to specialized inputs to minimize transportation costs, highly skilled labor, and the possibility for knowledge/information spillovers (Gordon & McCann, 2000). Under these circumstances, cities New York's population more than tripled between 1800 and 1830, with similar trends in Boston, Washington, and Philadelphia (Sedlak, 2020).

1.4 Challenges for Water Provision with a Decentralized Physical Water Infrastructure Network

Consequences of a decentralized water infrastructure network built in reaction to demographic shifts have three main consequences. First, there is very little information on broad water provision trends as there is no nation-wide information on water bill charges, demographic trends, or customer service level (Gaudin, 2006). Second, risk assessments and adaption plans for local water infrastructure focus on urban systems in isolation and fail to acknowledge important interconnections to other systems (Burian et al., 2013). Third, this approach sets the stage for the underfunding of water infrastructure at the national level (CBO, 2014). To elaborate on the first consequence, a decentralized network of water companies leads to lack of uniformity in important components of communication practices between water companies and the public and affects customer service. Effectiveness of communication varies by locality and often even by water provider. For example, a nation-wide study of the U.S 78 percent of water providers provided no information in water bills other than the total amount required for payment and progressive pricing schedules are difficult to understand for consumers (Gaudin, 2006; Olmstead & Stavins, 2009; Ruijs, 2009). These types of data are particularly valuable since research shows that without accurate pricing information, households underestimate the price of water and consume more than what is economically rational (Binet et al., 2014). A decentralized water infrastructure policy public health communication too. For instance, while lead in water remains present in household drinking water for years after construction work disrupts service lines of municipal water systems (Hawthorne, 2016), Chicagoans were not informed by potential health risks posed by lead after water mains were replaced (Hawthorne, 2016). Without easily accessible consumer health communication by water providers, most people draw conclusions about water safety based on organoleptic properties such as taste, hardness, color, odor and turbidity which do not pose measurable health risks (Celik & Muhammetoglu, 2008; A. Q. Jones et al., 2007; Wright et al., 2012).

Secondly, water providers across the US provide to consumers based on political and jurisdictional boundaries rather than watershed boundaries, and often there are multiple water providers at the neighborhood level (Burian et al., 2013). Risk mitigation plans for climate effects and urbanization adaptation are often localized at the individual water company or municipal level in isolation from other systems such as energy, though a larger scale approach would often be more effective and efficient for long-term planning (Burian et al., 2013). As for climate change in particular, urban water systems must adapt to pollution and climate change and other factors that influence the water cycle affecting water supplies available as well as water quality (Barnett et al., 2005; Taylor et al., 2013; Tu, 2009). For example, climate change is expected to increase the intensity of rainfall, potentially overwhelming sewer infrastructure and increasing operating costs (Ruth et al., 2007). However, without an overarching plan to adapt to large-scale climate changes, climate adaption plans executed exclusively at the local level may lead to inefficiencies.

Regarding the third and final consequence of a decentralized water infrastructure network, these issues all must be evaluated in the context of stagnant federal funding for water infrastructure and increasingly aging physical infrastructure (CBO, 2015). For instance, though the federal government just passed an infrastructure plan that allocates $55 billion towards water infrastructure (USA White House, 2021), infrastructure outlays required for replacements and improvements over the next two decades totals $600 billion (EPA, 2020). Outdated infrastructure increases the costs of maintenance and operations for American utility companies, particularly eroding the razor-thin margins of small water companies, if they are making a profit at all (Cohen, 2012; U.S. Congressional Budget Office (CBO), 2015; U.S. Environmental Protection Agency (EPA), 2018, 2020a). To overcome these challenges, water companies largely pass these added expenses to customers in the form of higher water bills. As reports emerge that residents in some cities struggle to afford water bills (Walton, 2016), this trend jeopardizes water providers' revenue stream in the event that water bills go unpaid (Gaudin, 2006; Kane & Tomer, 2019; EPA, 2020; Walton, 2016). Though water services bills comprise a small share of household budgets in the United States (BLS, 2017), it is important to consider the size of water bills relative to overall household income levels, particularly in the case of low-income households. While the dollar amount spent on water is likely to be lower for low-income households, water bills on average comprise a larger proportion of their overall monthly expenditures, increasingly putting water bill payments out of reach for vulnerable citizens (Mack & Wrase, 2017; Ruijs, 2009; BLS, 2017).

Outdated infrastructure, stagnating federal funding for water investment and operations, a decentralized network of water providers, pollution, climate change, and demographic shifts have all strained water companies (Tu, 2009; VanDerslice, 2011). However, the effects of these problems are not felt evenly throughout the American population since water crises are overrepresented in low-income and/or predominantly minority communities (Y. J. McDonald & Jones, 2018; Mohai, 2018). The Flint Water Crisis is unfortunately one of many contamination events that disproportionately affected minority communities and areas with high poverty across the U.S. Other examples include Martin County, Kentucky, where impacts of a mining spill still pose health risks such as cancer from water contamination (Scott et al., 2012). In Denmark, South Carolina, long-term use of treatment chemicals unauthorized by the U.S. Food and Drug Administration has led to rust-colored tap water and concern about residents' health (Woodward, 2020). Though federal regulation like the CWA and SDWA were imperative for establishing standards and funding the water infrastructure in place today, studies have found racial and economic disparities in those who are exposed to contaminated drinking-water in their homes through community water systems (CWS). For instance, (Y. J. McDonald & Jones, 2018) find that higher minority racial/ethnic composition and lower socioeconomic status of counties served by CWS were disproportionately more likely to receive repeat violations of the safe drinking water information system (SDWIS). These authors find that as the population size served by CWS increased, the proportion of non-Hispanic Blacks and Hispanics in a community was associated with an increase in initial SDWIS violations. Switzer and Teodoro (2018) also use regulatory records to evaluate justice in safe drinking water. These authors confirm the finding that racial/ethnic composition is a predictor of experiences of contaminated drinking water. In addition, Switzer & Teodoro (2018) stress that these racial trends are closely tied with socioeconomic status. For instance, they find Black and Hispanic Americans are more likely to experience SDWA violations. It should be noted further that SDWIS is criticized for a lack of representative analysis of CWS compliance due to the cost-prohibitive nature of testing water quality across the U.S, so many smaller water systems are often missed (Beecher, 1994). Further, federal water legislation has failed to keep up with novel manmade types of pollution as in the case of Per- and Polyfluoroalkyl Substances (PFAS). PFAS are manmade chemicals associated with negative health implications including cancer, immune system disorders, fertility problems, and developmental disorders in infants (Herrick et al., 2017; Hoffman et al., 2011). The public health risk of PFAS is most pronounced for those consuming water from private wells and small public water suppliers especially where there are landfills or military bases nearby (X. C. Hu et al., 2016a). Though contaminated tap water is the major PFAS exposure source for water-contaminated communities, in the absence of contaminated household water supplies diet is the predominant PFAS exposure pathway (De Silva et al., 2021).

Beyond the CWA and SDWA another law related to mitigating water pollution, and in particular PFAS is the Comprehensive Environmental Response, Compensation, and Liability Act (informally Superfund), passed in 1980 (CERCLA, 1980). CERCLA is a federal law enacted to ensure environmental remediation of heavily polluted sites in part by allowing the EPA to initiate and monitor cleanup efforts and hold parties accountable for funding Superfund cleanup projects (EPA, 2020b). Thousands of contaminated sites are deemed hazardous to the public, having received designated status through CERCLA. The threat of groundwater contamination is particularly relevant since approximately 85% of Superfund sites include response actions for mitigation of groundwater contamination indicating heightened exposure risk to groundwater supplies (EPA, 2021a). While PFAS are not yet regulated as hazardous substances through CERCLA, the EPA released guidance for PFAS Groundwater for Federal cleanup programs in December, 2019 (EPA, 2019). PFAS was found at elevated levels (at or above 70 ppt) in the water and soil at approximately 10 percent of Superfund sites in the contiguous U.S. (SCEPW, 2019).The Pentagon acknowledges that PFAS contaminates groundwater within proximity to Superfund sites contamination is present and estimate cleanup activity, including pumping and treating groundwater, which may take up to several decades at military bases (DOD, 2020).

The three chapters of this dissertation evaluate how contemporary water-related issues contribute to challenges associated with environmental justice in the form of access, affordability, and distribution of ecosystem services that watersheds provide. All three chapters of this dissertation fit within a distributional environmental justice framework. Specifically, this dissertation is an investigation of how increasing costs of distributing water affect vulnerable households, gauge the household perceptions of these experiences, and research inequities of potential exposure to harm from pollution in the local environment. The first chapter of this dissertation asks: “How do increases in household water costs affect households of various socio-economic, demographic subsets of the population, and the economy at large? Are there particular industries that are affected indirectly by increased water bills?” From an environmental justice perspective, this chapter explores the distribution of burdens of increased water infrastructure costs. Particularly, information is provided about the budgeting decisions households make when faced with increased household water costs, and whether these changes disproportionally affect racial/ethnic minorities and low-income individuals. The academic literature associated with questions of water cost often focuses on how pricing structures affect the quantity of household water demand, finding that while progressive water schemes such as block-rate pricing may reduce water demand, other forms such as time-of-day has little effect (Dalhuisen et al., 2003; Ruijs, 2009). However, we do not understand how household spending changes due to projected increases in water bills, or how these changes affect overall levels of demand for particular goods and services, or particularly vulnerable communities. The analysis of this chapter helps us understand whether consumers in the U.S. change spending behavior in response to increased water bill costs, and if so, who?

The second chapter of this dissertation evaluates public perceptions of whether household water bills are too high. The question this paper addresses is: “Are there differences between individuals belonging to various demographic and socio-economic groups in their perceptions of the fairness of water bills?” Evaluating this question adds to the existing body of environmental justice research by providing information on whether the costs of water services are perceived as fair for respondents according to race, ethnicity, class, and other characteristics. Knowledge about this topic also sheds light on the experiences of households participating in utility programs designed to ease financial hardship in paying for water services. Until now, research on perceptions of water value has focused on a few key areas: (1) the safety and palatability of drinking water including perceptions of re-use (A. Q. Jones et al., 2007; Wright et al., 2012), (2) the quality of water service including customer service and water service interruptions (Celik & Muhammetoglu, 2008; Wright et al., 2012) and (3) the factors affecting the willingness to pay for tap water (Dolnicar & Schäfer, 2009; Javidi & Pierce, 2018). Trends in perceptions about whether water bills are fair or unfair are not yet explored. This paper fills in knowledge gaps about the demographic and socio-economic characteristics of those who feel their water bills are unfair, and how water policies may influence these perceptions.

The final chapter focuses on the distribution of harm associated with within proximity to ‘Superfund’ sites polluted with PFAS. Whether low-income and racial/ethnic minorities are more likely to be exposed to pollution is a common focus of environmental justice literature (Bullard, 1983; Cutter, 1995; Mohai, 2018). However, this study is the first to provide knowledge about whether there are clusters of high social vulnerability and PFAS contamination problems surrounding Superfund sites. Two questions are posed to explore this issue. The first question asks: “Are there statistically significant patterns of social vulnerability around Superfund sites known to have elevated PFAS levels (≥70 parts per trillion), and if so, where?" Answers to this question provides insight into levels of combined and interactive effects of various forms of social vulnerability as they may relate to risk of exposure to environmental pollutants. The second question of this study asks "Which aspects of vulnerability, if any, are most strongly associated with spatial proximity to PFAS Superfund sites?" This subsequent question allows for a deeper understanding of which measures of vulnerability, if any are more strongly associated with PFAS exposure individually. It is important to study PFAS in a Superfund context because improving drinking water quality improvements remain a key target at the majority of Superfund sites, and drinking water is the most common source of PFAS exposure in areas with PFAS in the environment (De Silva et al., 2021).

2. A SCENARIO-BASED APPROACH FOR UNDERSTANDING CHANGES IN CONSUMER SPENDING BEHAVIOR IN RESPONSE TO RISING WATER BILLS[1]

2.1 Introduction

High- and low- income countries face challenges ensuring clean, abundant and affordable household water and wastewater services for all (Dalhuisen et al., 2003; Espey et al., 1997; Sebri, 2014). Although there is an abundance of research on water access and affordability in the developing world, (Dinar et al., 2015; Le Blanc & Perez, 2008; Roson & Sartori, 2015), water access is emerging as an increasingly critical issue in higher income countries as well (Griffin et al., 2013; Haddeland et al., 2014; Warner et al., 2018). One indicator that water provision in higher income countries is an issue are water shutoffs. In 2016, an estimated 15 million people experienced a water shutoff (Food and Water Watch, 2018). For this same year, data indicate that a sizeable proportion of households in some American cities experienced a water shutoff. These cities include Oklahoma City, Oklahoma (23%); Tulsa, Oklahoma (20%); Springdale, Arizona (19%); and New Orleans, Louisiana (17%) (Food and Water Watch, 2018).

Rising costs of water are anticipated to exacerbate affordability challenges for lower income households (Mack & Wrase, 2017). One of the drivers of these challenges is aging infrastructure as the United States (U.S.) finds itself in an era of water infrastructure replacement (AWWA), 2012). America's water infrastructure was established with investments in reservoirs, pumps, pipes, and treatment plants spanning from the 19th to the early 20th centuries (Burian et al., 2000). Although remnants of this infrastructure remain (AWWA, 2012), the bulk of the water

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infrastructure systems in use today were built in the post WWII period as a reaction to the Clean Water Act, passed in 1972, and the Safe Drinking Water Act, passed in 1974. This legislation was followed by the highest percentage of funding by the federal government in new water infrastructure from the mid 1970's to the mid-1980s (CBO, 2015). Since the 1970s, federal investments in water infrastructure have remained relatively stagnant while operation and maintenance costs have steadily increased (CBO, 2014; Walton, 2015).

An estimated $600 billion in investments towards water infrastructure will be required over the next two decades to maintain and improve America's water service provision (EPA, 2020a). This places utilities in a difficult position of finding funds for necessary improvements. For public utilities in the United States, the main source of recovering costs is the rates charged to consumers (AWWA, 2019; EPA, 2019b) and there is evidence that these increasing costs of providing services are making their way into consumers' water bills. Between 2010 and 2015, data for 30 major U.S. cities indicate rate increases of 41% (Walton, 2015). Between 2016 and 2018, there was a 7.2% increase in America's overall household water bills (AWWA, 2019b).

Rising infrastructure costs for water providers and the rising cost of water for households, pose several challenges for water providers, policymakers, and the research community. Among these challenges is understanding the response of consumers to the rising costs of water services. Consumers may utilize several strategies for coping, including reduced water use or spending reductions on other household goods and services. This study tackles the latter outcome given the importance of consumer spending to the health of the economy. In the United States, consumer spending accounts for 70% of GDP (The World Bank Group (WBG), 2018). This link between spending and economic health was highlighted during the Covid-19 pandemic when spending decreased 13% between March and April of 2020 (U.S. Bureau of Economic Analysis

(BEA), 2020). This crisis led to systematic changes in household spending behavior; grocery spending increased while spending on travel, shopping, transportation and entertainment and restaurants decreased (Leatherby & Gelles, 2020). Even household spending on healthcare, an industry generally resistant to recessions, was down 29% (BEA, 2020).

To provide a first glance at the link between rising water bills and consumer spending, this study incorporates data from a household survey about water issues in nine regions across the United States (Harlan et al., 2019) into a choice modeling framework to answer the following research questions. One, does U.S. household spending change with an increase in water bill levels? Two, at what level increase in water bill levels do American households significantly change household spending behavior? Three, what types of goods are most impacted by changes in water bill levels? Four, what role do demographic and socio-economic status play in changing household spending patterns?

Results of this analysis provide insights into the demographics of households likely to be affected, the industries that could be affected, and at what bill increase levels these trends are most pronounced. While additional research on this topic is needed, these results suggest a stronger emphasis on long-term water management planning and allocation of resources to building and maintaining water infrastructure may be required (Haddeland et al., 2014; Larson et al., 2016; Stikker, 1998). For utilities this means a consideration of non-revenue sources of funds to pay for rising water costs and strategies for making water more affordable for customers without deferring infrastructure improvements.

2.1.1 Linking Water Infrastructure Costs to Consumer Expenditures on Water Services

To understand how rising costs of water provision are passed on to consumers, Figure 1 presents key elements of this process. First, replacing aging infrastructure coupled with other pressures on water systems increases the cost of providing services (CBO, 2015; EPA, 2016). From 2007 to 2017 in the United States, public spending on infrastructure fell by $5.6 billion dollars (adjusted for inflation) (Kane & Tomer, 2019). This decline in federal support for infrastructure, coupled with the estimated $600 billion needed to improve water services provision (EPA), 2020) places public utilities in a difficult situation. Annually, there are approximately 240,000 water main breaks resulting in $2.6 billion losses and 75,000 of sanitary sewer overflows that discharge untreated wastewater into water systems (EPA, 2010). Climate change compounds the stress of outdated infrastructure and leads to uncertainty about the quantity and quality of water available, (Barnett et al., 2005; Dai et al., 2018; Taylor et al., 2013) by altering the function of natural systems including: soil moisture, the distribution of runoff, evaporation, and rainfall patterns. Additional strains on water provision and wastewater services in the U.S. include population increases, urbanization, and increased per-capita water service consumption (EPA, 2018).

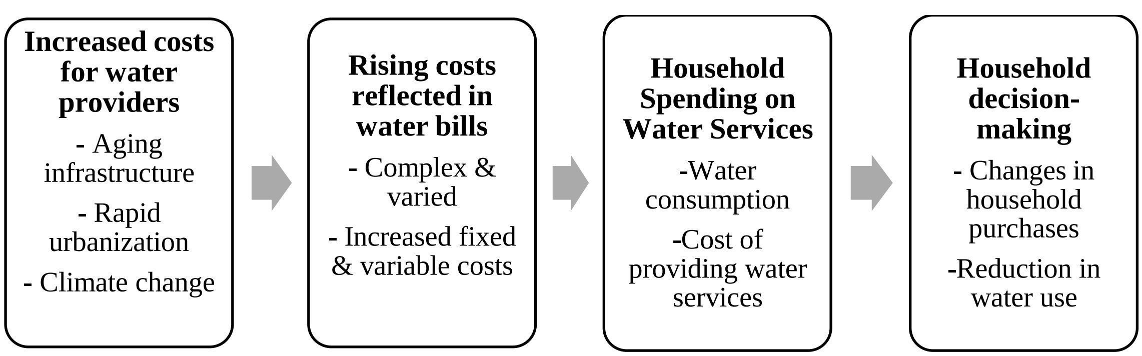

Figure 1 *Linking Infrastructure Costs to Consumer Spending Choices*

Second, declining funds from the federal government means the primary means for utilities to recoup the rising costs of providing water services is to pass these costs on to consumers, regardless of the billing structure (Gaudin, 2006). Third, households serviced by a water utility receive a bill for their water use. This bill is driven by two main factors: water usage and the costs of providing water services, as determined by their designated water services provider.

Fourth, households make decisions about future water consumption and spending in response to their bill for water services. If the overall level of water bills increases, consumers can use two coping strategies. One of these strategies is to reduce water consumption. Americans in particular are heavy consumers of water for outdoor use compared to other high-income countries (Inman & Jeffrey, 2006). Cultural norms such as maintaining a large green yard, owning swimming pools, and gardens contribute to this water intensive lifestyle (Renwick & Green, 2000). High-income households in particular use the most water because they are more likely to live in households with both indoor and outdoor water amenities, offsetting water savings from efficient appliances and fixtures (Harlan et al., 2009). While this is certainly one option, research indicates it may not be possible for all households. Lower income households may be less able to reduce overall consumption than are wealthier households (Olmstead et al., 2007). Studies also note that in the short run, consumers do not change their water consumption behavior (Gaudin, 2006; Renwick & Green, 2000).

A second strategy for coping with rising water costs is to reduce spending on other household budget items. Several studies have analyzed how consumers change spending behavior during times of recession (Hampson & McGoldrick, 2017) and in response to income inequality (Charles & Lundy, 2013). However, they have not analyzed whether rising water costs change consumer spending behavior. It is important to evaluate if these changes are evident not only because of the importance of consumer expenditures to the global economy, but also because systematic changes in household expenditure patterns may have broader economic implications related to the phenomenon of expenditure cascades (Frank et al., 2014). In other words, when one consumer group changes their spending behavior, these changes are mimicked by other consumer groups. For example, increased spending by high-income groups promotes changes in spending down the income ladder and causes lower-income groups to also spend more (Kamakura & Du, 2012). These cascades can also apply to reductions in spending behavior and studies find evidence that spending reductions in lower income groups can trickle up the income ladder and reduce spending in high-income households (Flatters & Willmott, 2009).

These changes take place because they redefine the frame of spending reference against which consumers compare themselves (Frank et al., 2014). Studies of relative consumption highlight that positional goods, which indicate status and wealth, as well as comparisons of spending relative to a reference group influence consumer spending choices and the associated utility derived from this spending (Kamakura & Du, 2012). Studies of expenditure cascades have provided important insights about changes in household spending during recessions (Dekimpe & Deleersnyder, 2018; Kamakura & Du, 2012). For example, Kamakura and Du (2012) found that during recessions, positional goods such as apparel, jewelry, home furnishings and airfare become less desirable than do essential goods such as food at home, and health insurance. To our knowledge, there are no studies that analyze how rising household water service bills impact consumer spending. This connection is important to evaluate because of the potential for expenditure cascades.

2.2 Data

Table 1 compares survey data for each region to data from the American Community Survey (ACS) data from the U.S. Census Bureau. This comparison highlights that survey respondents are quite similar to the populations of these regions with a few exceptions. One, there is a slight overrepresentation of higher educated individuals (with a bachelors/graduate degree) and underrepresentation of respondents with less than a high school diploma. Younger respondents (ages 25-44) are also slightly overrepresented compared to respondents 45-64.

Table 1 *Comparing Demographic Composition of SWISSH Survey with the U.S. Census American Community Survey*

Variable Description	% Households	SWISSH	ACS
Income	Less than 50k	40%	40%
	$50k-$99.9k	30%	30%
	100k	30%	30%
Education	Less than a high school degree	02%	12%
	High school degree or GED	18%	23%
	Some college or associates degree	25%	29%
	Bachelor's degree	32%	22%
	Graduate/professional degree	23%	14%
Age	Between 25 – 44 years	40%	41%
	Between 45 – 65 years	41%	39%
	Over 65 years	19%	20%
Race/ Ethnicity	White alone	58%	57%
	Black or African American alone	13%	13%
	Asian alone	06%	06%
	Hispanic/Latinx	21%	21%

*All non-race variables are for population 25 years or older

This survey contains a question that asks respondents to indicate how they would react to an increase in the overall cost of their water bill. The text of this question is as follows:

“Suppose your water bill increases by $x a month ($xxx a year) beginning January 1, 2018. Your income stays the same. Please show how this increase in your water bill would affect your spending.”

Respondents were presented with one of five possible increases (Table 2) and were asked to select one of the following responses for each of the expenditure items outlined in Table 2:

(1) not currently spending anything

(2) no change in spending

(3) cut back on spending

(4) would not be able to afford this

The dollar values presented in Table 2 are based on increases in water bills of 10%, 30%, 50%, 80% or 100% using $120/month as a base water bill value (Mack & Wrase, 2017; U.S. Congressional Budget Office (CBO), 2018; Walton, 2015). The dollar value associated with this question was randomized across respondents. Table 2 breaks down the number of respondents for each bill increase scenario.

Table 2 *Bill Increases, Goods and Services, and Response Options in SWISSH Survey*

Hypothetical Monthly Water Bill Increase & Respondent Count	Expenditure Category		Response Options
	Essential Goods	Less Essential Goods	
$12 (n = 1836) $36 (n = 1927) $60 (n = 1840) $96 (n = 1788) $120 (n = 1854)	- Car/Truck Payments, Repairs & Maintenance - Childcare Expenses - Doctor Visits - Electric/Gas/Heating Bills - Groceries - Health Insurance - Internet - Mortgage/Rent Payment - Prescription and Over the Counter Medicine - Public Transportation Smart Phones/Pre-Paid Phones	- Alcohol - Books/Magazines - Cable TV - Car/Truck Insurance - Clothing - Education - Educational Loans - Food Away from Home (FAFH) - Gifts and Charitable Giving - Gym Membership - Home Furnishings - Home Insurance - Movie Theatre Tickets - Personal Care Products/Services Pets - Sporting Events - Theater Tickets - Tobacco - Vacations/ Personal Travel	- Not Currently Spending Anything - No Change in Spending - Cut Back on Spending - Would Not be Able to Afford This

***** Expenditure categories are based the Consumer Expenditure Survey from the Bureau of Labor Statistics (BLS 2017).

The distribution of respondents assigned to each scenario ranges from 1,787 to 1,927. Thus, there are roughly the same number of individuals assigned to each scenario.

2.3 Methods

Multivariate logistic regression models were estimated to analyze if and how households change their spending behavior in response to rising water bill levels controlling for socio-economic, demographic, and geographic characteristics.

Table 3 *Explanatory Variable Names and Descriptions*

Variable Name	**Variable Type**	**Variable Description/Values (Base variable in bold)**
Water Bill Increase Category	Categorical	Hypothetical increase in monthly household water bill (USD) by: **$12,** $36, $60, $96, $120
Age	Numerical	Age in years
Race/Ethnicity	Categorical	- Hispanic - **Non-Hispanic White** - Non-Hispanic Black - Non-Hispanic Asian - Non-Hispanic Other (Other includes Middle Eastern, Native American, Native Hawaiian or Pacific Islander, and Mixed race)
Gender	Indicator	- **Male** Female
Income	Categorical	Annual salary: - less than $50,000 - $50,000- $100,000 - **Greater than $100,000**
Employment Status	Categorical	- **Working Full-Time or Part-Time** - Unemployed - Retired Student, Homemaker, or Other
Household Type	Categorical	- **Single Family Home** - Multi-Family Unit or Apartment - Mobile home or Other
Education	Categorical	- No high school - High school - Community college - **College Graduate or higher**
Region	Categorical	- Eastern Massachusetts (Boston - Worcester) - Front Range-Colorado (Denver – Fort Collins) - Mid-Atlantic (Washington, DC – Baltimore, Maryland) - Pacific Northwest-Oregon (Portland – Eugene) - **Piedmont Atlantic (Atlanta, Georgia – Charlotte, North Carolina)** - Southeastern Florida (Miami – Palm Bay-Melbourne) - Southeastern Michigan (Detroit – Flint) - Southern California (Los Angeles – San Bernardino) - Sun Corridor-Arizona (Phoenix – Tucson).
Wave	Categorical	**Wave 1: Collected 2018** Wave 2: Collected 2018 Wave 3: Collected 2019

The model contains a discrete choice independent variable pertaining to each of the four expenditure response options (see Table 2). The coefficients resulting from the regression analysis are estimated using maximum likelihood. The predicted probability of a change in spending behavior is estimated as follows:

$$\Pr(y = j) = \frac{e^{z_j}}{1 + \sum_{k=1}^{J-1} e^{z_k}} \quad \text{for } j = 1, 2, J - 1 \tag{1}$$

$$\Pr(y = J) = \frac{1}{1 + \sum_{k=1}^{J-1} e^{z_k}} \tag{2}$$

where j=1 pertains to not spending anything, j=2 pertains to a cut back in spending and j =3 pertains to would not be able to afford this. Expenditure choice *J* is "No change in spending," the reference category. The *z* variable is specified as follows:

$$z_j = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n \tag{3}$$

where β_0 is the intercept of each model, β_i (i = 1, 2, …, n) is a vector of slope coefficients of the MLM and X_i (i = 1, 2, …, n) is a vector of independent variables which include (1) the water bill level, (2) the socioeconomic characteristics of respondents and (3) demographic characteristics (see Table 3). Results for this variable are interpreted relative to the reference expenditure category. In this analysis, Y^* is a ratio between the probability of selecting each expenditure change option (wouldn't afford, cut back spending, not currently spending) relative to the probability that no spending change occurs. The odds ratios (also referred to as relative risk ratios) are detailed in Equations 4 – 6 using information from Equations 1 – 3:

$$Y_{WA}^{*} = \ln\left(\frac{P(wouldn't\ afford)}{P(no\ spending\ change)}\right) \tag{4}$$

$$Y_{CB}^{*} = \ln\left(\frac{P(cut\ back\ spending)}{P(no\ spending\ change)}\right) \tag{5}$$

$$Y_{NS}^{*} = \ln\left(\frac{P(not\ spending)}{P(no\ spending\ change)}\right) \tag{6}$$

Base comparison categories were also selected for several categorical control variables included in the models. The base categories chosen for each independent variable are bolded in Table 3. In general, indicators of high socioeconomic status were selected as the comparison category: Non-Hispanic White (for race/ethnicity), Greater than $100,000 (for income), Male (for gender), College Graduate or Higher (for education), Working Full-Time or Part-Time (for employment). The base category for the water bill increase variable was the lowest dollar value at $12/month. This means the odds ratio for a water bill increase of $36 is interpreted as *individuals are x percent more likely to change spending on good y if water bills increase by $36 compared to $12.* Therefore, these odds ratios are used to determine how socioeconomic status, demographic characteristics and water bill increases affect systematic household spending choices.

The specification of the models estimated and presented in the next section is based on variables known to affect spending behavior including: household income, geographic variables, household type, and demographic characteristics (Harlan et al., 2009; Inman & Jeffrey, 2006;

Renwick & Green, 2000). Based on the work of (Du & Kamakura, 2008), separate models were estimated for each good or service separately. This approach also allows for the multivariate estimation of the four response choices simultaneously as outlined in equations 4 – 6. All models were estimated with probability weights and the study regions as strata[2].

2.4 Results

This section discusses general trends in survey responses and then the results of the multinomial logit regression models. This discussion focuses on two expenditure categories, cut back in spending and would not be able to afford, since these options represent changes in behavior. The options, not currently spending anything and no change in spending, do not represent changes in behavior.

2.4.1 Trends in Survey Responses

Table 4 presents a breakdown of survey responses by expenditure change option for each water bill increase scenario. The number of respondents is highlighted in grey and the corresponding percentage for this count is provided below. These responses are grouped into two categories, essential and less essential goods (see Table 2) (Bronner & de Hoog, 2016; Du & Kamakura, 2008). Examples of essential goods are groceries and doctor visits. Examples of less essential goods are gym memberships and food away from home (FAFH) (i.e. dining out).

[2] This involved use of the svyset command in Stata. Pweights was the weighting function used in the estimation of model results.

Table 4 *Average of Tabulation Data for Household Expenditure Response to Water Cost Increase (Weighted)*

		Water Cost Increase Scenario				
	Household Expenditure Change Option	**$12**	**$36**	**$60**	**$96**	**$120**
Less Essential	Not Spending	540.3	570.3	550.3	538.5	542.2
		29.4	29.6	29.9	30.1	29.3
	No Change	803.3	743.7	681.7	606.9	625.2
		43.8	38.6	37.0	34.0	33.7
	Cut Back	377.2	462.4	453.6	482.9	511.4
		20.6	24.0	24.7	27.0	27.6
	Wouldn't Afford	114.8	150.2	154.2	159.6	174.6
		6.3	7.8	8.4	8.9	9.4
	Total	1835.5	1926.7	1839.8	1787.8	1853.3
		100.0	100.0	100.0	100.0	100.0
Essential	Not Spending	355.7	381.2	367.1	359.3	363.5
		19.4	19.8	20.0	20.1	19.6
	No Change	1148.6	1138.4	1081.0	1000.5	1030.8
		62.6	59.1	58.8	56.0	55.6
	Cut Back	259.4	326.9	307.60	342.1	365.1
		14.1	17.0	16.7	19.1	19.7
	Wouldn't Afford	71.8	80.3	84.1	85.9	93.9
		3.9	4.2	4.6	4.8	5.1
	Total	1835.5	1926.7	1839.8	1787.8	1853.3
		100.0	100.0	100.0	100.0	100.0

*Percentage of respondents in white below

An examination of the rows for cut back and wouldn't be able to afford highlights a difference between these two good categories. A successively higher percentage of respondents reported they would cut back on less essential goods the higher the water bill increase. For example, 20.6% of respondents indicated they would cut back on essential goods for a $12 increase in their water bill. This percentage increases to 27.6% with a $120 increase in water bills. 6.3% of respondents indicated they would not be able to afford less essential goods for a $12 increase in their water bill compared to 9.4% for a $120 increase in their water bill. A similar pattern is true for essential goods. However, the percentage of respondents in the cut back and would not be able to afford categories is lower for every bill increase scenario. 14.1% of respondents indicated they would cut back on essential goods with a $12 increase in water bills compared to 19.7% of respondents for a $120 bill increase. Only 3.9% of respondents indicated they would not be able to afford essential goods for a $12 bill increase compared to 5.1% of respondents for a $120 bill increase.

Figure 2 provides more detail about all of the goods respondents indicated they would cut back on or not be able to afford. This is a stacked bar graph where the bottom of the bar corresponds to the percentage of respondents for a $12 bill increase. Each subsequent bill increase raises the cumulative percentage of people who indicated they would cut back or not be able to afford a particular item. So, the height of the bar correspond to the largest bill increase of $120. Using groceries as an example, at a $12 increase in water costs, 30% of individuals reported they would cut back spending. At a $36 increase, 36% said they would cut back on spending. This trend continues until approximately 40% indicated they would cut back spending on groceries at a $120 water cost increase. The bars for other goods in this figure may be interpreted similarly.

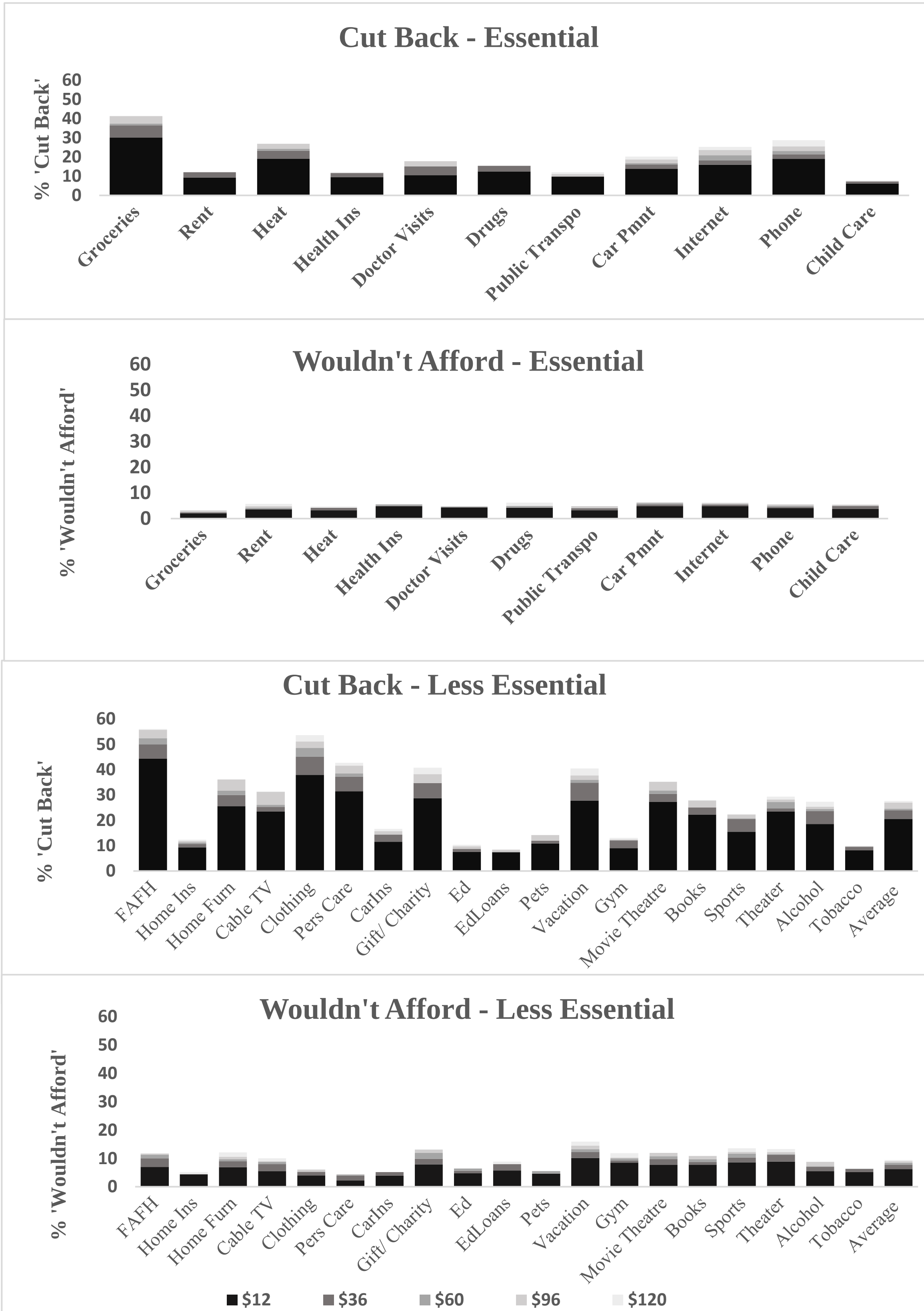

Figure 2 *Distribution of Responses by Bill Increase Amount and Type of Good/Service*

This figure highlights two factors contribute to expenditure changes: (1) the type of good and (2) the magnitude of the water bill increase. Regarding the types of goods, a larger proportion of individuals indicated a change in spending on less essential goods compared to essential goods regardless of the water cost increase. 3-4% of respondents indicated they would not be able to afford essential goods, and 4-6% of respondents indicated they would not be able to afford less-essential goods. The magnitudes of effects for goods such as food away from home (FAFH), clothing, gifts and charity, personal care items and vacation spending are particularly striking. Conversely, essential goods like rent, health insurance, public transportation and childcare are less sensitive to water bill increases.

Aside from the type of good in question, households' responses also depended upon the magnitude of the bill increase; higher percentages of respondents indicated they would cut back spending on goods the larger the bill increase. For example, about 44% of respondents indicated they would cut back on FAFH for a $12 bill increase while 50% and 52.5% of respondents indicated they would cut back on FAFH for bill increases of $36 and $60 respectively.

2.4.2 Regression Results

Table 5 summarizes model results focusing on the magnitude of the water bill change and the type of good. The columns in table 5 are the bill increase scenarios. The rows of the table correspond to the two expenditure changes of interest: cut back in spending and would not be able to afford. Within these two changes, results for the individual regressions for each good are subdivided further into essential and non-essential. Goods are only included in the table if the odds ratio for a price change was statistically significant at the 10% level. For example, items in the cell corresponding to the essential row and the $36 price change column are goods that had a statistically significant odds ratio. This means that compared to a price change of $12, respondents indicated they would be more likely to cut back spending on those goods (groceries, doctor visits, medicine, heating bills, and car payments). The goods appearing in bold indicate a change in spending behavior for the first time at that bill increase level. For example, the bolded good childcare in the essential row for cut back in spending in the $96 column is the first time that bill level change became statistically significant in model results. Based on the number of less essential goods listed in table 5, it is clear respondents prioritized spending changes on these items relative to essential goods. It is also interesting to see variations in answers depending upon the amount of the bill increase. For example, people did not indicate they would cut back on childcare or health insurance until a $96 change in their water bill. No cutbacks in spending were indicated for public transport until bills increased by $120.

***Table 5** Water Service Cost Increases Leading to Significant Change in Spending Behavior*

		$36	**$60**	**$96**	**$120**
Cut Back on Spending	**Essential**	· **Car payment** · **Doctor visits** · **Groceries** · **Heating bills** · **Internet** · **Phone** · **Prescription Medicine** · **Rent**	· Car payment · Doctor visits · Groceries · Heating bills · Internet · Phone	· Car payment · **Childcare** · Doctor visits · Groceries · **Health insurance** · Heating bills · Internet · Phone · Prescription Medicine · Rent	· Car payment · Childcare · Doctor visits · Groceries · Health insurance · Heating bills · Internet · Phone · Prescription Medicine **Public transport** · Rent

Table 5 *(cont'd)*

Cut Back on Spending	**Less Essential**	· **Alcohol** · **Books** · **Cable TV** · **Car insurance** · **Clothing** · **Education** · **FAFH** · **Gifts/charity** · **Gym** · **Home furnishings** · **Movie theatre** · **Personal care** · **Sports** · **Theater** · **Tobacco** · **Vacation**	· Alcohol · Books · Cable TV · Car insurance · Clothing · FAFH · Gifts/charity · Gym · Home furnishing · Movie theatre · Personal care · Sports · Theater · Vacation	· Alcohol · Books · Cable TV · Car insurance · Clothing · Education · **Education loans** · FAFH · Gifts/charity · Gym · Home furnishing · **Home insurance** · Movie theatre · Personal care · **Pets** · Sports · Theater · Tobacco · Vacation	· Alcohol · Books · Cable TV · Car insurance · Clothing · Education · FAFH · Gifts/charity · Gym · Home furnishing · Home insurance · Movie theatre · Personal care · Pets · Sports · Theater · Tobacco · Vacation
Would not be able to Afford	**Essential**	· **Childcare** · **Health insurance**	· **Car payment** · Childcare · **Groceries** · **Phone**	· Car payment · Childcare · Groceries · **Internet** · Phone · **Public transport** · **Rent**	· Childcare · Groceries · **Heating bills** · Internet · **Prescription Medicine** · Phone · Public transport · Rent
	Less Essential	· **Alcohol** · **Books** · **Cable TV** · **Car insurance** · **Clothing** · **Education** · **Education loans** · **FAFH** · **Gifts/charity** · **Home furnishings** · **Movie theatre** · **Personal care** · **Sports** · **Theatre** · **Tobacco** · **Vacation**	· Alcohol · Books · Cable TV · Clothing · Education · Education loans · FAFH · Gifts/charity · **Gym** · Home furnishings · Movie theatre · Personal care · **Pets** · Sports · Theatre · Tobacco · Vacation	· Alcohol · Books · Cable TV · Car insurance · Clothing · Education · Education loans · FAFH · Gifts/charity · Gym · Home furnishings · Movie theatre · Personal care · Sports · Theatre · Tobacco · Vacation	· Alcohol · Books · Cable TV · Car insurance · Clothing · Education · Education loans · FAFH · Gifts/charity · Gym · Home furnishings · Movie theatre · Personal care · Pets · Sports · Theatre · Tobacco · Vacation

To summarize the results of the individual models for each good, Table 6 presents average odds ratios, grouped into the essential and less essential good categories. These numbers were computed for odds ratios greater than one with a statistically significant p-value ($p \leq 10\%$). If the odds ratio is not statistically different from the base value of $12 for a good, the odds ratio was assigned a value of 1. This table is valuable because it provides a sense of how people respond to water bill changes of varying magnitudes, as well as the socio-economic, demographic, and geographic characteristics that explain spending behavior changes.

Table 6 *Water Service Cost Increases Leading to Significant Change in Spending Behavior*

	Essential		Less Essential	
Variable	Wouldn't Afford	Cut Back	Wouldn't Afford	Cut Back
Water Bill Increase = 36	1.017	1.222	1.541	1.341
Water Bill Increase = 60	1.187	1.240	1.828	1.443
Water Bill Increase = 96	1.433	1.498	2.079	1.761
Water Bill Increase = 120	1.516	1.617	2.309	1.865
Age	0.984	0.991	0.988	0.994
Hispanic	1.579	1.533	1.456	1.377
Black	1.196	1.190	1.246	1.194
Asian	1.036	1.392	1.156	1.278
Other	1.503	1.465	1.553	1.309
Female	1.083	1.164	1.779	1.317
Income: <50k	11.039	4.049	11.084	3.141
Income: 50k-100k	4.962	2.980	5.275	2.576
Unemployed	1.221	1.000	1.468	0.990
Retired	1.000	0.902	0.898	0.807
Student/Home/Other	0.962	0.978	0.976	0.941
Multi-Family Unit/ Apartment	1.089	1.002	1.131	0.993
Mobile Home/ Other	1.254	1.000	1.130	1.000
No High School	3.415	2.323	2.568	1.775
High School	1.878	1.312	1.776	1.108
Com College	1.694	1.421	1.746	1.291
Mid-Atlantic	0.920	0.868	0.861	0.902
Eastern Massachusetts	0.852	0.697	0.734	0.867
Southeast Florida	1.064	0.982	0.997	0.952
Front Range	0.848	0.788	0.823	0.918
Southern California	1.000	0.906	0.964	0.961
Southeast Michigan	1.000	0.936	1.015	0.975
Pacific Northwest	0.965	0.845	1.035	0.928

Table 6 (cont'd)

Variable	Essential		Less Essential	
	Wouldn't Afford	Cut Back	Wouldn't Afford	Cut Back
Sun Corridor	0.978	0.965	1.031	0.965
Wave 2	0.937	1.000	1.000	1.072
Wave 3	0.887	0.983	0.986	1.048
Constant	0.019	0.116	0.029	0.276

Compared to the $12 base value increase in water costs, on average, individuals are 22% more likely to *cut back spending* on essential goods if water bills increase by $36. Households are 24% more likely to *cut back spending* on essential goods if water bills increase by $60. This trend is stronger for less essential goods. Individuals are 34% more likely to *cut back spending* on less essential goods for bill increases of $36 and 44% more likely to cut back spending for increases of $60. Similar trends emerge for the *would not be able to afford* option. Compared to the $12 base value increase in water costs, on average, individuals are only about 2% more likely to indicate they *would not be able to afford* essential goods if water increases by $36. The average odds ratio jumps to a 19% increase in likelihood that households *would not be able to afford* essential goods when water costs increase by $60. The magnitude of the probability that households *would not be able to afford* goods is higher for less essential goods compared to essential goods at all water cost increase levels. Respondents were 54% more likely to deem less-essential goods unaffordable for bill increases of $36. Households were 83% more likely to indicate they would not be able to afford less-essential goods for a $60 water cost increase.

2.4.3 Age

After controlling for other demographic and socio-economic factors, age factored into responses about spending behavior. In fact, as age increased, people were less likely to indicate they would cut back on spending or be unable to afford goods. On average, respondents were 1% less likely to cut back spending on both essential and less essential goods for each year of age. Respondents were 1.2% less likely to indicate they would not be able to afford less-essential goods and 1.6% less likely to indicate they would not be able to afford essential goods. For some goods these trends were particularly notable. For each additional year of age, respondents were 2% less likely to indicate they would cut back spending on health insurance, prescription medicine and car insurance. Respondents were 3% less likely to report they would not be able to afford home insurance, personal care, or doctor visits.

2.4.4 Race and Ethnicity

Model results also revealed important differences in spending behavior changes related to race and ethnicity. Overall, all races and ethnicities in the study (Hispanics, Blacks, and Asians) indicated they would be more likely to change spending behavior compared to White respondents. However, different patterns emerge when breaking down these changes into *cut back* on spending or *wouldn't be able to afford* particular goods. For example, non-White respondents were significantly more likely to cut back spending on several forms of insurance (health insurance, home insurance and car insurance). Also, non-White respondents indicated they would be more likely to cut back spending on alcohol, childcare, rent, cable TV, household heating, phone services, and pets.

Aside from these general trends, there were also unique trends in spending behavior changes for each of the racial/ethnic groups included in this study. For example, Asians were 54% more likely to cut back on tobacco expenditures than Whites. Results also indicate Asians were more likely to cut back on childcare (56% more likely), electric/gas heating bills (67%

more likely), pets (63% more likely), and rent (72% more likely). Black respondents were more likely than Whites to cut back spending on essentials like rent, heat, childcare, health insurance, internet and phone bills. They were also more likely to cut back spending on the following goods: internet (47% more likely), education loans (49% more likely), alcohol (44% more likely), home insurance (58% more likely) and pets (63% more likely)[2]. Interestingly, Hispanic households were the most sensitive to water bill increases compared to the other race/ethnicity groups. Hispanic respondents were more likely to cut back spending on all 11 of the essential goods, and 17 of the 19 less essential goods. Specifically, Hispanics were more likely to cut back spending on pets (65% more likely), prescription medicine (56% more likely), rent (70% more likely), home insurance (70% more likely) and health insurance (70% more likely).

There were also differences between White and non-White respondents in their propensity to indicate they *would not be able to afford* goods as water bills rise. This trend is consistent for both essential and non-essential goods and services. Asians were on average 4% more likely to report essential goods would become unaffordable and 16% more likely to report less essential goods would become unaffordable. Hispanic respondents were the most likely to report they would not be able to afford goods with rising water bill levels. They were 58% and 46% more likely to indicate they would not be able to afford essential and less essential goods respectively. Blacks were 20% and 25% more likely to indicate they would not be able to afford essential and less essential goods respectively.

2.4.5 Geography

There were also geographic differences across survey respondents. Respondents in the Mid-Atlantic, Eastern Massachusetts and Front Range responded differently to water bill increase scenarios than did respondents from the other regions (Southeast Florida, Southern California, Southeast Michigan, the Sun Corridor and the Pacific Northwest). Respondents in these three regions were comparatively *less likely* to cut back spending on essential goods and services than those in the other six regions. On average, respondents in the Mid-Atlantic region were 13% less likely to indicate a cut back in spending on essential goods and 10% less likely to indicate a cut back in spending on less essential goods. Households from the Front Range were 21% less likely to cut back on essential goods, and 8% less likely to cut back spending on less essential goods. Eastern Massachusetts households were the least sensitive to water bill increases. They were 30% less likely to cut back spending on essential goods, and 13% less likely to cut back spending on less essential goods. Compared to the other six regions, the Mid-Atlantic, Eastern Massachusetts and Front Range regions were also less likely to report not being able to afford goods and services. Households in the Mid-Atlantic were 8% less likely to report they would not be able to afford essential goods, and 14% less likely to report they would no longer be able to afford less-essential goods. Front Range households were 15% and 18% less likely to report they would not be able to afford essential goods and less essential goods respectively. Households in Eastern Massachusetts were 15% less likely to report that essential goods were unaffordable, and 27% less likely to report less-essential goods were unaffordable.

2.4.6 Income

Of the control variables in the models, household income was the single most important characteristic in explaining changing spending behaviors in response to rising water bill costs. Households earning less than $50,000 a year were on average 4 times more likely to cut back spending on essential goods and 3.1 times more likely to cut back spending on less essential goods than households with an annual income over $100,000. However, the differences in behavior change were stronger for *not being able to afford* goods. On average, households with an annual income less than $50,000 were approximately 11 times more likely to indicate they would not be able to afford both essential and less essential goods compared to households earning over $100,000 per year. On a per good basis, some of the model results are striking.

Households with a combined income less than $50,000 a year were 10.6 times more likely to report they *wouldn't be able to afford* groceries. They were 16.7 times more likely to report they *wouldn't be able to afford* phone bills, 13.6 times more likely for personal care items, and 9.4 times more likely for home insurance.

Households earning $50,000 to $100,000 a year were also more likely to indicate a change in spending behavior if water bills were to increase, but the change was not as strong as lower income households. They were 3 times more likely to cut back spending on essential goods and 2.6 times more likely to cut back on less essential goods than households with an annual income over $100,000. These same households were approximately 5 times more likely to indicate they would not be able to afford both essential and less essential goods than households with an annual income over $100,000.

2.5 Discussion and Conclusion

Consistent with the literature, households were more likely to change consumption on less essential goods relative to essential goods (Kamakura & Du, 2012). A concerning aspect of results however was that respondents reported they would reduce spending or would not be able to afford goods like healthcare, household heating, and prescription medicine if water costs increased substantially. The analysis also revealed that changes in spending behavior were indicated for relatively minor increases in water bills. Hispanic households were particularly sensitive to potential bill increases, as were middle- and low-income households. The results for income likely reflect a limited ability to absorb cost increases and/or reduce water consumption sufficiently to offset cost increases. Here, high-income households have an advantage. They make more money to offset cost increases and can reduce water consumption, particularly for outdoor uses. Combined, these results are informative from a geographic but also demographic perspective in the context of projected water cost trends. They provide insights into the demographics of households likely to be affected, the industries that could be affected, and at what bill increase levels these trends are most pronounced.

While these results provide meaningful information, it is important to note a few limitations to this study. First, this paper provided a sense of the goods for which people could change spending behavior but did not estimate cross-price elasticities for these goods. This latter goal is challenging for several reasons. First, although heads of households typically have an understanding of a reasonable range of expenditures on household water services, issues of water bill recall may arise (Srivastava & Raghubir, 2002). Heads of households may have a general sense of the approximate amount they pay for utilities, but do not regularly monitor the exact dollar amount of their bills (Binet et al., 2014). Second, people also make errors or have biases in recalling the prices of goods (Raghubir, 2006) which makes survey questions asking about the amount they would reduce spending on other goods problematic. Thus, survey questions designed to elicit information to compute cross-price elasticities may prove problematic for acquiring this information. A second limitation is that it was not possible to determine if respondents' reactions to bills fell in line with what was described in their survey responses. To mitigate this issue as much as possible, several ex-ante approaches detailed in the methods section were employed to minimize the potential effects of social desirability bias and cognitive dissonance (Loomis, 2014).

That said, this is the first study to examine changes in consumer spending in response to water bill increases. Therefore, there are several possibilities for future work. First, it is recommended that extensions to the present paper focus on estimating cross-price elasticities by using an experimental design that provides detailed information to participants during the experiment. This type of research design would mitigate some of the issues with eliciting price information from survey questions and provide supplemental information to this study about the amount purchases on goods could decline given a change in water bill levels. Second, the survey data used in this study did not contain a question about reduced water use in response to rising water expenses. This would be good to evaluate in a follow-up study to see the extent that this coping strategy is used instead of or in addition to changes in spending behavior.

At present, we lack good data on consumer uses of water and consumer reactions to changing costs of water services. These data are critical to understanding consumer choices in an era of rising costs of water services provision (AWWA, 2012). This is important not only because unaffordable water bills can result in disconnection for non-payment of services but because policy responses may be necessary to help both utilities and consumers grapple with the rising costs of water services. Given these challenges, a stronger emphasis on long-term water management planning and allocation of resources to building and maintaining water infrastructure may be required (Haddeland et al., 2014; Larson et al., 2016; Stikker, 1998). For utilities, one area of consideration is how to pay for the costs of increased service from non-revenue sources of funds that do not involve customers. Here, there are several options including grants, bond issues, and public-private partnerships. The best combination of funding sources will depend on the characteristics of the utility.

Another consideration that is also utility specific is how to make water more affordable for customers without deferring infrastructure improvements. Here too, the options are varied and range from income-based bills (Mack et al., 2020) to the provision of low-cost water-saving devices, homeowner water-use education, and inspections and installation of household water infrastructure repair (J. A. Beecher, 1994; Sebri, 2014). Other options include community assistance, more frequent billing, arrearage forgiveness, payment discounts, disconnection moratoria, and flow restrictions (J. A. Beecher, 1994; Gaudin, 2006; Mumm, 2012).

Certainly, the cost of water services for both utilities and consumers is dynamic. This study provided evidence that rising costs of service may change the spending behavior of people. If these decisions are subject to the phenomenon of expenditure cascades, they may have economy-wide impacts in the future. While this merits additional investigation, trends in water costs are certainly something to track in the years to come.

3. AN ANALYSIS OF HOUSEHOLD PERCEPTIONS OF WATER COSTS ACROSS THE UNITED STATES, A SURVEY-BASED APPROACH[3]

3.1 Introduction

Approximately 68% of the world's population is projected to live in cities by 2050, representing a 13% increase in demand for water services in urban areas (United Nations (U.N.), 2018). In addition to this rise in demand, water service providers face additional pressures related to institutional fragmentation, the inability to defray costs to replace deteriorating infrastructure, and increased capital costs to mitigate the impacts of climate change (T. A. Scott et al., 2018; U.S. Environmental Protection Agency (EPA), 2020b). In the face of these challenges, urban water providers struggle to balance the rising costs of providing quality water service while simultaneously keeping the cost of service low for customers (T. A. Scott et al., 2018; Sik Lee et al., 1999; Wu & Malaluan, 2008).

While long-due investments in restoring and replacing water and sewer infrastructure are behind rate increases and rising water costs in the United States, this increasing price tag for water services follows on the heels of large-scale water shutoffs in states such as Oklahoma, Arkansas, Louisiana, and Florida (Food and Water Watch, 2018). This is particularly important for utilities and city officials who bear the responsibility for making these upgrades to maintain water service quality, but who also hear consumer complaints about the rising cost of water services.

[3] This essay is published as Medwid, L., & Mack, E. A. (2022). An Analysis of Household Perceptions of Water Costs across the United States: A Survey Based Approach. *Water*, *14*(2), 247.

3.2 Literature

In the United States, there is some indication individuals feel their water bills are too high. Anecdotal evidence from news stories cite a lack of billing transparency and a complex mesh of reasons for rising water costs from city to city (Adams, 2018; Davis, 2021; DiBono, n.d.; Ivory et al., 2016). In San Diego, CA for example, residents are confused about the sudden spike in water bills and meter readings, which they say cannot be explained by rate increases alone (Harlan et al., 2009; Inman & Jeffrey, 2006; Renwick & Green, 2000). In Bayonne, New Jersey, the city cut a deal to have its water managed by a Wall Street firm (Ivory et al., 2016). In return, the investors in the city's water infrastructure are guaranteed a rate of return on their investment, which has contributed to rising water costs for residents (Ivory et al., 2016). These consumer concerns and the rising cost of providing water services mean it is important to understand consumer perceptions of the cost of water services. To our knowledge, research about this aspect of water services is scarce. Instead, research analyzing perceptions of water services, has focused so far on water quality (Dolnicar & Schäfer, 2009; Martinez-Espineira et al., 2009), water safety (Celik & Muhammetoglu, 2008; A. Q. Jones et al., 2007; Levêque & Burns, 2017; Wright et al., 2012), and how perceptions affect individuals' propensity to consume tap water or bottled water (Auslander & Langlois, 1993; P. Huang & Lamm, 2015). A Canadian study found 72% of respondents in Toronto were 'somewhat' or 'extremely' concerned about chemical pollutants in the water (Auslander & Langlois, 1993). Results from U.S. oriented studies however suggest mixed perceptions about water quality [18-19]. A study of the state of Georgia, found that approximately half of the respondents rated drinking water quality as very safe, safe, or fair (Jordan & Elnagheeb, 1993). In a study within the state of Florida, respondents who had experienced water quality issues previously were more likely to perceive that water quality problems were getting worse (P. Huang & Lamm, 2015). The same study also found that participation in extension programs improved the perceptions of water quality.

In the absence of evaluating the levels of bacterial and chemical contaminants in household drinking water, many water consumers base their perceptions of water quality on their understanding of the water quality of local surface or groundwater nearby (Z. Hu et al., 2011; Merkel et al., 2012; Syme & Williams, 1993). Interestingly, Hu et al. (Z. Hu et al., 2011) found that while there was a significant association between perceptions of drinking water safety and local groundwater quality, perceptions about surface water did not have any effect. When there are known polluters nearby such as natural gas drilling processes and nuclear power plants, households reported increased concerns about drinking local tap water (Merkel et al., 2012). While the quality of nearby waterbodies may not influence the quality of a household's tap water, this confusion is understandable given the lack of public knowledge about household drinking water sources. A 2016 survey of 998 Americans conducted by YouGov found that only 21 percent of individuals reported that they were very confident about where their household tap water comes from and how it is treated. Conversely, 40 percent said they were not familiar with the source of their water supply (Moore, 2016).

Studies also find that people's perceptions of quality are based on superficial characteristics. These organoleptic properties such as taste, hardness, color, odor and turbidity do not pose health risks to people compared to invisible quality issues related to microbial or chemical contamination (Celik & Muhammetoglu, 2008; A. Q. Jones et al., 2007; Wright et al., 2012). Studies with these findings have pointed to a misunderstanding about health impacts of water characteristics as a reason for this trend. For instance, hardness of tap water was found to be a main reason why individuals avoid consumption of tap water, despite the fact that hardness does not pose any health risk (Celik & Muhammetoglu, 2008). Studies of bottled water consumption also find a divergence or paradox between product characteristics and consumption preferences (Debbeler et al., 2018). This paradox is tied to the perceptions of taste (Levallois et al., 1999; Saylor, 2010) and perceptions of water safety (Z. Hu et al., 2011). A study of Quebec consumers found for example that the preference for bottled water was related to its taste, which was perceived to be better than tap water (Levallois et al., 1999). As regards safety perceptions, research also finds that consumption of bottled water as an alternative to tap water is tied to perceptions of safety. Specifically, a U.S. study of 5,800 consumers found that the quantity of bottled water consumed for drinking decreased as individuals reported increased perceived safety of tap water (Hu et al., 2011). From a financial perspective, research illustrates perceptions of water quality are linked to the willingness to pay for water services. Uncertainty about water quality increases the willingness to pay for water services (Arbues & Villanua, 2006). Vulnerable populations such as low-income households, females and racial/ethnic minorities perceive a higher likelihood of experiencing poor water quality (Jordan & Elnagheeb, 1993). It then makes sense that women and minority households (Merkel et al., 2012; Moore, 2016; Syme & Williams, 1993) are more likely to purchase bottled water. This perhaps indicates a willingness to pay a risk premium to avoid perceived harms of drinking tap water.

In terms of research that examines water costs directly, several studies have conducted research on water resource valuation, demand and willingness to pay (Arbues & Villanua, 2006; García-Rubio et al., 2015). Though overall demand for water is inelastic (Arbues & Villanua, 2006), several trends have emerged in the literature. For instance, in Jordan and Elnagheeb's (1993) study, Black Americans were willing to pay more for improvements in water quality than non-Black Americans. Willingness to pay was also found to increase with the level of education.

This result implies the importance of education in creating and raising people's awareness about environmental problems, in general, and in particular, water contamination. Interestingly, if consumers pay more for water, they are likely to perceive their water as higher quality (García-Rubio et al., 2015). This finding suggests that there may be a circular aspect for consumers' perceived value for water. Community engagement affects public willingness to pay for watershed services as well as the level of public engagement in watershed management (Kosoy et al., 2007). Therefore, there is the potential for consumers to change the quantity of water consumed based on water cost, education, community cohesiveness and public utility pricing policy.

One of the largest disconnects between the perception of water costs and actual costs is access to clearly delineated water bills for household water consumers (Arbues & Villanua, 2006; Walton, 2016). Interestingly, research indicates that public perceptions of water companies are affected by the clarity of water bills (Gaudin, 2006). Specifically, studies find that progressive price schedules are difficult to understand for consumers (Gaudin, 2006; Olmstead & Stavins, 2009; Ruijs, 2009). For example, a nation-wide study of the U.S. found that only 17% of utilities indicated marginal prices next to the unit consumed and 78% provided no information other than the total amount required for payment (Gaudin, 2006). More recent studies suggest this lack of clarity about water pricing may be linked to water consumption practices. For example, Binet et al. (2014) investigated the perceived price of drinking-water when consumers are imperfectly informed about pricing schedules and found that households underestimate the price of water and consume more than what is economically rational. To this point in time however, research has not yet evaluated the public's perception of whether water costs are too high.

To advance our knowledge about public perceptions of household water costs, this study incorporates information from a nationally representative survey of water issues into logistic regression models to answer the following research questions: Do households perceive their water bills to be too high? What are the characteristics of households who perceive their water bills to be too high? Model results indicate that low-income and racial/ethnic minority households were more likely to perceive their water bills to be too high. There are also geographic variations in household water perceptions about the cost of water that may reflect widespread affordability issues in particular parts of the country (Lynch, 2016; Zamudio & Craft, 2019). For example, respondents in the Detroit and Flint regions were the most likely to report their water bills are too high compared to other regions in the U.S.

From a public policy perspective, model results indicate two ways that utilities and city governments can affect consumer perceptions of water prices. In particular, model results indicated that billing frequency and participation in payment assistance programs affects consumers' perceptions of whether water bills are too high. Compared to those billed monthly, households billed quarterly are more likely to say their water bills are too high. Yet, when extended to annual or semiannual billing, this trend reverses and households are more likely to report their water bills are about right. These results indicate that monthly or annual billing may be ideal billing frequency options for utility companies. Participants enrolled in payment assistance programs were also less likely to perceive water bills were too high. This suggests the development of customer assistance programs (CAPs) could improve perceptions of the cost of water services.

3.3 Materials and Methods

To provide a first glance at perceptions of residential water costs across the United States, this study uses data from the Survey of Water Innovation and Socioeconomic Status of Households (SWISSH). This survey was designed by the authors to address the lack of household data in the United States about water issues and administered to a panel of 9,250 households by the Qualtrics survey firm (Harlan et al., 2019). The survey was administered to respondents at least 25 years of age in households across nine regions in the U.S. between December of 2017 and March of 2018. These regions represent geographically, as well as socioeconomically and demographically diverse locations. Rim weights that combine race/ethnicity and income into one probability weight for each respondent are available so that the data are representative of households in the nine regions in terms of race/ethnicity and income, as indicated by 2011–2015 American Community Survey data from the U.S. Census Bureau (Harlan et al., 2019).

The survey covers a variety of water issues, one question in particular asks respondents about their views on the amount of money they spend on water. The text of this question reads as follows: “In your opinion, is the amount you pay for water fair or unfair?” Respondents were given five response options to this question: (1) “unfair, the price of water should be higher,” (2) “unfair, the price of water should be lower,” (3) “fair, the price of water is about right,” (4) “don’t know,” or (5) “prefer not to answer.” Survey responses were coded with a “1” if consumers perceived them to be unfair and too high. The other responses were coded as a “0” if respondents indicated that the amount they pay for water is fair and about right or unfair because they were too low. Responses of “do not know” or “preferred not to answer” were excluded from our analysis.

Logistic regression models were estimated in STATA 14 (StataCorp, 2007) using the ‘logit’ command and were weighted with the ‘svy’ command. Rim weights were used to ensure representative samples that align with the demographic composition of the U.S. Census’ American Community Survey. The probability that households report their water bills are too high is as follows:

$$\Pr(y = 1|x) = e^{x'\beta}/(1 + e^{x'\beta}) \tag{7}$$

where y = 1 indicates water bills are too high. Vector β consists of slope coefficients corresponding to the independent variables and an intercept. The overall predicted probability, Y^* is a ratio between the probability that households feel their water bills are either too high or not too high, as shown in equation 8.

$$Y^* = \ln\left(\frac{P(water\ cost\ too\ high)}{P(water\ cost\ not\ too\ high)}\right) \tag{8}$$

The base category (denominator) is any response in which households did not consider their water bills too high including a response of fair/ about right, or unfair because they believe the cost could be higher. Vector *x* in equation 7 includes the exogenous variables chosen based on prior research associated with water quality and risk perceptions, willingness to pay for water, and awareness of environmental issues (Arbues & Villanua, 2006; Ivory et al., 2016). This body of work shows that demographic and socio-economic factors such as income, education, employment and race/ethnicity, are important to understanding perceptions of a range of water issues (Z. Hu et al., 2011). Independent variables in this model therefore include: (1) water bill characteristics such as water billing frequency and whether the household is enrolled in a water bill payment assistance plan, (2) socioeconomic characteristics including age and income, (3) demographic characteristics,

(4) regional variables, and (5) other control variables. For example, we elected to include controls in the model, such as whether respondents have health insurance, because these factors may place them at financial risk. Therefore, health insurance status may affect their perceptions of financial issues, including the cost of water services. The complete list and description of variables are found in Table 7.

Odds ratios are used to estimate the relative increase or decrease in the perception that water bills are too high associated with each explanatory variable. These odds ratios should be interpreted relative to reference groups for each variable, which are highlighted in bold in Table 7. In general, indicators of high socioeconomic status were selected as the base comparison category including those who are non-Hispanic White, earners over USD 100,000, male, college graduate or higher, and full-time or part-time employment.

Table 7 *Variables Included in Logistic Regression of Water Bill Perception Responses*

Variable Name	**Survey Question**	**Variable Description/Values**
Perception	In your opinion, is the amount you pay for water fair or unfair?	Responses considered too high: Unfair, the price of water should be lower Responses not considered too high: Fair, the price of water is about right Unfair, the price of water should be higher
Region	[Region based on zip code]	Eastern Massachusetts (Boston - Worcester) Front Range-Colorado (Denver – Fort Collins) Mid-Atlantic (Washington, DC – Baltimore, Maryland) Pacific Northwest-Oregon (Portland – Eugene) **Piedmont Atlantic (Atlanta, Georgia – Charlotte, North Carolina)** Southeastern Florida (Miami – Palm Bay-Melbourne) Southeastern Michigan (Detroit – Flint) Southern California (Los Angeles – San Bernardino) Sun Corridor-Arizona (Phoenix – Tucson)
Wave	[N/A]	**Wave 1** Wave 2 Wave 3
Race	With which racial or ethnic group(s) do you identify yourself?	Hispanic Non-Hispanic African-American or Black Non-Hispanic Asian or Asian-American Middle Eastern, Native American or American Indian, Native Hawaiian or Pacific Islander, Other **White**
Age	In what year were you born?	[Age was calculated according to year survey was administered]
Gender	Are you…	Female **Male**
Education	What is the highest level of school you have completed?	Did not finish high school High school Community college or vocational/technical school **4-year college or graduate/professional degree**
Health Insurance	Do you have health insurance? Which of these types of insurance do you have?	Medicaid Medicare No health insurance **Private health insurance**
Assistance paying water bill	Do you participate in any program that helps you pay your water bill?	**No** Yes
Employment status	Which of the following **best** describes your current employment or labor force status?	**Full-time/part-time** Unemployed/disability/not working/not looking Retired Student/homemaker/other
Income	What was the total combined income before taxes of everyone in your household in [year]?	Less than $50, 000 $50,000 - $100,000 **More than $100,000**

Note: Response options in bold indicate the reference category for each variable.

Table 7 (Cont'd)

Variable Name	**Survey Question**	**Variable Description/Values**
Household type	Do you live in…	**A single-family home/ townhouse/patio home** A multi-family home l/apartment building A mobile home or trailer Other
Frequency of water bill	How is the water bill paid in your household?	**Monthly to the service provider** Quarterly to the service provider Annually to the service provider Water bill is covered by our rent Water bill is covered by HOA/condo association Have a well and do not pay service provider Other

Note: Response options in bold indicate the reference category for each variable.

3.5 Results

A tabulation of too high/other responses for select variables are presented in Table 8. A complete tabulation of all variables can be found in Appendix 1A. Most households (63.3%) reported that their water bills were about right or should be higher. Approximately 36.7% reported their water bills are too high. There were also regional differences in the percentage of respondents who felt their water bills were too high. The Pacific Northwest (40.9%), Southeast Michigan (51.9%), and Southern California (40.8%) were regions where the largest proportion of individuals reported their water bills were too high. Regions where most respondents said their water bills were about right or too low are in the Piedmont Atlantic (69.2%), the Mid-Atlantic (69.9%), and the Sun Corridor (67.1%). Several demographic and socio-economic factors impacted the perceptions of water bills. Females were more likely to indicate they felt water bills were too high as were racial/ethnic minorities. Blacks, Hispanics, and respondents identifying as some other race (e.g. Native American, Native Hawaiian or Pacific Islander, or Middle Eastern) were more likely to indicate they felt their water bills were too high. People with lower levels of educational attainment were also more likely to report that their water bills were too high. In particular, people without a high school education were the most likely to report that their water bills were too high. Relatedly, people with incomes under 50,000 reported feeling water bills were too high.

Table 8 *Tabulation of Water Cost Perceptions by Race, Gender, Education, and Income*

Variable Category	**Variable Option**	**Fair/ Should be Higher**		**Too High**		**Total**
		#	%	#	%	#
TOO HIGH/OTHER		4147	63.3	2400	36.7	6611
RACE/ETHNICITY	White	2580	66.7	1291	33.3	3937
	Hispanic	791	59.6	537	40.4	1387
	NH Black	444	55.1	361	44.9	860
	NH Asian	270	62.2	165	37.8	497
	Other	63	56.9	47	43.1	167
GENDER	Male	1686	66.6	845	33.4	2598
	Female	2452	61.3	1550	38.7	4064
HIGHEST LEVEL OF EDUCATION	Bachelor's or Graduate Degree	2548	67.0	1254	33.0	3870
	No High School	54	50.0	54	50.0	159
	High School	604	58.1	435	41.9	1097
	Community College	929	58.3	664	41.7	1652
INCOME LEVEL	<50k	1162	54.0	989	46.0	2206
	50k-100k	1320	61.8	815	38.2	2198
	> 100k	1664	73.6	596	26.4	2334

Table 9 presents the logistic regression results, which help us understand whether these variables remain important explanatory variables of water bill perceptions, even after controlling for these factors simultaneously. Overall, income, geographic location, and race explained whether individuals considered their water bills to be too high. Compared to Whites, Black, Asian, and Hispanic individuals were more likely to perceive their water bill charges as too high. Particularly, Hispanic respondents were 27.4% more likely to report water bills were too high, Black respondents were 43.8% more likely, and Asians were 32.1% more likely.

Table 9 *Odds Ratios for Logistic Regression of Factors Affecting Perceptions of Water Bills*

Variable Category	Base Variable	Variable Option	Odds Ratio	Standard Error
REGION	Piedmont Atlantic	Mid-Atlantic	1.112	(0.147)
		Eastern Massachusetts	1.452***	(0.204)
		Southeast Florida	1.207	(0.155)
		Front Range	1.191	(0.149)
		Southern California	1.638***	(0.212)
		Southeast Michigan	2.588***	(0.330)
		Pacific Northwest	1.704***	(0.206)
		Sun Corridor	1.157	(0.143)
WAVE	Wave 1	Wave 2	1.104	(0.130)
		Wave 3	0.974	(0.111)
RACE/ETHNICITY	White	Hispanic	1.274***	(0.119)
		NH Black	1.438***	(0.136)
		NH Asian	1.321***	(0.128)
		NH Native American, Native Hawaiian, Middle Eastern, Other	1.233	(0.191)
GENDER	Male	Female	1.063	(0.069)
HIGHEST LEVEL OF EDUCATION	Bachelor's or Graduate Degree	No High School	0.719	(0.207)
		High School	1.006	(0.093)
		Community College	1.067	(0.081)
HEALTH INSURANCE	Private Health Insurance	Medicaid	1.131	(0.134)
		Medicare	0.826**	(0.078)
		None	1.162	(0.157)
SOCIAL	Enrolled in water bill	Note enrolled in water bill	0.738**	(0.114)
EMPLOYMENT STATUS	Full time/ Part time	Unemployed/ Disability/ Not Working & Not	1.121	(0.150)
		Retired	0.842*	(0.085)
		Student/ Homemaker/	1.213	(0.145)
INCOME LEVEL	> 100k	<50k	2.343***	(0.217)
		50k-100k	1.745***	(0.131)
HOUSEHOLD TYPE	Single family home/ townhome	Multi-Family Home/	0.943	(0.086)
		Mobile Home/ Trailer	1.175	(0.314)
WATER BILLING FREQUENCY	Monthly	Quarterly	1.182**	(0.100)
		Annually/ Semiannually	0.504**	(0.147)
		Bimonthly	1.107	(0.191)
		HOA/ Condo	0.508***	(0.133)
		Have Well	0.089***	(0.039)
		Other	1.289	(0.368)
AGE	N/A	Age	1.009***	(0.003)
CONSTANT		Constant	0.148***	(0.032)

N= 6,198; F-statistic=9.305*** ; ***P<0.10, **P<0.05; ***; P<0.01

Income was also a strong indicator of whether respondents felt water bills were too high. Respondents in the lowest income bracket, making less than $50,000 per year were approximately 2.3 times more likely to report their water bills were too high compared to those making over $100,000 per year. Individuals in households making between $50,000 and $100,000 were approximately 75% more likely to report their water bills were too high compared to those making over $100,000.

There were also statistically significant regional trends to water bill perceptions. Compared to the Piedmont Atlantic region, four regions were statistically more likely to have respondents that perceived their water bills to be too high. In Eastern Massachusetts, respondents were 45.2% more likely to report water bills were too high. In Southern California, respondents were 63.8% more likely to indicate that water bills were too high. In Southeast Michigan respondents were 2.59 times more likely to indicate they were billed too much for water, while in in the Pacific Northwest, respondents were 70% more likely to indicate their water bills were too high.

From a water provider perspective, two significant variables are particularly interesting. Billing frequency and enrollment in a water payment assistance program were significant explanatory factors behind perceptions of water bills. Households on a quarterly schedule for water bill payments were 18% more likely to consider their water bills to be too high. However, respondents indicating they paid their water bills annually or had their water included in their homeowners' association (HOA) fees were approximately half as likely to indicate they perceived their water bills as too high. Households enrolled in a payment assistance program were about 26% less likely to perceive their water bills to be too high.

Table 10 presents information from the U.S. Census Bureau and the Environmental Protection Agency's Environmental Quality Index (EQI) (EPA, 2021b) for each of the regions to provide context to the regression results. These data correspond to the counties containing the city pairs of interest in each region, as listed earlier in Table 7. Social and demographic information comes from the U.S. Census Bureau's American Community Survey 2015–2019 (U.S. Census Bureau, 2021). The EQI index presents a county-level ranking of overall environmental quality according to five categories: air, water, land, built, and sociodemographic environments across the U.S (EPA, 2021b). Table 10 includes a measure of the total overall ranking, as well as the water subset of the EQI. Low rankings represent lower levels of degradation. The rankings are based on percentiles across U.S. counties as follows: lowest (0–5th percentile); very low (5th–20th percentile); low (20th–40th percentile); moderate (40th–60th percentile); high (60th–80th percentile); very high (80th–95th percentile); highest (95th–100 percentile). In Table 10, the regions are divided into two groups according to the previous regression results: regions where respondents were less likely to perceive their water bills to be too high and regions that were more likely to perceive their water bills to be too high.

__Table 10__ Study Region Social, Economic, and Environmental Quality Characteristics

State	County	% Non-White	% High School or Below	Median Income (USD)	% Unemployed	Median Household Value (USD)	% Poverty	Density	Water Quality Degradation Level *	Environment Quality Degradation Level *
Regions Less Likely to Report Water Bills Too High		**0.30**	**31.30**	**USD 63,519**	**5.27**	**USD 287,238**	**6.41**	**1562.7**	**High-Highest: 5/10**	**High–Highest: 3/10**
Sun Corridor-Arizona										
Arizona	Maricopa	0.22	31.18	USD 64,468	5.03	USD 260,200	6.41	470.6	Highest	High
Arizona	Pima	0.24	29.79	USD 53,379	6.96	USD 184,100	7.65	111.8	Highest	Moderate
Front Range-Colorado										
Colorado	Denver	0.24	25.28	USD 68,592	3.75	USD 390,600	6.31	4602.8	Moderate	Very Low
Colorado	Larimer	0.09	20.09	USD 71,881	4.65	USD 363,800	6.13	132.826	High	Moderate
Mid-Atlantic										
District of Columbia	District of Columbia	0.59	23.26	USD 86,420	6.91	USD 601,500	9.01	11330.3	Very Low	Very Low
Maryland	Baltimore	0.39	31.04	USD 76,866	4.79	USD 261,500	4.40	1383.8	Highest	Highest
Piedmont Atlantic										
Georgia	Fulton	0.55	22.78	USD 69,673	5.54	USD 313,300	6.86		Low	Low
North Carolina	Mecklenburg	0.46	24.47	USD 66,641	4.76	USD 238,000	5.03	2052.2	Very High	High
Southeastern Florida										
Florida	Brevard	0.18	31.32	USD 56,775	5.19	USD 196,400	4.90	576.8	Lowest	Low
Florida	Miami-Dade	0.25	43.19	USD 51,347	5.31	USD 289,600	6.64	1421.7	Lowest	Low
Regions More Likely to Report Water Bills Too High		**0.43**	**38.24**	**USD 64,985**	**6.60**	**USD 457,382**	**6.93**	**2527.5**	**High-Highest: 6/8**	**High – Highest: 3/8**
Eastern Massachusetts										
Massachusetts	Suffolk	0.45	32.85	USD 69,669	6.39	USD 496,500	8.95	13676.7	Very Low	Moderate
Massachusetts	Worcester	0.16	33.54	USD 74,679	5.00	USD 280,600	4.75	546.0	Very High	Highest
Southeastern Michigan										
Michigan	Genesee	0.25	36.75	USD 48,588	9.33	USD 111,100	8.36	640.3	Moderate	Low
Michigan	Wayne	0.47	38.67	USD 47,301	9.20	USD 113,000	10.43	2871.4	High	Very High
Pacific Northwest										
Oregon	Lane	0.13	26.95	USD 52,426	6.90	USD 263,200	8.30	81.9	Very High	Low
Oregon	Multnomah	0.22	22.02	USD 69,176	4.93	USD 386,200	6.34	1866.4	Very High	Low
Southern California										
California	Los Angeles	0.49	39.69	USD 68,044	6.09	USD 583,200	6.26	2484.3	Highest	Moderate
California	San Bernardino	0.39	43.20	USD 63,362	7.66	USD 328,200	7.01	107.1	Highest	High

Data sources: U.S. Census Bureau 2015–2019 County Level Estimates (U.S. Census Bureau, 2021) and the U.S. Environmental Protection Agency's Environmental Quality Index (U.S. Environmental Protection Agency (EPA), 2021b)

The regions more likely to say their water bills are too high have on average, a higher percentage of individuals with a high school education or below (38.24% compared to 31.3%), a higher non-White population (43% compared to 30%), and higher population densities. Median household income and poverty levels were similar for both. Regions with a higher percentage of households more likely to say their water bills are too high are located in counties with a ranking of water quality problems ranging from high to highest (75% for regions more likely to report bills too high compared to 50% for those less likely). These regions also have higher levels of environmental degradation (37.5% compared to 30%). Therefore, respondents from regions that perceived their water bills to be too high are more likely to live in areas of lower water and lower environmental quality.

Table 11 *Contextual Survey Questions Related to Experiences with Water Services*

Question	Variable Option	Response Options	#	%
In the Past 12 Months Have You Had…	Water Use Restriction	Yes	443	**32.8**
		No	909	67.2
		Total	1353	100.0
	Water Shutoff Notification	Yes	180	**32.2**
		No	378	67.8
		Total	558	100.0
	Water Shutoff	Yes	94	**23.3**
		No	311	76.7
		Total	405	100.0
	Electric Shutoff Notification	Yes	248	**36.3**
		No	435	63.7
		Total	683	100.0
	Electric Shutoff	Yes	98	**20.5**
		No	381	79.5
		Total	480	100.0
Do you agree or disagree with the following statements?	Cost of Water has Increased	Disagree	127	5.3
		Neither agree nor disagree	439	18.4
		Agree	1822	**76.3**
		Total	2388	100.0
	Easily Afford my Water Bill	Disagree	635	26.5
		Neither agree nor disagree	689	28.8
		Agree	1068	**44.7**
		Total	2392	100.0
	Worried about Cost of Water	Disagree	149	6.2
		Neither agree nor disagree	301	12.6
		Agree	1939	**81.2**
		Total	2388	100.0
	I Conserve Water due to Expense	Disagree	212	8.9
		Neither agree nor disagree	377	15.8
		Agree	1802	**75.4**
		Total	2392	100.0

Note: Affirmative responses (yes or agree) are presented in bold in this table.

Table 11 presents tabulations of survey questions for respondents who felt their water bills were too high, which provide important contextual information about respondents' experiences with water and utilities (e.g. water and electricity). Based on the information presented in this table, most households who perceive their water bills to be too high worry about the cost of water and are less likely to feel they can easily afford their water bills. Only 44.7% of these households reported they could easily afford their water bills and 81.2% say they worry about the cost of water. However, a lower percentage of these same respondents have had prior experience with utility affordability issues. Of the respondents who indicated their water bills were too high, just over a third had experienced prior restrictions on water use (32.8%) or had received a water (32.2%) or electric shutoff notification (36.3%); 23.3 percent and 20.5 percent had experienced a water or electric shutoff respectively.

Table 12 *Questions in SWISSH Survey Related to Trust in Institutions*

Question	Variable Option	Response Options	#	%
As far as these institutions and their leaders are concerned, how confident are you in each of the following?	Your Local Water Utility	Not confident	381	16.4
		Neutral	503	21.6
		Confident	1444	**62.0**
		Total	2329	100.0
	City/ Town Government	Not confident	537	23.0
		Neutral	614	26.3
		Confident	1181	**50.6**
		Total	2333	100.0
	Your Drainage/ Flood Control District	Not confident	337	15.8
		Neutral	635	29.7
		Confident	1167	**54.6**
		Total	2139	100.0
	Public Health Agencies	Not confident	395	17.2
		Neutral	562	24.4
		Confident	1348	**58.5**
		Total	2305	100.0

Interestingly however, these views and experiences have not impacted respondents' trust in public institutions to this point in time. Table 12 presents tabulations of survey questions and includes information about trust in public institutions, which may be a driver of water bill perceptions; households with low trust in institutions may be more likely to water bills to be too high. However, the majority of respondents felt confident in institutions like their local water utility (62%), flood control district (54.6%) and public health agencies (58.5%). A somewhat lower percentage of respondents felt confident about their city/town government (50.6%).

3.6 Discussion

The United States is in an era of infrastructure replacement, which will require massive investments totaling an estimated $600 billion towards water infrastructure over the next two decades (EPA, 2020b). These investments, along with recent widespread shutoffs in water service in several cities across the United States and the Flint water crisis, suggest that trust in water service and also the perceptions of water services are important to analyze at this juncture in history. Aside from consumer reactions to water costs, the perceptions of these costs is also important for water utilities to bear in mind since a sizable customer base that considers water bills to be too high may lead to the inability or unwillingness to pay for water services. It may also cause consumers to switch to alternate water sources, such as private wells or bottled water, which could erode the revenue streams of utilities (NARUC, 2021). Combined, these coping strategies may erode the long-term customer base of utilities and public engagement in local water policy decisions (Lakhani, 2020). To this point in time however, studies of water perceptions in the developed world have assessed dimensions of water services (e.g. quality and willingness to pay) other than perceptions of water costs. To address this research gap, the goal of this paper was to analyze the perceptions of households regarding the cost of water services and to assess the characteristics of households who felt their water bills were too high.

Not surprisingly, income was one of the more important factors in explaining water bill perceptions. Households making less than $50,000 were more likely to feel that their water bills were too high. Even after controlling for income, race was also a significant characteristic behind households' perceptions of water bills. Non-white, minority households were more likely to perceive that their water bills were too high. This finding is in line with recent research showing that high water costs disproportionately affect communities of color (Butts & Gasteyer, 2011; Montag, 2019). Studies suggest that these high costs are a result of population decline in urban areas and postindustrial divestment (Butts & Gasteyer, 2011). It may also reflect the fact that Black and Hispanic neighborhoods are at higher risk for water shutoffs due to non-payment than predominantly White neighborhoods (Walton, 2016).

Another important finding of this study was variations in household perceptions across particular regions of the country. Households in four regions of the country (e.g. Eastern Massachusetts, Southern California, Southeast Michigan, and Pacific Northwest) were more likely to perceive water bills as being too high. This may reflect the higher cost of living in three of these areas of the country (Eastern Massachusetts, Southern California, Pacific Northwest). In Southeast Michigan, which includes the cities of Flint and Detroit, these results may reflect consumer awareness of shutoffs in Detroit and also rising water rates in these cities (Lynch, 2016; Zamudio & Craft, 2019).

The results show that frequency of water billing affects perceptions of water bills, and that those who are billed quarterly were more likely to consider their water bills unfairly high compared to customers billed monthly or annually. Therefore, one recommendation based on these findings is for water companies to bill monthly, where households are shown to be better able to budget (J. A. Beecher, 1994). Alternatively, companies may also bill households annually, allowing for customers to easily anticipate this one-time annual payment without focusing on water costs for the rest of the year. Another important result was that water payment programs reduced the likelihood that households perceived their water bills to be too high. This finding suggests that water provider should work to establish water assistance programs for customers in need. At present there is no federal framework guiding the implementation of customer assistance programs (CAPs) (Grigg, 2017) which provides utilities with a good deal of flexibility in structuring these programs. Types of CAPs that may be offered range from water efficiency programs to bill discounts to lifeline rates (EPA, 2016). Important considerations in CAP design that influence program cost include the program size and the type of assistance offered. State laws governing utility regulation and the wording and interpretation of state statutes are also important considerations to keep in mind when designing programs because the legal barriers to CAPs do vary across states and utility type (EPA, 2016). If a utility already has a CAP in place, providers may want to develop outreach programs to communicate with customers and enhance their awareness of CAPS.

While this paper highlighted key indicators affecting the perceptions of household water costs, it is important to acknowledge three limitations of this study, which present opportunities for future research. One limitation is that this study does not have information about the actual cost of water bills against which customer perceptions of water bills may be compared. Future work could collect water cost information from individual utilities and also survey customers of these utilities to make these comparisons. This would likely need to involve the cooperation of a utility since it is quite difficult to obtain these data. A related and second limitation of this study is that it does not contain information about customer water use, which may be driving perceptions that water bills are too high. In particular, customers that use more water may have higher bills and may also perceive their bills to be too high. Similar to the question about water rates, obtaining information about water usage would require the cooperation of a utility since these data are also difficult to obtain. Third, the results of this study suggest that consumers' exposure to changes in water rates may affect their perceptions of water bills. In particular, respondents from Southeast Michigan were more likely to perceive their water bills to be too high, and people in this region have experienced rising water rates. Future work that collects time series information about water rates in conjunction with perception data could expand on this finding and help discern the extent and the amount of rate changes that make consumers feel the price they pay for water is too high.

3.7 Conclusion

This study provided the first examination of household perceptions of water bills and covered nine geographically, demographically, and socioeconomically distinct regions of the United States. As water utilities, consumers and city governments navigate the need to upgrade water systems in the present era of infrastructure replacement, it is important for utilities to monitor the impacts of these upgrades on water rates, as well as customer perceptions of the cost of water service. The results of this study suggest that frequency of billing and the offering of customer assistance programs, in conjunction with customer outreach and engagement, may be fruitful avenues for navigating the challenges associated with maintaining quality water services during a period of tremendous environmental and societal changes.

4. A SPATIAL ANALYSIS OF SOCIAL VULNERABILITY IN COMMUNITIES SURROUNDING SUPERFUND SITES CONTAMINATED WITH PER- AND POLYFLUOROALKYL SUBSTANCES (PFAS)

4.1 Introduction

Over 98 percent of Americans have measurable levels of per- and polyfluoroalkyl substances (PFAS) in their blood, which are associated with cancer, developmental problems, and disruptions to the immune, metabolic, and endocrine systems (Dong et al., 2019; Sunderland et al., 2019). The likelihood and severity of these health impacts depends on duration and concentration levels of PFAS (Birnbaum, 2022). Indeed, the risk is particularly high from household tap water consumption near facilities that have manufactured, disposed, or used PFAS (Hu et al., 2016). This paper studies potential PFAS exposure through an environmental justice (EJ) lens, evaluating whether vulnerable neighborhoods are more likely to have an elevated risk of PFAS exposure near highly contaminated ‘Superfund’ sites (CERCLA), 1980). The EJ literature provides information on whether the development, implementation, and enforcement of environmental laws and policy is equitable regardless of race, color, national origin, or income (Banzhaf et al., 2019; EPA, 2022). In looking at the topic of potential PFAS exposure in the environment through an EJ lens, this research closes a gap in knowledge about the community characteristics, including the poverty rate, disability rate, proportion of racial minorities, close to known sources of PFAS contamination in the environment.

To date, research on environmental justice and PFAS has predominantly focused on blood levels of individuals (Buekers et al., 2018; De Silva et al., 2021; Panikkar et al., 2019). For example, Chang et al. (2021) measured blood PFAS levels among 453 pregnant Black women in

Atlanta, Georgia. Another study assesses blood and urine PFAS levels of 311 refugees and 89 urban anglers around a Superfund site in New York (Wattigney et al., 2022). While these types of studies are useful for understanding levels of individual exposure, there is a gap in knowledge about neighborhood exposure to PFAS in the environment, particularly from Superfund sites. A broader scale approach is necessary to understand overall trends in the composition of communities most likely to be exposed to high PFAS levels. Secondly, studies on PFAS exposure evaluate aspects of vulnerability separately, potentially missing the combined and interactive effects of various forms of vulnerability. Despite this tendency, Switzer & Teodoro (2018) found that while race alone is associated with environmental injustice, majority Black or Hispanic communities' disadvantages might be compounded if those communities are also poor.

To fill these gaps, spatial cluster analysis is used to answer the first research question, whether there are statistically significant patterns of social vulnerability around Superfund sites known to have elevated PFAS levels (≥70 parts per trillion), and if so, where? This approach is an improvement over previous studies because it provides information on the overall vulnerability including levels of poverty, racial minorities, disability status, among others, of neighborhoods surrounding heavily polluted sites known to be associated with high PFAS exposure (Hu et al., 2016). This study uses an index approach to capture multiple aspects of social vulnerability simultaneously with regards to PFAS exposure from Superfund sites. This index has never been utilized in environmental justice studies of Superfund sites related to PFAS, though there is a case study unrelated to Superfund sites using a vulnerability index in relation to areas of heightened measures of pollution in California (Huang & London, 2012). This method is necessary since no studies have captured the additive and/or interactive effects of various forms of social vulnerability related to Superfund exposure. Until now, no studies have considered three or more dimensions of vulnerability simultaneously when looking at potential PFAS Superfund exposure (Mohai et al., 2009; Teodoro et al., 2018). The second question of this study considers which aspects of vulnerability, if any, are most strongly associated with spatial proximity to PFAS Superfund sites? Regression analysis is used to tease out which social vulnerability indicators, and therefore, which segment(s) of vulnerable populations, have the highest potential risk of PFAS exposure near Superfund sites.

4.2 Literature

The environmental justice movement garnered broad recognition in 1982 in response to illegal polychlorinated biphenyl (PCB) dumping in a landfill in Warren County, which had the highest proportion of Black residents across the state of North Carolina (Mohai, 2018). This controversy and subsequent environmental disasters led to calls for the equal distribution of environmental benefits and harm, regardless of income or race/ethnicity (Banzhaf et al., 2019; Cutter, 2012). Studies such as those by Bullard (1983), Cutter (1995) and the UCC (1987) established environmental justice as a unified subject of study in the academic literature. These studies and others evaluated whether low-income and racial and ethnic minorities are more likely to be exposed to chronically polluted land (Bryant, 1995; Dion et al., 1998). Modern academic EJ research questions are evaluated predominantly in the context of (1) the need for an equitable distribution of ecological benefits and hazards, (2) the integration of contexts of oppression in environmental actions, and (3) the need for political representation in environmental policy decisions (Schlosberg, 2007; EPA, 2022). Recent studies show that distributional problems of inequitable exposure to environmental benefits and harm persist in terms of environmental pollution (Ashby et al., 2020; Banzhaf et al., 2019; Mohai et al., 2009) and subsequently through consumption of household tap water (Mohai, 2018; Panikkar et al., 2019). Studies contextualizing racial oppression is an important component of EJ research, whether it takes the form of historical or present-day cultural factors. For instance, emerging EJ studies draw upon the historical efforts of the US government to decimate Native American populace and cultural identity to better understand increased proximity to PFAS contamination (EWG, 2021) and less rigorous enforcement of water quality standards (Teodoro et al., 2018). Participation in governance decisions, particularly in the form of laws, regulation and policies is fundamental for ensuring environmental justice (Schlosberg, 2004, 2007). For instance, contemporary water-related issues contribute to environmental injustice in the form of access, affordability, and the distribution of ecosystem services that watersheds provide (Teodoro et al., 2018).

An example of legislation intended to protect the American population from environmental harm is the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA, 1980). CERCLA provides official designations of highly polluted sites colloquially referred to as ‘Superfund.’ Living within proximity to these sites is associated with health risks including lower life expectancy, congenital anomalies, depression, cancer, immune system disorders, and decreased life expectancy (Ashby et al., 2020; Bevc et al., 2007; Currie et al., 2011; Maranville et al., 2009). A study by Currie et al. (2011) shows the effect of contaminated Superfund sites on infant health, whereby a Superfund designation is associated with a 20 to 25% increase in the risk of congenital anomalies. Indicators of class such unemployment, low-income, and poverty status are associated with proximity to Superfund sites and other environmental hazards (Banzhaf et al., 2019; Bullard, 1983). Burwell-Naney et al. (2013) confirm that among all populations below the poverty line in North Carolina, 57% are located directly within Superfund host census tracts. However, many studies confirm that race is a stronger indicator than class for these types of risk (Maranville et al., 2009; Stretesky & Hogan, 1998).

Usually race and class effects are compared, known as the race-class debate (Allaire et al., 2018; Banzhaf et al., 2019; Burwell-Naney et al., 2013; Stretesky & Hogan, 1998). Alba et al. (2000) further shed light on the interactions of vulnerability finding that middle-class African Americans often live amidst whites who are less affluent, and their neighborhoods are not the equivalent of whites with a similar socioeconomic status. While race and income have been explored extensively in the environmental justice literature, studies are emerging that include other forms of vulnerability such as elder status, disability status, single-parent households, immigration status, and prisoner populations (Ashby et al., 2020; Chakraborty, 2020; D. N. Pellow, 2017; D. Pellow & Vazin, 2019). Various indicators of vulnerability are associated with increased environmental health risk for many reasons including a higher prevalence of prison populations, juvenile detention centers, and public housing within proximity to Superfund sites (Ashby et al., 2020; Coffey et al., 2020; D. N. Pellow, 2017). For instance, 70% of the country's superfund sites are within one mile of federally assisted housing, according to a report by the nonprofit Shriver Center on Poverty Law (Coffey et al., 2020). A few emerging studies evaluate the interaction effects of two vulnerability variables on exposure to pollution, though these do not focus directly on Superfund sites. For example, in their study of drinking water compliance using SDWIS data, Teodoro et al. (2018) find that although race is associated with more frequent water quality violations, this trend is compounded in communities that are both significantly non-white as well as high poverty. Similarly, in studying toxic waste sites Chakraborty (2020) interacted disability status with other indicators of vulnerability. One finding of this study showed that people with a disability who identify as White showed a negative relationship with proximity to toxic sites, yet if they identified as Black alone there was a positive association. While these emerging examples confront compounding effects of vulnerability, they do not use a comprehensive measure of several variables to represent overall vulnerability.

Superfund sites represent extreme cases of known pollution sources in America, which may shed light on persistent environmental justice issues often related to water consumption. In 2019, the U.S. Senate Committee on Environment and Public Works (SCEPW) acknowledged that elevated PFAS levels ($\geq$ 70 parts per trillion) are present in the water and soil at 175 Superfund sites in the contiguous U.S, shown in figure 1 (SCEPW, 2019). PFAS are known as 'forever chemicals' because they bioaccumulate in the human body and do not degrade in nature due to their carbon fluorine bond. This is one of the strongest bonds that exists and barely is found in nature (Hale et al., 2020). Therefore, PFAS pose a unique threat because they are persistent, mobile, and bioaccumulative (Hale et al., 2020). Since PFAS chemicals are resistant to environmental breakdown, they are ubiquitous in the air, surface water, and soil, with particularly high levels in groundwater near facilities that manufacture, dispose, or have used products with PFAS (George & Dixit, 2021; X. C. Hu et al., 2016a; Panikkar et al., 2019). Major sources of PFAS exposure are leachate from landfills or the use of aqueous film-forming foam (AFFF) found at military bases, airports, or fire stations (Hagstrom et al., 2021). The resulting public health risks are most pronounced for those consuming water from private wells and small public water suppliers (Hepburn et al., 2019; X. C. Hu et al., 2016a). For instance, PFAS was tested at or downstream of landfills in an Australian study of groundwater contamination and all 13 had PFAS present, with between 1-14 PFAS types at each location (Hepburn et al., 2019). As such, one of the most common PFAS Superfund site types are landfills (24 of 175). Further, Wattigney et al. (2022) used blood and urine PFAS levels of refugees and urban anglers around a

Superfund site in New York. These authors found that education, parity, BMI, drinking water source, and cosmetic use were associated with serum PFAS concentrations. Conversely, nascent datasets, provide evidence that areas PFAS contamination are associated with vulnerable populations such as the Environmental Working Group's (EWG, 2021) spatial overlay of PFAS contamination and Tribal Lands. Despite PFAS use in products dating back to the 1950's, academic interest in EJ implications of PFAS is relatively recent. Therefore, there is not sufficient information on the community characteristics of neighborhoods with elevated PFAS risk.

4.3 Data

Through the U.S. Environmental Protection Agency (EPA), thousands of contaminated sites are deemed hazardous to the public, having received designated status through CERCLA (informally Superfund), passed in 1980 (CERCLA, 1980). This label allows the EPA to initiate and monitor cleanup efforts and hold parties accountable for funding Superfund cleanup projects, where possible (EPA, 2020b). Superfund site data including spatial information and updates on clean-up activities are provided by the EPA (EPA, 2020b). A Superfund designation aims to increase land re-use and improve economics and quality of life for nearby neighborhoods (Ashby et al., 2020; EPA, 2020b) (Ashby et al., 2020; EPA, 2020b). The national priorities list (NPL) site specifies Superfund sites with the worst hazardous waste problems. Currently, there are over 40,000 federal Superfund sites nation-wide and 1,778 Superfund sites listed on the NPL. Henceforth sites on the NPL will simply be referred to as Superfund sites, as those not listed on the NPL are beyond the scope of this study. See figure 1 for a map of PFAS Superfund sites nation-wide according to NPL status with EPA regions 1 to 3 highlighted.

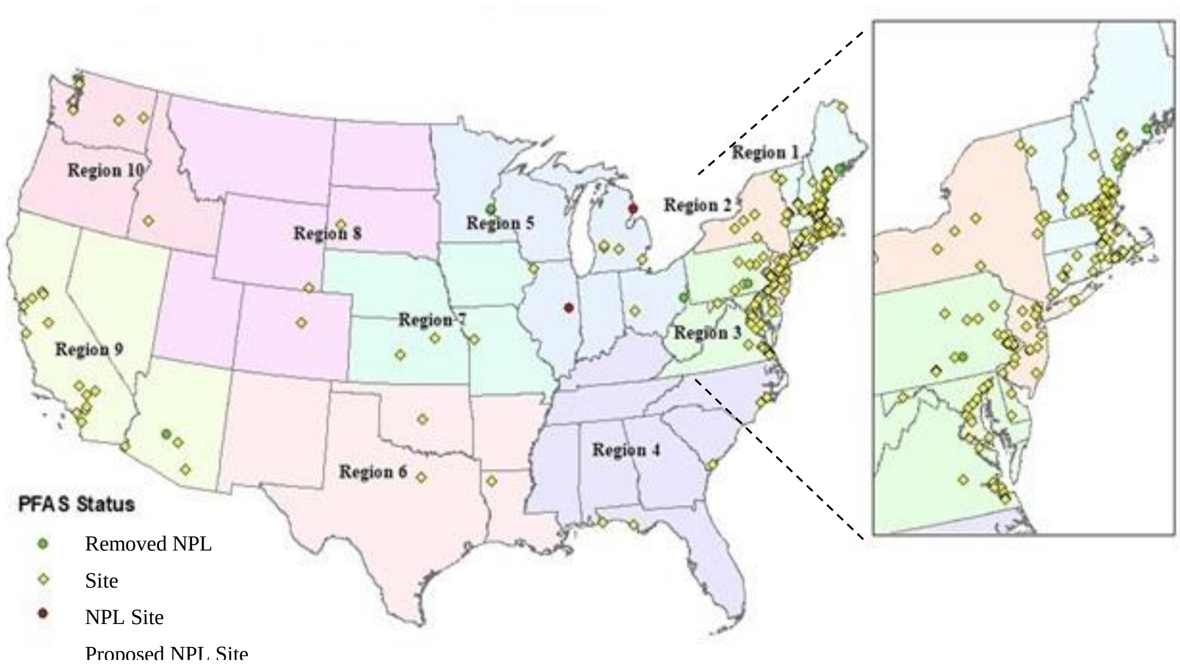

Figure 3 *Superfund Sites with PFAS Designation by EPA Region*

Data Source: http://superfund.ciesin.columbia.edu/sfmapper/mapviewer.jsf?width=1133&height=734

Of the 175 total PFAS Superfund sites in the contiguous United States, 164 are currently active, 9 have been removed from the Superfund list, and 2 are proposed Superfund sites as of January 2020. There is no distinction between NPL status of Superfund sites in this analysis since the sample size is small for removed and proposed PFAS Superfund sites and PFAS does not breakdown in the environment. The number of PFAS contaminated Superfund by EPA region are listed in Table 13.

Table 13 Superfund Sites with Elevated PFAS Levels by EPA Region

EPA Region Name	Region	Total Superfund	Percent all Superfund	Total PFAS*	Percent PFAS	Total Military PFAS
New England	1	123	6.9	68	38.9	13
New Jersey & New York	2	274	15.5	20	11.4	10
Mid-Atlantic	3	225	12.7	39	22.3	25
Southeast	4	253	14.3	5	2.9	5
Great Lakes	5	340	19.2	11	6.3	4
South Central	6	152	8.57	3	1.7	3
Midwest	7	100	5.6	3	1.7	2
Mountains & Plains	8	76	4.3	3	1.7	3
Pacific Southwest	9	132	7.4	17	9.7	16
Pacific Northwest	10	99	5.6	6	3.4	6
	Total	1,774	100	175		87

**In the contiguous U.S. Removed outside contiguous U.S. include Northern Marianas – 1 site removed, Federated States of Micronesia – 1 deleted, Guam – 2 removed, Virgin Islands – 2 removed, Alaska – 5 removed.*

It is evident that EPA regions 1 through 3, New England, New Jersey, and New York, and the Mid-Atlantic respectively have the most PFAS Superfund sites, representing over 72% of the total. Therefore, these three EPA regions represent the study area for the current chapter. An added benefit of this study area is the geographic proximity of the regions and relatively homogenous cultural, economic, and political standing. These characteristics reduce geographic heterogeneity in the data as well as reduces the potential for outlier effects. Contiguous states in EPA Region 1 include Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont. EPA Region 2 consists of New Jersey and New York. EPA Region 3 includes Delaware, Maryland, Pennsylvania, Virginia, West Virginia, and the District of Columbia. PFAS Superfund sites are differentiated between whether they are affiliated with military operations, or have been in the past, due to different demographic characteristics of military servicemembers compared to the general public. Table 13 lists the number of PFAS Superfund sites with a military association (whether current or past). Both spatial and statistical analysis is carried out at the Census tract level. Census tracts are small, statistical subdivisions that average 4,000 individuals each (Darden et al., 2010; U.S. Census Bureau, 2020). Census tracts most closely resemble neighborhoods, which is ideal for measuring the impact of Superfund sites on neighborhoods of various demographic compositions (Darden et al., 2010; Noonan et al., 2009).

The first question of this dissertation chapter is whether there are statistically significant patterns of social vulnerability within proximity to Superfund sites with a PFAS designation. To measure social vulnerability, a multivariate measure is used, loosely derived from the CDC’s Social Vulnerability Index (SVI). The SVI was created to anticipate, confront, repair, and recover from the effects of a natural disaster (CDC, 2022). The original CDC index is used in various academic studies in the literature, mostly for health and evacuation planning studies (Horney et al., 2017; Lue & Wilson, 2017) and even Covid-19 mortality assessments (Nayak et al., 2020). The four domains of the CDC’s original SVI are socioeconomic status, household composition/disability, minority status/language, and housing/ transportation. Variables included in the CDC’s SVI domains are listed in Table 14. The CDC’s social vulnerability index is modified for this study’s purposes, namely combined in index form for cluster analysis and subsequently the same variables are used separately in regression analysis to isolate each variable’s effect. A selection of variable(s) from each category of the original CDC variables were selected for the modified index based on correlations among the entire SVI. This approach was necessary to avoid potential multicollinearity in the regression analysis. The selected variables for the modified SVI are bolded in Table 14.

Table 14 *Social Vulnerability Variables Related to Exposure to PFAS at Superfund Sites*

Domain	SVI Variable	Description
Socio-economic Status	**Below Poverty**	Individuals below federally defined poverty line.
	Unemployed	Unemployed persons 16 years or older actively seeking work divided by total civilian population.
	Income	The mean income computed for every person in the census tract.
	No Highschool Diploma	Percentage of persons 25 years of age and older, with less than a 12th grade education.
Household Composition/ Disability	Aged 65 or Older	
	Aged 17 or Younger	
	Civilian with a Disability	Percentage of persons civilian population not in an institution who are at least 5 years with a disability.
	Single Parent Household	
Minority Status/ Language	**Minority**	A sum of the following: Black or African American alone; American Indian and Alaska Native alone; Asian alone; Native Hawaiian and other Pacific Islander alone; some other race alone; two or more races; and Hispanic or Latino – white alone.
	Language Barrier	Percentage of persons who speak English “not well” or “not at all.”
Housing Type and Transport*	**Crowding**	At the household level (of occupied housing units), there are more people living in the house than rooms.
	Mobile Homes	Mobile homes as a % of total housing units
	Multi-Unit Structures	Percentage of housing in structures with 10 or more units
	No Vehicle	Percentage of households with no vehicle available.
	Group Quarters	Percentage of persons in group quarters (a place where people live or stay, in a group living arrangement, that is owned or managed by an entity or organization).

Variables were selected from the CDC’s SVI ensuring the broad themes are maintained. Refer to table 21 in the Appendix for a pairwise correlation and corresponding statistical significance of each of these variables, calculated using the pwcorr command in STATA 14. First, several of the socio-economic variables are correlated, with poverty status associated with all three other variables in this category: unemployment, income, and no high school diploma with correlation values of 0.60, -0.55 and 0.64 respectively. Therefore, poverty is selected as the vulnerability indicator representing socio-economic status theme. Similarly, disability status and single parent households are kept in this chapters' analysis and will stand in for the percentage of those with disability status (correlated with percentage over 65 years), and single parent households (correlated with percentage under 18 years). The minority status and language category of the SVI will be unaltered in this chapter's analysis. While limited English and minority status are correlated, it is hypothesized that these factors are both unique in their association with proximity to Superfund sites. Post-estimation analysis VIF tests are used to determine whether multicollinearity is a problem in regression analysis. The fourth domain, housing/ transportation is modified for this study's analysis. The CDC's original SVI includes five variables: multi-unit structures, mobile homes, crowding, no vehicle, and group quarters. These variables do not all directly translate from natural disaster evacuation preparedness to spatial proximity to Superfund sites. Therefore, only crowding is kept from this category.

The original source of the variables from the SVI is the American Community Survey (ACS), 2014-2018 (5-year) data. The date of this data collection corresponds to the Superfund PFAS data provided by SCEPW in 2019. The method for calculating index values by Census tract is based on the CDC's Social Vulnerability Index, detailed in the five steps outlined in table 15.

Table 15 Calculating the Social Vulnerability Index

Variable Code	Step 1: Name of variable ranked by percentile (low to high vulnerability)	Step 2: SPL_Theme variables: sum of series for each social vulnerability theme	Step 3: Percentile ranking of each SPL_Theme	Step 4: Sum of series of themes	Step 5: Percentile ranking of SPL_Themes variable
Poverty	EPL_ Poverty	**SPL_Theme1 =** EPL_ Poverty	**RPL_Theme1**	**SPL_Themes =** RPL_Theme1 + RPL_Theme2 + RPL_Theme3 + RPL_Theme4	**RPL_Themes**
Disability	EPL_Disability	**SPL_Theme2 =** EPL_Disability + EPL_Guardian	**RPL_Theme2**		
Guardian	EPL_Guardian				
Minority	EPL_Minority	**SPL_Theme3 =** EPL_Minority + EPL_Language	**RPL_Theme3**		
Language	EPL_Language				
Crowding	EPL_Crowding	**SPL_Theme4 =** EPL_Crowding	**RPL_Theme4**		

First, variables are ranked by percentile for each Census tract. The second step sums the variables' percentiles by theme for each Census tract, generating SPL_Theme variables**.** In the third step, each of the four theme's percentiles, SPL_Theme variables, are ranked by percentile over Census tracts, resulting in four RPL_Theme variables. The fourth step is summing the SPL_Theme variables into one combined vulnerability variable, SPL_Themes with a value unique to each Census tract. The final step ranks the SPL_Themes variable by percentile, yielding one final 'RPL_Themes' variable ranking each Census   according to vulnerability level. Therefore, this chapter's index provides a ranking variable 'RPL_Themes' from highest to lowest vulnerability across all Census tracts in the three EPA regions in the study area with a non-zero population.

4.4 Methods

Spatial cluster analysis is used to answer the first research question, whether there are statistically significant patterns of social vulnerability around Superfund sites known to have elevated PFAS levels (≥70 parts per trillion), and if so, where? The Local Moran's *I* is a local spatial autocorrelation statistic that identifies local clusters and outliers (Anselin, 1995). In this case, this statistic is used to estimate the magnitude and significance of vulnerability clusters of Census tracts within a 6-mile buffer from PFAS Superfund sites. Regression analysis is then used to address research question two, which asks whether PFAS Superfund site locations are associated with race, income, and other vulnerability factors independently, and if so at what magnitude? A review of the hedonic literature shows that Superfund and other hazardous sites' impacts typically extend no more than 6 miles away from the site (Noonan et al., 2009). This finding is consistent with buffer choices in the environmental justice literature that compare smaller buffers up to approximately five miles (Ashby et al., 2020; Burwell-Naney et al., 2013; Maranville et al., 2009). For this reason, a 6-mile buffer zone is chosen for estimating potential PFAS Superfund exposure. However, sensitivity analysis is used for 1-, 3-, and 10-mile buffer distances to confirm consistency in results and evaluation of the magnitude of the multivariate areal unit problem (results are presented and discussed in detail in tables 27 and 27 in the Appendix).

Spatial cluster analysis using local Moran's *I* is present in environmental planning research and pollution hotspot evaluation in the literature (Anselin, 1995; C. Zhang et al., 2008). The local Moran's *I* may show a clustering of similar high or low values *j* within distance *d* of the geographic area of focus or may expose whether a dissimilarity exists between the geographic area of focus *i* compared values of *j*. The Local Moran's *I* categories include cluster designations of high-high and low-low. The high-high Census tract designations imply a Census tract is high vulnerability and also surrounded by tracts with high vulnerability. Census tracts categorized as low-low are low vulnerability tracts surrounded by tracts also categorized as low vulnerability. The Local Moran's *I* statistic also provides information useful in outlier analyses with low-high and high-low designations. A high-low (or alternatively a low-high) designation indicates that a Census tract with high (low) vulnerability is surrounded by low (high) vulnerability Census tract. The outlier analysis is important for answering this chapter's research questions since, for example, a PFAS Superfund Census tract may have high vulnerability, but be surrounded by neighborhoods with low vulnerability (a high-low result), or vice-versa. Tabulations of Local Moran's *I* categories are calculated for Census tracts within the 6-mile buffer zone surrounding PFAS Superfund sites and for the entire study site for comparison. A first order queen-contiguity weight matrix is used to select neighbors for the Local Moran's *I* statistic, whereby Census tracts with communal borders are considered neighbors. There are 999 permutations issued in the calculation of Local Moran's *I* clusters. Clusters and outliers are only included if they are significant at the 99.999% level.

Logistic regression analysis is used to answer question two: "Which aspects of vulnerability, if any, are most strongly associated with spatial proximity to PFAS Superfund sites?" This approach is used to tease out individual effect of each vulnerability variable, and geographic control variables. The logistic regression model predicts the probability that each Census tract has a PFAS Superfund site within a 6-mile radius. The left-hand side binary variable has a value of 0 for Census tracts not located within this 6-mile distance, and 1 for Census tracts within a 6-mile buffer from a PFAS Superfund site. The regression is specified as:

$$\Pr(y_i = 1|x) = \frac{e^{x'\beta}}{1+ e^{x'\beta}} \tag{9}$$

where y_{ij} is a binary variable indicating whether Census tract i is situated within a 6-mile buffer zone of a Superfund site. The $x'\beta$ is a matrix of independent variables and their corresponding coefficients specified as follows:

$$\beta_0+\beta_1 x_1+\beta_2 x_2 + \cdots +\beta_m x_n \tag{10}$$

where β_0 is the intercept of each model, β_j (j = 1, 2, …, m) is a vector of slope coefficients of the model estimated using maximum likelihood. Since the estimated parameters are in the log-odds scale, they do not have any useful interpretation other than the direction of the sign. Therefore, the logistic results are transformed in two ways. First, marginal effects are estimated using the margins command in STATA 14 and used to determine differences in probabilities of having a PFAS Superfund site within a buffer zone. Second, odds ratios are used to interpret the results. The vector x_i (i = 1, 2, …, n) consists of independent variables, which includes the vulnerability variables used in the four themes of the CDC's social vulnerability index used for spatial cluster analysis and listed in table 14. Geographic control variables include EPA region, Census tract population density, and Census tract area. An indicator variable for the presence of non-PFAS Superfund sites is included as an exogenous variable to capture compounding effects of Superfund sites.

In determining the specification of model parameters, it is important to acknowledge that the use of aggregated data across space poses unique challenges for analysis. Two of these challenges are spatial heterogeneity (associated with spatial structure of the data) and spatial autocorrelation (a second order process characterized by spatial dependence). Spatial heterogeneity occurs when there is a lack of uniformity of trends over space (Anselin, 1988). Aggregated units such as Census tracts are comprised of heterogeneous areas and shapes, governance structures, and population characteristics (Anselin, 1988). Problems of spatial heterogeneity are addressed by incorporating missing variables that are the source of this heterogeneity across space (Anselin et al., 2013). First, indicator variables for each EPA region are used as geographic control variables in the analysis. EPA region variables are used to capture dissimilarities between regions including EPA governance differences across the regions as well as lack of uniformity in population characteristics. Similarly, population density is included in the regression to control for differences between urban and rural communities. Rural/urban designations exists according to population density, urbanization, and commuting patterns using Rural-Urban Commuting Area (RUCA) codes (ERS, 2022). However, a single population density variable is used in place of a RUCA type categorization for this analysis due to lack of variation in RUCA code across Census tracts. For instance, of the 3,651 Census tracts within six miles of a PFAS Superfund site, 96% were metropolitan statistical areas, with 2% micropolitan, 1% in a small town, and the remaining 1% either rural areas or have no data available. Therefore, regression analysis includes a single population density variable in addition to including indicator variables for each EPA region to reduce problems of spatial heterogeneity.

4.5 Results

The first set of results are summary statistics for vulnerability and descriptive variables of Census tracts across the entire study area, those within 6-miles of military Superfund sites, and those within 6-miles of non-military affiliated Superfund sites (Table 16).

Table 16 *Summary Statistics for Social Vulnerability Index and Regression Analysis Variables*

	All Data		Within 6-Mile Buffer Non-Military			Within 6-Mile Buffer Military		
Variable	Mean	Std. Dev.	Mean	Std. Dev.	T-Test P-Value*	Mean	Std. Dev.	T-Test P-Value*
% Poverty	13.09	11.63	14.65	13.73	< 0.00	11.85	10.67	0.00
% With Disability	12.48	5.66	12.15	5.34	0.01	12.36	5.46	0.47
% Single Parent	8.73	6.88	10.39	7.81	< 0.00	9.35	7.60	0.01
% Minority	36.18	30.97	42.06	32.18	< 0.00	43.73	30.48	< 0.00
% Limited English	4.26	6.95	5.38	7.24	< 0.00	2.23	3.22	< 0.00
% Crowding	3.01	4.70	2.92	4.11	0.36	2.10	2.485	< 0.00
Population Density	10902.28	21224	8634.35	9947.37	< 0.00	6002.90	8285.12	< 0.00

*testing the null hypothesis (Ha) that each variable mean for non-military or military census tracts (t) do not equal the mean of each variable using all data (T) (i.e. Pr[|T|>|t|]).

Findings suggest there are statistically significant differences in the composition of neighborhoods depending on a Census tract's proximity to PFAS Superfund sites. However, trends differ depending on the Superfund site type. Census tracts within 6-miles of Superfund sites with no military affiliation are associated with slightly higher levels of neighborhood vulnerability including a statistically higher proportion of individuals with a poverty designation, single parent households, people who are part of a racial or ethnic minority group, and people who have linguistic barriers. However, while the magnitude of the effect is slight, the direction of the effect of these groups is flipped for these groups near current or former Superfund military bases. The summary statistics in Table 16 suggest slight statistically significant differences in community vulnerability surrounding military PFAS Superfund sites compared to Superfund sites in this region as a whole, and in particular sites not related to military operations. This trend is likely due to the demographic and employment differences leading to lower levels of vulnerability among military service members compared to the general American public (PEW Research Center, 2017). Military service members have lower unemployment and higher than average income levels, and therefore the average decrease in poverty levels and many other indicators of vulnerability near military Superfund sites are to be expected. Due to these results, PFAS Superfund sites without military association are the primary focus of the results moving forward and will simply be referred to as PFAS Superfund sites.

Several factors are associated with an increased probability that a Census tract is located within 6-miles of a PFAS Superfund site. The average levels of poverty, single parent households, ethnic and racial minorities, and limited English are all higher for Census tracts within 6-miles from Superfund sites. Notably, the percentage of ethnic and racial minority groups in Census tracts near PFAS Superfund sites is approximately 6% higher on average compared to the entire study region, an increase from 36.18% to 42.06%. T-tests evaluating whether this value (t) is equivalent to the mean percentage of ethnic and racial minorities for all data (T) is less than 0.001 indicating a statistically significant difference. On the other hand, measures of vulnerability including the percentage with disability status and crowding rate are lower for Census tracts surrounding these Superfund sites. While the poverty rate for Census tracts surrounding non-military Superfund sites (t) is slightly higher than the rate using the entire study area (T), the p-value for the null hypothesis that these means are not equal (i.e. $|T| > |t|$) is 0.118. However, the null hypothesis that the poverty rate is no greater for non-military Census tracts than across the entire study area (i.e. $T > t$) cannot be rejected with a p-value of 0.47. For the entire region, the average percentage of those with a disability and crowding are 12.48% and 3.01% respectively, and these values decrease slightly to 12.15% and 2.92% respectively for tracts within 6-miles of PFAS Superfund sites. Overall, summary statistics suggest that Census tracts within 6-miles of non-military Superfund sites have slightly higher vulnerability levels compared to the greater study area.

The local Moran's *I* statistic provides information beyond the summary statistics, namely information on cluster analysis of social vulnerability index values across Census tracts. The local Moran's *I* values suggest a slightly higher clustering of social vulnerability among Census tracts within 6-miles of Superfund sites compared to the entire study area. Table 17 provides a proportional breakdown of how Local Moran's *I* values are distributed across space in figure 4. The left-hand side of table 17 lists tabulations of local Moran's *I* categories across all Census tracts in EPA regions 1 – 3. This information is subsequently depicted in figure 4. The right-hand side of table 17 uses a subset of the Local Moran's *I* data in the left-hand side tabulation, exclusively focusing on Census tracts from figure 4 that are within 6-miles of a Superfund sites.

Table 17 *Tabulation of Local Moran's I Cluster and Outlier Values*

	All Data		Within 6-Miles of PFAS Superfund Site (No Military Association)	
Local Moran's *I* Categories	Freq.	%	Freq.	%
Not Significant	12,908	73.74	1050	62.99
High-High	2,441	13.94	365	21.90
Low-Low	1,954	11.16	231	13.86
Low-High	77	0.44	7	0.42
High-Low	119	0.68	14	0.84
No Neighbors	6	0.03	0	0.00
Total	17,505	100	1,667	100

The local Moran's *I* value for the entire study area is 0.569 with a Z-value of 127.26. This high and positive Z-value combined with a statistically significant pseudo p-value of 0.001 (999 permutations) indicates overall positive autocorrelation across the study area. This table shows us that the distribution of Local Moran's *I* categories differ slightly depending on whether tracts are within 6-miles of Superfund sites, compared to the entire study area.

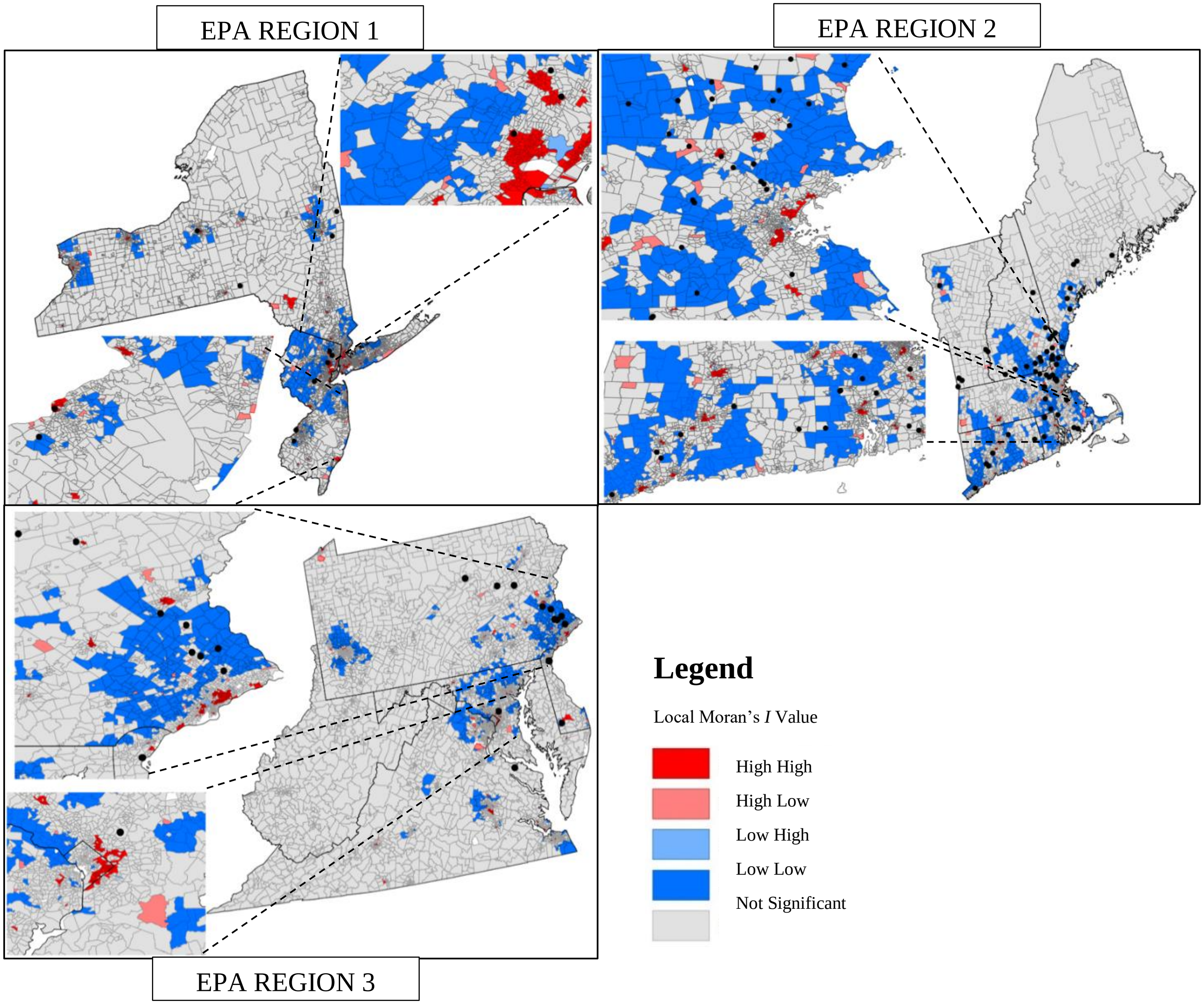

Figure 4 *Spatial Correlation of Social Vulnerability Index using Local Moran's I* Value Across Census Tracts in EPA Regions 1 - 3

The map of local Moran's *I* values corresponding to table 17 is presented in figure 4. Note that the local Moran's *I* was calculated once across the entire study area, but results are presented by EPA region in panel form to allow for the presentation of magnified results.

Table 17 and figure 4 depict a slightly higher percentage of Census tracts within 6-miles of a PFAS Superfund site are in high-high clusters of vulnerability (21.9%) compared to the entire study area (13.94%), a difference of 7.96%. This finding suggests that neighborhoods with higher concentrations of vulnerability are more likely to live near Superfund sites. Interestingly, Census tracts within 6-miles of PFAS sites also have a slightly higher percentage of Low-Low clusters (13.86%) compared to the overall study area (11.16%). This low-low difference is less pronounced than the high-high vulnerability result and beyond the scope of this study. The Local Moran's *I* categories of low-high and high-low represent Census tract outliers. A low-high (high-low) categorization represents a low (high) vulnerability Census tract within a cluster of high (low) vulnerability Census tracts. Here, the neighboring values, *j* differ from the Census tract of focus, *i*. The percentages of the low-high and high-low categories are very low for the overall study area and within a 6-mile buffer of Superfund sites. Therefore, no meaningful outlier effects were found from the Local Moran's *I* analysis.

To test the robustness of these Local Moran's *I* results, the G_i^* was also used to evaluate spatial cluster analysis. The Local Moran's *I* measure different aspects of this definition of spatial association compared to the G_i^*. A positive G_i^* value suggests a spatial clustering of high values, and a negative value a spatial clustering of low values, while for the Local Moran's *I*, a positive Z-value indicates spatial clustering of similar values (either high or low) and negative Z-Z-values a clustering of dissimilar values (for example, a location with high values surrounded by neighbors with low values). Another related difference between these statistics is that the G_i^*

statistic includes the value that is currently under investigation, while the Local Moran's I does not. To ensure robustness in results despite these differences, the Getis-Ord G_i^* statistic is calculated using the same methodology from findings in 17 and are reported in Appendix table 22 and Appendix figure 5. Overall, the Getis-Ord G_i^* yielded similar results, and these findings are discussed in greater detail in the Appendix.

While the cluster analysis provides insight into combined vulnerability levels surrounding Superfund sites, logistic regression analysis enhances these findings with an estimate of the direction and magnitude of each vulnerability factor. Each coefficient value and statistical significance finding allows for the evaluation of the impact of each factor holding other measures of vulnerability, as well as several control variables constant. Marginal effects and odds ratios of the logistic regression are reported in table 18. Variables from the SVI that are included in the regression are the percentage of household poverty, single parent households, crowding, ethnic and minority status, limited English spoken in the household, and those with disability status. The model also includes several spatial variables as controls to ensure changes associated with spatial variation are not attributed to social vulnerability indicators. These are the EPA region of Census tracts, the presence of non-PFAS Superfund sites within the buffer zone, and the population density (population/square miles) of each Census tract. Several models are tested to ensure robustness and optimal specification. To ensure model fit, pairwise correlations of SVI variables were calculated (reported in Appendix table 21). Further, a variance inflation factor (VIF) is also used to ensure multicollinearity is not beyond an unacceptable threshold. The output of the VIF is detailed in full in Appendix table 26.

__Table 18__ Logistic Regression Results of Spatial Proximity to Non-Military PFAS Superfund Sites

VARIABLES	Likelihood of Site within 6-Miles: Marginal Effects	Likelihood of Site within 6-Miles: Odds Ratios
EPA Region 1	0.1476***	3.7518***
	(0.0098)	(0.2668)
EPA Region 2	0.0523***	1.7963***
	(0.0065)	(0.1244)
Population Density	0.0000***	1.0000***
	(0.0000)	(0.0000)
% Poverty	0.0011***	1.0126***
	(0.0003)	(0.0031)
% Single Parent Households	0.0013***	1.0151***
	(0.0004)	(0.0047)
% Minority	0.0009***	1.010***
	(0.0001)	(0.0013)
% Limited English	0.0021***	1.0254***
	(0.0004)	(0.0053)
% Crowding	-0.0049***	0.9437***
	(0.0008)	(0.0092)
% With Disability	-0.0031***	0.9636***
	(0.0005)	(0.0056)
Superfund sites without known PFAS within buffer	0.0353*	1.4453*
	(0.0163)	(0.2189)
		Pseudo R^2 = 0.0609
		Prob> chi2 = 0.0000
		N = 17,031

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Beyond the evaluation of degrees of correlation among independent variables, other characteristics of social vulnerability such as unemployment are considered and tested in alternate logistical regression analysis (Appendix table 26). However, unemployment is not included in the model because a likelihood ratio test indicated it was not statistically significant (at the 95% level) in the model when added ($\chi^2 = 3.53$ and $p > \chi^2 = 0.06$).

Regression results evaluating the probability a PFAS Superfund site is situated within 6-miles of each Census tract observation show that individual vulnerability factors are often associated with spatial proximity to PFAS Superfund sites. Only regression results for PFAS Superfund sites with no military association are included in this analysis. These are the same Superfund sites selected for use in the cluster analysis section of this paper. For instance, a 1% increase in the racial and ethnic minority population of a Census tract is associated with an increase in the probability of living within 6 miles of a PFAS Superfund site by 0.09 percentage points. In other words, according to the odds ratios, a one percentage increase of racial and ethnic minority residents in this regression is associated with an increased likelihood of the presence of a PFAS Superfund site by a factor of approximately 0.010. Results also show a class difference in Census tracts within 6-miles of PFAS Superfund sites. A 1% higher rate of poverty is associated with an increased probability that a Census tract is situated within a 6-mile buffer of a PFAS Superfund site by 0.11 percentage points, or an increase in the probability a Superfund site is situated within 6-miles by a factor of approximately 0.013. While industry siting in impoverished neighborhoods may contribute to this result, it is also well-documented that relocation is cost prohibitive for many families, particularly those living in poverty (Dasgupta et al., 2022). Logistic results for these Superfund sites also show a slight yet positive statistical association with single-parent households and limited English spoken at home. A 1% increase in single-parent households and limited English spoken in the household is associated with a 0.13 and 0.21 percentage point increase in the probability of living within 6 miles of a PFAS Superfund site respectively. Therefore, while cluster analysis showed that Superfund sites were more likely surrounded by clusters of both high and low neighborhood vulnerability, regression analysis confirms that most indicators of vulnerability are positively associated with spatial proximity to PFAS Superfund sites.

Results from spatial variables including indicator variables for EPA regions and population density show that indeed, there is some spatial heterogeneity in Superfund site placement across EPA regions. EPA region 1 contains the largest proportion of Superfund sites while EPA Region 3 has the fewest. While a statistically significant difference in population density was detected in the model, the magnitude of the coefficient values were not meaningfully different than zero. This result indications no consequential difference between a Census tract's population density and the likelihood a Census tract is situated within 6-miles of a Superfund site. One explanation for this finding is simply the lack of variation in the population density across the study area since most Census tracts are located in high-density areas. The majority of Census tracts near PFAS Superfund sites (as well as across the entire study area) are located within metropolitan statistical areas. As mentioned previously, across the entire study area, approximately 87% of Census tracts are located within statistical metropolitan areas, whereas approximately 96% Census tracts within 6-miles of Superfund sites are within metropolitan statistical areas (and the remaining 2% are located in micropolitan areas, 1% in small towns, and 1% either rural areas or have no data available). Therefore, while there was not a meaningful population density effect detected in the model, this finding may be in part due to lack of significant population density variation across the study area. Further, it is important to note the connection between population density and Census tract size in this analysis. This study uses Census tracts as units of analysis, which approximate neighborhoods at approximately 4,000 individuals (Darden et al., 2010; U.S. Census Bureau, 2020). Since population size is approximately constant by Census design, the population density variable (calculated as population / area [in square miles]) is essentially an estimate of the effect of Census tract area in square miles. Therefore, a larger number of geographically smaller Census tracts fit within a 6-mile buffer, perhaps affecting the population density estimate in this model.

4.6 Discussion

This paper addresses the gap in knowledge about whether social vulnerability is associated with greater risk of PFAS from spatial proximity to Superfund sites. Overall, non-military Superfund sites (typically are current or former landfills, private businesses, or otherwise) are associated with characteristics of higher vulnerability in nearby neighborhoods. The analysis also indicates a clustering trend among these high-vulnerability Census tracts. In this study, regression analysis provides information on which characteristics of vulnerability are associated with spatial proximity to these PFAS Superfund sites. Neighborhoods within these buffers are associated with increased rates of poverty, single parent households, ethnic/racial minority groups, and limited English. There may be several factors that make relocation particularly difficult for socially vulnerable groups. While low-income residents are forced to move more frequently, this pattern of residential mobility achieves survival of immediate crises rather than selecting better opportunities for school, jobs, and environmental services (DeLuca & Jang–Trettien, 2020). Environmental justice studies also show there are also racial differences in the willingness to avoid various types of environmental contamination. In a study of relocation in the face of air pollution in Los Angeles, California the authors find for example that members of Hispanic communities may be willing to pay more to avoid cancer risk compared to other risks associated with pollution (Depro et al., 2015). In terms of single parent households, studies find that residential relocation has deleterious effects on child well-being due to lack of social, emotional and family financial stability (Hausman and Reed; Devine; Austin; Pittman & Bowen, 1994). Single parents, particularly those of divorce (Austin, 2008) may choose to delay relocation since this change may hinder academic and increase psychological distress and negative social outcomes including high school dropout rates, repeating grades, lower test scores, and increases peer conflict (Hausman & Reed, 1991; Pittman & Bowen, 1994; Scanlon & Devine, 2001; Hausman & Reed, 1991; Scanlon & Devine, 2001). Individuals with disability status are found to be lower near Superfund sites than the general population. While more information is needed to better understand this result, there are a few potential reasons for this trend. First, Superfund sites are not typically located in rural areas, which often have higher rates of disability in populations due to increased rates of elderly individuals as well as an increased prevalence of manual labor including farming activity (Von Reichert et al., 2014). Secondly, since vulnerable populations are more likely to live within 6-miles of Census tracts, those with disabilities close to Superfund sites may have limited access to healthcare to have a disability formally diagnosed. Indeed, social vulnerability indicators such as single parent households, racial and ethnic minority groups, and poverty are only slightly more likely to live within 6-miles of Superfund sites. However, these marginal differences likely represent many individuals in communities surrounding the 175 PFAS Superfund sites.

Census tracts within six miles of PFAS Superfund sites have particularly higher poverty rates all else equal. This result is concerning since residents below the poverty level are financially restricted in their ability to reduce PFAS exposure, including the purchase of bottled water (Doria, 2006). While PFAS exposure is ubiquitous throughout America and indeed most of the world (Birnbaum, 2022) there are two main methods to avoid elevated PFAS exposure through waterways: living in areas with no/low environmental PFAS water contamination and installing household water filters. Products for household water filtration certified to reduce PFAS in household tap water are readily available (Environmental Working Group (EWG), 2021b). Reverse osmosis filters, which pushes water through a microscopically small filter material, may cost hundreds of dollars for each system and installation, putting them out of budget for low-income individuals. Additionally reverse osmosis units use approximately three times as much water as they treat, which may lead to especially significant costs in the face of increasing American household water bills (Mack & Wrase, 2017; US EPA [US Environmental Protection Agency], 2005). Containers using activated carbon filters are a lower upfront-cost option for filtering PFAS, the filters may be cost-prohibitive for lower-income households over time as the filters need to be replaced (Environmental Working Group (EWG), 2021b). Therefore, lower-income individuals may find that purchasing filtration devices to reduce PFAS exposure are unaffordable.

Beyond filtration devices, better communication about water quality empowers communities to self-advocate for drinking water (Nicholas & Vedachalam, 2021). Unfortunately, there are often information gaps between water providers and their customers that inhibit public awareness about PFAS and other water contaminants. Public outreach by water companies varies considerably by provider (Hubbart & Gootman, 2021). Though tap water testing and quality reporting is legally required across the United States, there are many reasons why this information remains inaccessible to segments of the public (Nicholas & Vedachalam, 2021). Those least able to access water quality information have linguistic barriers, including lack of English fluency, reading comprehension below a college level, or are visually impaired (Nicholas & Vedachalam, 2021). Water quality testing among consumers of private drinking well water due to a lack of knowledge about drinking water testing and steep costs (Collins & Steinback, 1993; MacDonald Gibson & Pieper, 2017). Therefore, there are financial and information barriers to reducing PFAS water consumption through household tap water that disproportionately affect socially vulnerable groups.

These findings that households in poverty, that have racial or ethnic minority status, who are single parents, or who face linguistic barriers are statistically slightly more likely to live within 6-miles of Superfund sites is an example of the inequitable distribution of environmental harm. This inequity breaks the first tenant of the environmental justice paradigm. The social vulnerability characteristics included in this study are also known to be associated with the other tenants of EJ beyond these distributional effects (Schlosberg, 2007). Namely, the other two tenants of EJ are the recognition of the diversity of experiences among communities disproportionately affected by environmental harm and access to participation in the political processes governing ecological management decisions are both important in achieving EJ (Schlosberg, 2007, 2013). The experiences of socially vulnerable individuals may be contextualized within underlying social mechanisms. Various groups experience adversity in structural, institutional, and social conditions through access to healthcare, education, criminal justice, and housing among others (Ashby et al., 2020; J. Jones, 2021; D. N. Pellow, 2017). The context of these issues may be directly or indirectly related to environmental justice. For instance, not only are racial and ethnic minorities and those with disability status overrepresented in prison populations, juvenile detention centers, and public housing (Ashby et al., 2020; Pellow, 2017; Coffey et al., 2020), these facilities are also more likely to be situated near Superfund sites (Coffey et al., 2020). Indeed, 70% of the country's superfund sites are within one mile of federally assisted housing, according to a report by the nonprofit Shriver Center on Poverty Law (Coffey et al., 2020). Therefore, while characteristics of social vulnerability may be directly related to potential PFAS exposure, there are likely other forms of institutional injustice that vulnerable communities experience simultaneously.

The last component of environmental justice is the ability to participate in political processes associated with environmental management decisions and outcomes (J. Jones, 2021). Socially vulnerable individuals such as those with disability status, linguistic barriers, who are below the poverty line, among others may be excluded from forms of civic engagement including voting, attending local government meetings, attending political rallies, making campaign contributions, or working/volunteering for political campaigns (PEW Research Center, 2018). According to the literature, inhibitors to voting among low-income and rural residents include geographic inaccessibility, inflexible operating hours, transportation barriers, and unaffordable fuel costs, and less ability to contribute financially to political campaigns (J. Jones, 2021; PEW Research Center, 2018). There are several examples of challenges to political participation beyond financial constraints. Those with linguistic barriers, are often faced with weaker communication networks between themselves and political leaders (Rodriguez, 2006). Further, those with disability status face various barriers for meaningful participation in political processes including reduced efforts in recruitment and mentoring, fewer monetary, time, and energy resources, the “hierarchy of impairments” (cultural attitudes about the type of impairment), and lack of adequate accessibility of political spaces and activities (Waltz & Schippers, 2021). While this paper focuses largely on the inequities in the distribution of potential PFAS exposure, these examples of injustice beyond distributional effects of harm, and the barriers to the policy-making process are important contributors to environmental injustice.

Despite this study’s contributions, there are limitations related to data availability to be addressed. Indeed, the literature provides plausible explanations for potentially elevated PFAS exposure including barriers for tap water quality, barriers to relocation for low-income households, those with linguistic barriers, and single-parent households for instance. However, community vulnerability analysis in this study was limited to information provided by the U.S. Census. Detailed survey questions tailored to the topic of environmental justice surrounding PFAS Superfund sites would provide more insight into the trends found in this paper. For instance, information about individual risk perceptions related to PFAS exposure could shed light on whether those who live near Superfund sites are less concerned about PFAS compared to people who do not live near PFAS Superfund sites. Relatedly, information is missing about the level of knowledge of PFAS in communities surrounding Superfund sites found to have elevated PFAS levels. Establishing a distinction between information barriers and risk preferences may provide context on the causes of slightly elevated social vulnerability in communities surrounding PFAS Superfund sites compared to the general population. Further, while a key tenant of environmental justice is equitable access to participation in the political process, there is a dearth of Census information on the political opinions and experiences of respondents. Information about both political perceptions and involvement would provide a nuanced perspective on potential disparities in political access faced by vulnerable communities. Indeed, it is hypothesized that people with linguistic barriers and who are below the poverty line in this study face outsized barriers to political participation in line with previous research on political participation (Rodriguez, 2006), however concrete evidence for this population would be more compelling. Though U.S. Census data is widely used in the literature (Horney et al., 2017; Mack & Wrase, 2017), the scope of the Census survey is broad. Future research may incorporate novel data sources designed to provide context to the findings presented in this chapter.

The second group of limitations are geographic in nature due to aggregation, scale, and boundary choices inherent in the data used as well as methodological choices made in the buffer analysis of this chapter (Atkinson & Tate, 2000). These challenges are captured within the modifiable areal unit problem (MAUP) framework. In terms of scale and aggregation, different results emerge as geographic areas of analysis are condensed into fewer and larger aggregated units. As aggregation levels increase, the mean values of estimators are expected to remain constant and the variance across data points are reduced. This leads to increased standard errors in the estimates (Arbia & Petrarca, 2011). In practice, however the aggregation effects of MAUP are often unstable (Openshaw & Taylor, 1979; Fotheringham & Wong, 1991). Estimates of effects do not necessarily smoothly increase or decrease in a uniform direction alongside an increase or decrease in aggregation level, increasing the challenge of MAUP (Openshaw & Taylor, 1979). Therefore, the findings of this chapter apply exclusively to trends at the Census tract level and cannot be generalized to different units such as the individual or county level.

Results may also be affected by the boundaries chosen (Masser et al., 1978; Openshaw & Taylor, 1979). The boundary problem presents challenges when different combinations of a given number of areal units yield different results and these types of distortions are particularly severe in multivariate regression analysis (Fotheringham & Wong, 1991; Openshaw & Taylor, 1979). In the context of this chapter, the boundary problem applies to the buffer choice for evaluating potential PFAS Superfund site exposure. Noonan et al. (2009) find that most toxic output from Superfund sites do not typically extend beyond 6 miles, motivating the choice of buffer-zones in this study. However, to gain insight into the boundary effects of MAUP, the logistical regression model was rerun at a range of buffer distances 1-, 3-, 6-, and 10- miles. These results are reported in detail in Appendix tables 27, 28, and figure 6. Comparing the model output at various buffer distances ensures the results are robust to other distances beyond the 6-mile buffer selected. The results of this sensitivity analysis indicated that coefficient values of the regressions did not vary significantly for these alternate buffer distances and therefore only the 6-mile buffer is reported in the main analysis of this chapter.

Another limitation of this study is data availability for characteristics of Superfund sites that may be associated with social vulnerability at higher magnitudes. For instance, it is hypothesized that the duration of a Superfund site designation may be associated with social vulnerability characteristics in surrounding neighborhoods. It is hypothesized that a Superfund site established many decades ago may be associated with more vulnerable neighborhoods. An exploratory ordinary least squares regression was estimated regressing the number of years a Superfund site on the same variables in equation 9. Results of this regression are found in Appendix table 30. Preliminary findings suggest that the age of these sites may slightly intensify the association between spatial proximity to Superfund sites and some vulnerability characteristics. More research is needed to better understand which Superfund characteristics may compound potential exposure to PFAS.

Overall, the three limitations of this study relate to data structure and availability. More detailed data evaluated at various geographic scales could provide deeper insight into the findings in this study. Subsequent studies may tailor survey questions toward the personal perceptions and experiences of individuals living near Superfund sites as well as include more detailed information about Superfund site characteristics. Further, while geographic problems such as the modifiable areal unit problem persists throughout the literature (Openshaw & Taylor, 1979), evaluating the effects of Superfund sites at various geographic levels will paint a more comprehensive picture of the types of individuals more at risk of PFAS exposure from Superfund sites.

Though there are certainly limitations in this research, the findings of this paper fills a significant gap in knowledge in the literature. Until this point, no studies capture the additive and compounding effects of various forms of inequity related to Superfund exposure. Instead, studies evaluate race and income separately, often leaving out other key indicators of vulnerability (Banzhaf et al., 2019; Stretesky & Hogan, 1998). This paper evaluates trends in the association between PFAS Superfund sites and neighborhood characteristics with an index of social vulnerability. This index has never been used for understanding vulnerability around PFAS Superfund sites, to understand how indicators of vulnerability combined may lead to a high level of in overall vulnerability, or these characteristics of vulnerability amplifies the probability of pollutant exposure. Secondly, no studies focus on the characteristics of neighborhoods surrounding PFAS-contaminated Superfund sites across multiple states. While there are many studies that evaluate case studies of PFAS exposure from Superfund sites (Maranville et al., 2009; Stretesky & Hogan, 1998; Tidwell et al., 2017), a multi-state analysis of environmental justice implications from PFAS-contaminated Superfund sites previously did not exist. This information is important to ascertain to better understand the characteristics of communities most likely to experience heightened PFAS exposure resulting from environmental pollution.

There are also policy implications for the findings of this study. PFAS is increasingly included in regulation at various levels of government, including the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (Birnbaum, 2022). The EPA is on track to regulate PFAS contamination of America's water, land, and air, stating for the first time that they intend to designate PFAS as "hazardous substances" under the Superfund law.

While the EPA submitted this regulation intent to the Office of Management and Budget (OMB) on January 10, 2022 (The National Law Review, 2022), the final ruling is expected to come by 2023. PFAS are a class of incredibly difficult substances to manage since they do not decompose in the environment. Even if PFAS is filtered out of water systems, the problem of what to do with this concentrated particulate is an unresolved problem (Birnbaum, 2022). Since this problem is likely to endure for the foreseeable future (DOD, 2020), the type of information provided in this analysis is important for understanding which populations are disproportionately experiencing environmental PFAS contamination.

4.7 Conclusion

Challenges of PFAS are widespread in the lives of the American public largely due to the industrial use of PFAS compounds, the inclusion of PFAS in household goods, residuals from water resource recovery facilities, and leachate from landfills (Birnbaum, 2022). It is well-known that elevated PFAS levels in tap water are common in neighborhoods close to landfills and industrial production facilities that use PFAS (Hu et al., 2016b). Though water access is a human right (United Nations (U.N.), 2014), and elevated PFAS levels in the water supply pose significant health challenges to the American public (Sunderland et al., 2019), eliminating PFAS in the water supply is no simple task. As actions to mitigate PFAS contamination mount, including legislation to minimize PFAS use and expedite cleanup, PFAS persists in drinking water (Birnbaum, 2022). The goal of this study is to shed light on the characteristics of neighborhoods currently the most at-risk of PFAS exposure in household water supplies due to heavily contaminated sites. Results show that racial and ethnic minorities, households experiencing poverty, those that speak limited English, and single-parent households would benefit from PFAS reduction at Superfund sites at slightly higher rates. As PFAS mitigation initiatives continue, these cleanup efforts may benefit from this contextual information associated with who is most at risk from environmental harm from PFAS.

5. CONCLUSION

5.1 Household Water Issues Across the United States

This dissertation provides quantitative information about the public's interaction with environmental services, namely water quality in the natural environment and subsequent household water use. Though America is a wealthy nation, and one in which most residents enjoy consistent access to household water services including tap water and wastewater services, water systems are faced with mounting pressures. These pressures include stagnant federal investments in a decentralized water infrastructure network (Haddeland et al., 2014; Stikker, 1998; EPA, 2020b), increasing variability in the hydrologic cycle due to climate change (Barnett et al., 2005; Dai et al., 2018), a rising population, urbanization, increased agricultural intensity, and increased per-capita water demand (McDonald et al., 2014; Varis & Somlyódy, 1997). Examples of water crises emerge in the press and academic literature, such as in Flint, Michigan, where residents were exposed to elevated water lead levels associated with negative health effects (Mohai, 2018). Since the majority of the water infrastructure in use today was built in the post WWII era, whereby improvements were funded to mediate crises one at a time, the result was an overall decentralized water provision network (Beecher et al., 2020). Households in America are already experiencing the effects of a largely outdated water infrastructure system. Overall, the under-funding of water infrastructure in the U.S. has negatively impacted the economy, impacted public health, and has decreased the quality of life for many residents (EPA 2020). For example, billions of gallons of raw sewage is discharged into local surface water each year from aging wastewater facilities (EPA, 2020). Approximately $2.6 billion is lost as water mains leak trillions of gallons of treated drinking water (EPA, 2020). In the midst of these failures, amendments to the Clean Water Act and Safe Drinking Water Act transfer significant responsibility for funding from the federal government to local communities (Congressional Research Service (CRS), 2016a) leaving water providers in a tight spot financially. Frequent shifts in ownership structure and access to funding puts strain on providers that largely provide household water services at-cost (J. Beecher et al., 2020).

This precarious infrastructure situation runs parallel to several other difficulties threatening public water provision. Uncertainty about water quality and availability as climate change alters the water cycle that increases the likelihood of drought in some regions, while others experience an unprecedented frequency of heavy rainfall events that overwhelm sewage systems (Taylor et al., 2013). Further, manmade chemical particulate such as PFAS (the most common subtypes being PFOS and PFOA) persists in groundwater and surface water and are cost-prohibitive to filter before reaching American consumers. As a result, low levels of PFAS substances are ubiquitous in American tap water, with elevated levels found in communities with PFAS-contaminated sites nearby (Hepburn et al., 2019). Lastly, as the population-density in cities grows, demand outstrips what water companies were built to provide. These pressures on water systems have all but ensured water bills must increase to cover the costs of modernizing infrastructure and modifying systems to accommodate climate and demographic shifts (Islam & Susskind, 2015; Warner et al., 2018). Evidence of higher water bills that are out of reach for vulnerable groups has already been documented (Walton, 2016) and water bills are expected to continue increasing (Mack & Wrase, 2017).

5.2 Summary of Dissertation Chapters and Contributions to the Literature

The first two chapters build on nascent research shedding light on the increasing cost of water bills, which are increasingly out of reach to low-income and otherwise vulnerable

Americans (Mack & Wrase, 2017). Despite this challenge, information related to public access to water services is lacking. Not only are the structures of water companies complex and ever-evolving (Beecher et al., 2020), water companies are not required to collect information on their customers (Gaudin, 2006). No studies have evaluated increased water bills in the context of where these payments fit within a household budget, perceptions of fairness, or the effects of rising bills on the greater economy. Despite widespread information about perceptions of water quality, or characteristics associated with water demand (Dalhuisen et al., 2003; Inman & Jeffrey, 2006; Ruijs, 2009), many studies overlook the relationship that the public has with water companies. Numerous issues associated with clean water access require a multipronged approach: from governments, water providers, and the public alike. As a first step to fill this gap, this dissertation uses a one-of-a-kind dataset called SWISSH to ask novel research questions across a nationally representative sample to better understand how these growing problems affect vulnerable populations.

The first chapter focuses on the broader effects of rising water service bills on household budgets, spending on various goods and services, and the potential for cascading effects of increased water costs on various sectors of the economy. It is the only academic paper to examine consumer spending in response to water bill increases. Evidence from the first chapter suggests that households change their spending behavior with relatively small increases in water bills. Hispanic households were particularly sensitive to these prices increases as were middle- and low-income households. Consistent with the literature, households were more likely to change consumption of less essential goods relative to essential goods. Concerningly, model results however reveal that respondents report they would reduce spending or would not be able to afford highly necessary goods like healthcare, heat, and electricity if water prices increase substantially. Overall, results provide insights into geographic trends, the demographics of households likely to be affected, the industries that could be affected, and at what bill increase levels these trends are most pronounced.

Chapter two in this dissertation fills a gap in understanding about perceptions of whether water bills are too high. From a theoretical standpoint, many studies evaluate the price elasticity of demand for water (Dalhuisen et al., 2003; Ruijs, 2009), and various factors that affect water consumption (Inman & Jeffrey, 2006). However, as water utilities, consumers, and city governments navigate the need to upgrade water systems in the present era of infrastructure replacement, it is important for utilities to monitor the impacts of these upgrades on water rates and customer perceptions of the cost of water service. This chapter's model results indicate that low-income and racial/ethnic minority households are more likely to perceive their water bills to be too high. There are also geographic variations in household water perceptions about the cost of water that may reflect widespread affordability issues in particular parts of the country (Lynch, 2016; Zamudio & Craft, 2019). Results of chapter two demonstrate that the frequency of water billing affects perceptions of water bill fairness, and that those who are billed quarterly are more likely to consider their water bills unfairly high compared to customers billed monthly or annual bills. This finding has implications for water companies as they select among billing frequency choices. The second chapter also provides results related to policy decisions and billing practices chosen by water providers to improve public perceptions of household water bills. Those in a payment assistance program are significantly more likely to feel their water bills are fair, indicating these programs are likely succeeding in their goals to provide financial relief for their vulnerable customers.

Though studies on the topic of water access often focus on developing countries (Dinar et al., 2015; Le Blanc & Perez, 2008; Roson & Sartori, 2015), studies of household access often overlook wealthy countries such as America. This trend likely persists because water service bills have historically comprised a small share of the overall American household budget (Gaudin 2006; Renwick & Green 2000**)**. Findings in chapters one and two suggest that the effects of increasing water bills on household budgets, and perceptions of whether bills are fair vary according to individual household needs, circumstances, and social/demographic characteristics.

The final chapter of this dissertation focuses on the distribution of benefits and harms associated with proximity to 'Superfund' sites polluted with PFAS. It provides a comparative analysis of environmental justice, finding slightly elevated proportion of clusters of neighborhood social vulnerability near PFAS-contaminated Superfund sites. Regression analysis is used to understand which characteristics of vulnerability have stronger associations with spatial proximity to PFAS Superfund sites. Key findings suggest that these neighborhoods have especially high rates of poverty, single parent households, ethnic/racial minority groups, and limited English spoken at home. Inequity of distribution of PFAS in water systems may be expected since we know from the literature that low-income and racial minority communities face drinking water contamination at higher levels from other pollutants such as uranium, nitrate, lead, coliform, and arsenic (Ranganathan & Balazs, 2015; Schaider et al., 2019). Unsafe levels of nitrates in public water systems are prevalent in agricultural regions and Schaider et al. (2019) find that Hispanic residents are particularly affected. There are also several case studies where water contamination affects vulnerable communities. Notably, the Flint Water Crisis in Michigan resulted in lead-contaminated water delivered to households after the local tap water source was changed without necessary corrosion controls added (Mohai, 2018). Other examples include Martin County, Kentucky, where impacts of a mining spill still pose health risks from water contamination (S. L. Scott et al., 2012) and the uranium water contamination Navajo reservation in Arizona and New Mexico (Corlin et al., 2016).

However, by focusing on Superfund sites found to have elevated PFAS levels, this dissertation provides more context about types of individuals potentially more likely to be exposed to PFAS. In the literature thus far, many studies consider PFAS exposure a problem disproportionately affecting privileged subsets of the population including wealthier, non-Hispanic White individuals (Buekers et al., 2018). However, these studies focus on exposure pathways beyond drinking water and environmental contamination such as diet that are beyond the scope of this study (De Silva et al., 2021). In the case where environmental PFAS contamination is particularly high such as in communities with PFAS Superfund sites, water is the major PFAS exposure source (Hu et al., 2016). Since chapter three shows socially vulnerable individuals are marginally more likely to live in areas known to have PFAS-contaminated Superfund sites, this dissertation provides more context into the social and demographic characteristics of individuals with potential PFAS exposure. These findings provide further evidence that vulnerable people may be at higher risk of exposure to environmental water contamination and subsequently perhaps household drinking water (Christian-Smith et al., 2012; Clough, 2018; Debbané & Keil, 2004; Y. J. McDonald & Jones, 2018; Schaider et al., 2019).

5.3 Policy Implications

Comprehensive information is needed for policymakers to understand how to efficiently allocate resources to improve water companies' financial standing, consumer relationships with water companies, and ensure equitable access to water services. While many studies have argued that a stronger emphasis on long-term water management planning and allocation of resources to building and maintaining water infrastructure is required, few studies look at water challenges from the individual and household perspective (Stikker 1998; Haddeland 2013; Larson et al. 2016). Findings in chapter one suggest that further evidence that policy makers at the state and local levels that set standards for billing practices must carefully consider water pricing options that minimize these household budgeting changes to higher water bills, particularly for vulnerable households. These findings also indicate larger economic ripple effects to businesses providing the types of household goods and services included in this study. If households respond as indicated to rising water prices, these businesses could see reduced profitability. Accounting for these additional effects is important as policymakers develop strategies to mitigate the impacts of increased water costs households are increasingly confronting.

Chapter two uncovers different avenues that are likely effective in maintaining positive rapport between water providers and their customers. Two main findings suggest billing frequency matters when it comes to public perceptions of bills and water payment assistance programs positively affect perceptions of water bills. First, to improve customer relations, water companies could bill monthly so households are able to incorporate water bills into their monthly budget. Alternatively, companies may also bill households annually, allowing for customers to easily anticipate this one-time annual payment without having water costs emerging at various intervals throughout the year. Another important result was that water payment programs reduced the likelihood that households perceived their water bills to be unfair. This finding suggests that water provider should seek to establish water assistance programs for customers in need. Developing federal frameworks to guide the implementation of payment assistance programs could help reach more people who struggle with paying their household water bills (Grigg, 2017).

Regarding the third chapter, as lawmakers and other policy makers continue to strengthen their focus on reducing public PFAS exposure, results suggest that a targeted cleanup approach that factors in issues of environmental justice may be necessary. Results highlight that some social vulnerability characteristics are slightly associated with increases in PFAS exposure risk. If policymakers focus PFAS clean-up efforts where historically oppressed groups are marginally overrepresented, goals of environmental remediation could be extended to include benefits associated with social equity as well. Since PFAS passes through most water filtration systems, findings in chapter three likely have implications for household drinking water of vulnerable communities (Birnbaum, 2022). If this chapter’s results are considered, focusing on the needs of low-income neighborhoods, those of racial and ethnic minorities, and those with high proportions of single parent households could be used as legislative priorities for PFAS Superfund cleanup and household water quality evaluation.

5.4 Limitations

Despite the contributions to the literature of this dissertation, there are some important research limitations. These are to be expected as the three studies synthesized complex social, environmental phenomena to fit into statistical analysis frameworks. The main limitations may be summarized as (1) a lack of comprehensive and accurate information on household water costs and quality available, (2) lack of information on the levels of PFAS that consumers are exposed to through household tap water, (3) lack of causality established for the slight associations between Superfund sites and social vulnerability, and (4) problems associated with spatial dependence across datasets used in this dissertation.

The first limitation category present in all three chapters is the lack of adequate water quality and pricing information, and a national database of utility rates does not currently exist. While there are projects focusing on household water costs, there is no comprehensive nation-wide dataset of water costs in part because there are no legal requirements for water providers to contribute water pricing information (Gaudin, 2006). Household water billing varies depending on the supplier including for fixed and/or variable rates, different units to calculate variable rates (cubic feet vs. liters), as well as frequency of billing. Further, basic information such as service areas, or water source (groundwater or surface water) are not well specified in the available data and developing an accurate large-scale dataset with this information would be challenging and prohibitively labor intensive. For instance, a single provider may supply household water services across multiple geopolitical areas or conversely several providers may be present within a single geopolitical area (Beecher et al., 2020). One household may be connected to a public water utility, while a neighbor may have a personal well. These characteristics add to the complexity of conducting a nation-wide analysis if a similar water cost database did exist. The SWISSH dataset was collected in response to this gap and is the only nationally representative survey asking a wide array of questions related to water services, household water costs, and perceptions of these services. Therefore, the best data on water costs currently available is through survey analysis rather than actual water costs charged to household consumers.

Despite a lack of water pricing information, water companies must collect and disseminate water quality information according to federal legislative requirements. For instance, the EPA’s Safe Drinking Water Information System (SDWIS) dataset has been widely used in water quality research (Allaire et al., 2018; Marcillo & Krometis, 2019; Switzer & Teodoro, 2018; Teodoro et al., 2018). However, significant limitations exist. Not only does this dataset not yet include PFAS level information, SDWIS is likely invalid and unreliable for research purposes due to misreporting and miscoding water system types, among other issues (Beecher et al., 2019). Without comprehensive large-scale data on water quality and household water bills, understanding precise community characteristics of those exposed to high levels of PFAS will remain unclear. Similarly, while water quality is monitored at Superfund sites, PFAS levels in groundwater are not regulated at a federal level and PFAS has not yet been designated as a 'hazardous substance' according to CERCLA. Notably though, this designation has been proposed for PFAS in early 2022 (Birnbaum, 2022). Therefore, there is no comprehensive data available for environmental or tap water PFAS contamination near Superfund sites. While data about the PFAS concentrations in tap water does not exist on the scale of the chapter three study area, Superfund site analysis does indeed provide an opportunity to focus on extreme cases of PFAS in the environment less related to in-household PFAS exposure.

The second limitation is a lack of information on the levels of PFAS consumers are exposed to from their household drinking water. While there is evidence in the literature that the number of nearby industrial sites using PFAS compounds are significant predictors of PFAS concentration in public water supplies (Hu et al., 2016) and that PFAS is not filtered out of public water systems (Birnbaum, 2022), PFAS concentration levels in tap water were not available for this study. There currently is no comprehensive information about the levels of PFAS that individuals within the Census tracts of this study are exposed to through local drinking water systems. Therefore, while elevated PFAS concentrations in household tap water near these PFAS Superfund sites are exceedingly likely, expected exposure to PFAS is probabilistic by design and PFAS concentrations are not yet known. With better PFAS data available, future studies could incorporate PFAS concentrations in tap water or blood-PFAS levels of the community into similar types of social vulnerability analysis surrounding PFAS Superfund sites.

There are also limitations on the causality of the association between Superfund sites and vulnerable communities. For example, one of the two overarching hypotheses in the environmental literature are that industry selects vulnerable areas due to various reasons including financial or even discriminatory considerations (known as industry siting) (Depro et al., 2015). Alternatively, the second hypothesis follows that upon the establishment of a polluting industry, there may be a devaluation of land, and those who cannot afford to live elsewhere will stay in the polluted area or ‘come to the nuisance’ (Depro et al., 2015). These effects are compared widely in the literature (Been, 1994). While this debate is beyond the scope of this study, causation may be inferred in the future if time-series data was available, perhaps through a diff-in-diff analysis. However causal analysis was not possible to carry out in this study due to data limitations. There isn’t sufficient data publicly available on measured PFAS levels across the EPA regions over an extended time-period. In the future though, this data will be important to examine changes in social and demographic composition of neighborhoods as PFAS levels fluctuate. Perhaps as PFAS becomes officially regulated under CERCLA, better time-series analysis will be available, and a focus on causation may be included in future environmental justice analyses on PFAS.

The final limitation of the three research chapters in this dissertation is associated with potential spatial dependence in the data. While regression analysis assumes that data points are independent (Wooldridge, 2012), it is well known in the literature that characteristics and trends in data, and in particular neighborhood effects, may be related to those in neighborhoods nearby, which is a form of spatial dependence (Anselin, 1988). There are two causes of this dependence, the first being measurement error and the second is underlying spatial interaction phenomenon (Anselin, 1988). The measurement error relates to chapter three in this dissertation in which aggregated Census data is used. The scope of PFAS the effect on characteristics of neighborhood vulnerability may not be limited to the unit of measurement (Census tracts). These effects may not fall neatly across Census tract lines, spilling across boundaries of spatial units. Further, the errors of one Census tract may spill over to a bordering tract yielding spatial autocorrelation of the error terms in regression analysis (Anselin, 1988). In the case of an underlying phenomenon unrelated to measurement error, this trend will be captured in the error terms unless otherwise accounted for. This second component of spatial dependence also leads to spatial autocorrelation and is likely affecting trends associated with the findings in each of these three dissertation chapters. While it is not possible to eliminate all effects of spatial autocorrelation in regression analysis, there are several techniques for minimizing distortions caused by spatial dependence such as modelling some form of spatial dependence correlation structure. While chapter three evaluated patterns of spatial dependence with respect to social vulnerability across neighborhoods using the Local Moran's *I*, spatial autocorrelation remains a limitation in the logistical regression analysis in this dissertation.

5.5 Avenues for Future Research

While this dissertation advances knowledge about the experiences of American households in the context of water provision challenges, opportunities for future research related to water access remain. As a first step, more academic research is needed to strengthen understanding about the main barriers to clean water access. In-depth and publicly available data on household water service costs, water quality, and associated household water consumer characteristics are needed. Without filling this data gap, limitations will persist throughout the environmental justice literature about who does not have access to safe and affordable household water services.

Next, understanding long-term changes in water demand in relation to rising water prices would enhance the findings of chapters one and two. For instance, the first chapter in this dissertation provided evidence that many households would cut back on spending or would no longer be able to afford household goods and services under instances of progressively increasing water service costs. While these findings provide novel insights into impacts of increased water costs on household budgets in the short-term, these trends might differ in the context of a long-term analysis. In the short run, research shows consumers do not change their water consumption behavior significantly according to water prices (Gaudin, 2006; Renwick & Green, 2000), yet they may in the long-term. In particular, lower-income households may be less able to reduce overall consumption than are wealthier households due to lower initial consumption (Olmstead et al., 2007). Households with water-intensive amenities such as pools, low-efficiency appliances may not immediately adapt to lower water consumption goals or may take some time to realize their water rates are increasing (Renwick & Green, 2000). As water cost increases persist, better information about the long-term impacts on household water use will be an important resource for understanding the effects of rising water costs in the long-term.

In the future, better quality data on PFAS levels in household water supplies is also needed, including a breakdown of which types of the 9000 compounds included in the umbrella term of PFAS are present in communities. Understanding where PFAS is prevalent, the magnitude of PFAS exposure, and type of PFAS contamination communities are exposed to are important gaps in knowledge. This information is particularly consequential for policy applications since PFAS persists in the environment and leads to human health consequences when present in public water supplies. Though the quality and availability of PFAS water contamination data will likely improve once associated regulatory legislation is passed, there is currently no regulation of PFAS in groundwater, nor determination of PFAS as a 'hazardous substance' according to CERCLA. In January 2022, the EPA submitted a proposal to have the two most common types of PFAS (PFOS and PFOA) regulated as a toxic substance under CERCLA. If enacted, individuals and companies deemed 'responsible parties' for contamination of these two types of PFAS will be financially responsible for recovery costs and held to enforcement actions to the same extent of parties responsible for Superfund contamination from other toxins under the CERCLA umbrella. Therefore, more accurate data on PFAS levels and risk to human health will likely be available as legislation associated with PFAS regulation gets passed at the federal level in the U.S.

Further, with strengthened PFAS regulations additional resources will be available for better understanding the maximum levels of PFAS acceptable for drinking water provision that will be critical for PFAS research in the future. Though the EPA has issued a lifetime health advisory of 70 ppt for the two most common forms of PFAS: PFOS and PFOA, these recommendations may change with improvements in data quality. Potentially, a higher proportion of the nine thousand PFAS chemicals recognized by the EPA beyond PFOS and PFOA may be included in this health advisory for instance (Birnbaum, 2022). To improve upon this dissertation research, studies must have access to improved PFAS data across Superfund sites, including detailed PFAS contamination information on case-by-case basis. Inclusion of this data is important for future work since Superfund sites vary greatly in the type and concentration of contaminants, as well as the ease of dispersion through the unique geographic landscape associated with each PFAS Superfund site (Tidwell et al., 2017).

Future studies of environmental justice related to water services could use a qualitative approach to incorporate the legislative and political engagement contexts. Representation in environmental policy is a key tenant of environmental justice and may provide insight into the causal effects of inequities related to water among the American population. Indeed, results from this dissertation show that low-income and racial/ethnic minorities may face more pronounced hardships in paying for water. Future research could provide deeper context to this information including a measure of political engagement in the development, implementation and enforcement of environmental laws, regulations, and policies. Shedding light on types of political exclusion that vulnerable groups face that may leave them at a disadvantage in terms of how much they pay for water services and the quality of services. There are also political contexts that may influence vulnerable communities' exposure to PFAS Superfund sites. Qualitative studies contextualizing the regulatory environment, particularly relating to PFAS exposure could shed more detailed light on environmental justice questions related to risk of PFAS exposure from Superfund sites. Indeed, as of January 2022, 27 states are considering policies with a primary focus of mitigating PFAS use, managing the production of PFAS products, and disposing of PFAS waste across over 180 bills (Birnbaum, 2022). As this legislation continues to be passed across the United States, research to understand the impacts of heterogeneous legislative activity across the country. Therefore, evaluating variations in PFAS exposure risk at different geographic levels, particularly that include the evolving political and regulatory context of communities, is currently an important gap in the literature.

Lastly, though chapter three findings suggest high vulnerability communities are associated with increased risk of exposure to PFAS, future research would be helpful to identify their underlying mechanisms and establish causation. Future research on areas with extensive PFAS contamination could benefit from additional data to understand more about the surrounding communities' depth of PFAS knowledge, perceptions about PFAS, and risk attitudes surrounding PFAS for example. Survey data tailored to communities at higher potential risk of PFAS exposure would be useful in determining whether there are systematic differences in perceptions of PFAS risk exposure according to education level, race and ethnicity, and disability status among others. Linguistic barriers may also make public outreach campaigns less accessible and decrease overall participation in the political process (G. Huang & London, 2012; Ramakrishnan & Espenshade, 2001). Studies show there are differences among racial and ethnic groups' willingness to pay to avoid environmental hazards (Depro et al., 2015; Macias, 2016). However, more studies are needed on this front since some studies dispute the magnitude of this problem and no studies have evaluated these trends as they apply to communities surrounding PFAS Superfund sites. The underlying reasons for environmental justice disparities are difficult to parse, but improved data in future research may provide critical context for the findings in chapter 3.

5.6 Summary

Water crises pose the largest risk to populations globally according to the level of potential impact, according to international organizations such as the World Economic Forum (WEF, 2015). An estimated four billion people face severe water scarcity globally, affecting both high- and low-income countries (Mekonnen & Hoekstra, 2016). These trends persist in part because underinvestment in water infrastructure is almost universal across countries worldwide

(Haddeland et al., 2014; Stikker, 1998). In the absence of adequate water infrastructure in less developed countries such as Nigeria, Indonesia, and Thailand, households themselves must cover the cost of private provision of water services, putting access to clean water out of reach for many poor households (Lee et al., 1999; Wu & Malaluan, 2008). Communities in America have also experienced the effects of water demand outstripping supply, causing political tension, including among counties in North Carolina for example (Griffin et al., 2013; Warner et al., 2018). Contamination events have also garnered coverage in the academic literature, whether due to industry contaminating water practices such as mining activities contaminating water supplies in Kentucky (S. L. Scott et al., 2012), or water infrastructure failures due to mismanagement by policymakers and water suppliers including the Flint water crisis (Mohai et al., 2009).

Given the essential nature of water services, environmental justice cannot be upheld without fair access to clean water and equal opportunity for engagement in water policy decisions regardless of race, color, income, or other personal characteristics (Clough, 2018; McGurty, 2009). As described previously, the three core components of environmental justice are (1) the equitable access to environmental benefits and protection from environmental hazards, (2) ensuring environmental decisions are made with consideration of historical contexts of societal oppression, and (3) balanced political representation amongst those with influence over environmental policy (Schlosberg, 2004; 2009). Each dissertation chapter investigates water access related to the three listed elements of environmental justice theory. Equitable access to local a clean and affordable source of drinking water, adequate wastewater services, and local watershed health are integral to the first component of environmental justice, the distribution of harms and benefits of the local environment (De Bell et al., 2017). The environmental justice literature provides evidence that clean water inequities persist among racial and ethnic minority groups and low-income communities. In New Zealand, Hales et al. (2003) show that neighborhood effects matter in the safety of community water supplies. The Hales et al. (2003) study finds that those with fewer financial and social support resources are more likely to be exposed to the most severe household drinking water-related health risks. In America, day labor employees on agricultural operations are largely lower-income, members of minority groups often live in nearby communities where the leaching of waste contaminates residential drinking water (Nicole, 2013). Water safety for low-income individuals also persist in the U.S. in part because rural water providers often have fewer resources for water sanitation and water quality compliance testing (Ranganathan & Balazs, 2015; Delpla et al., 2015). In terms of the second environmental justice component, recognition of the context of oppression, the literature finds populations have experienced discrimination throughout history including racial and ethnic minorities and low-income populations face higher exposure to toxic chemicals in waterways in developing and developed countries alike (Bullard, 1983; McGurty, 2009). The last tenant of environmental justice emphasizes representative political participation in decisions about watershed management, public water infrastructure, and household water provision. Representation in these decisions is important for ensuring sustainability of water access and distribution moving forward. Without representation in policy decisions, livelihood of vulnerable populations may be threatened if excluded from the political process. In that case, sustainability cannot be achieved (Bullard, 1994). Public engagement is necessary to help individuals understand reasons behind continued increases in water bills, provide input for plans for water companies to recoup costs of infrastructure replacement, ensure a willingness to consume water from public utilities, and provide feedback about local watershed quality communities experience.

Overall, this dissertation addresses the distribution of environmental benefits and harm associated with water across the U.S. in the form of three unique studies. The first chapter provides information about how household budgets may shift to accommodate higher water bills, and how minority communities, and low-income households may adapt to these costs. Chapter two is the first analysis of how households perceive their water bills in terms of whether households feel they are overcharged for their access to water services. Chapter three contributes information about communities most likely to be struggling with potential PFAS exposure. The first two chapters explore how the increasing costs of providing public household water services affect vulnerable households and gauge the public's perceptions of these experiences. Until this point in the literature, most studies evaluating water costs and quality often focus on the water providers' perspective such as how price elasticity of demand for water affect profits (Espey et al., 1997; Jordan & Elnagheeb, 1993; Martinez-Espineira et al., 2009). However, goals of sustainable and equitable water access can only be met by incorporating unique needs and circumstances of water consumers into policy decisions. These two chapters leverage a unique database that sheds light on consumer experiences with water that have thus far only received anecdotal mention in the media (Lakhani, 2020; Lynch, 2016). Regarding the first chapter, as mounting infrastructure costs are passed along to consumers, this paper provides an important first look at how other industries are set to be affected in terms of cascading effects. Broader questions of how these changes will affect various sectors of the economy are also considered. The second study provides evidence that the challenges consumers face in paying their water bills are affected by personal and household characteristics. Taking a slightly different approach, the third chapter of this dissertation provides evidence that extreme cases of pollution in the form of manmade contaminants put vulnerable communities at higher likelihoods of risk for experiencing water contamination. Though PFAS has been widely used in products since the 1950’s (Birnbaum, 2022), complex issues associated with PFAS contamination are currently emerging as an urgent component of the environmental justice conversation in the literature (Environmental Working Group (EWG), 2021a; Hagstrom et al., 2021; Hepburn et al., 2019). Chapter three uses PFAS contamination information first provided by the U.S. Senate Committee on Environmental and Public Works in 2018 to understand the characteristics of communities living near extreme cases of PFAS contaminated land.

In the context of a confluence of challenges facing water providers, with cost projections of necessary infrastructure investment requirements needed in the tune of billions of dollars (U.S. EPA, 2020), it is important to understand which segments of the population are most impacted by water-insecurity, their perceptions of water access, and/or who is more likely to be faced with contaminated tap water. This dissertation sheds light on inequities that result from needed water infrastructure replacement, modern forms of environmental contamination, and rapidly changing hydrologic systems. Though America is a wealthy nation, the three chapters in this dissertation provide information about water-related problems faced by American households and the characteristics of individuals affected by these problems.

APPENDIX

Table 19 *Tabulation of Perception Responses for Variables Relevant to Water Bills*

Variable Category	Variable Option	Fair/ Should be Lower		Too High		Total
		#	%	#	%	#
	TOO HIGH/ OTHER	4147	63.3	2400	36.7	6611
REGION	Piedmont Atlantic	580	69.2	258	30.8	907
	Mid-Atlantic	488	69.9	210	30.1	768
	Eastern Massachusetts	404	65.2	216	34.8	684
	Southeast Florida	422	62.3	256	37.7	740
	Front Range	517	68.9	234	31.1	819
	Southern California	411	59.2	283	40.8	753
	Southeast Michigan	352	48.1	379	51.9	779
	Pacific Northwest	432	59.1	299	40.9	790
	Sun Corridor	542	67.1	266	32.9	875
WAVE	Wave 1	366	61.1	233	38.9	660
	Wave 2	1364	61.0	873	39.0	2298
	Wave 3	2417	65.1	1294	34.9	3777
HEALTH INSURANCE	Private Health Insurance	2503	64.9	1351	35.1	3919
	Medicaid	280	51.0	270	49.0	601
	Medicare	1015	66.9	502	33.1	1584
	None	217	53.5	188	46.5	458
WATER PAYMENT PROGRAM	Enrolled	165	61.3	104	38.7	330
	Not Enrolled	3970	63.4	2288	36.6	6321
EMPLOYMENT STATUS	Full time/ Part time	2530	63.5	1453	36.5	4046
	Unemployed/ Not Working/ Looking	233	52.1	214	47.9	500
	Retired	1077	67.9	508	32.1	1653
	Student/ Homemaker/ Other	300	57.7	220	42.3	578
HOUSEHOLD TYPE	Single family home/ townhome	3467	63.7	1976	36.3	5506
	Multi-Family Home/ Apartment	582	62.0	357	38.0	1001
	Mobile Home/ Trailer	56	52.7	50	47.3	158
WATER BILLING FREQUENCY	Monthly	2799	63.3	1626	36.7	4489
	Quarterly	908	59.7	614	40.3	1582
	Annually/ Semiannually	71	75.0	24	25.0	170
	Bimonthly	114	60.2	75	39.8	249
	HOA/ Condo	108	79.6	28	20.4	215
	Have Well	115	95.5	5	4.5	215
	Other	32	53.6	28	46.4	114

Table 20 *Comparing Demographics of SWISSH Survey to the U.S. Census American Community Survey*

	Variable Description % Households	SWISSH	ACS
Income	Less than 50k	40%	40%
	$50k-$99.9k	30%	30%
	100k	30%	30%
Education	Less than a high school degree	02%	12%
	High school degree or GED	18%	23%
	Some college or associates degree	25%	29%
	Bachelor's degree	32%	22%
	Graduate/professional degree	23%	14%
Age	Between 25 – 44 years	40%	41%
	Between 45 – 65 years	41%	39%
	Over 65 years	19%	20%
Race/ Ethnicity	White alone	58%	57%
	Black or African American alone	13%	13%
	Asian alone	06%	06%
	Hispanic/Latinx	21%	21%

*All non-race variables are for population 25 years or older

Table 20 compares information about weighted survey characteristics for 9,250 households and the profile of households in each region, as indicated by data from the American Community Survey (ACS) data from the U.S. Census Bureau. This comparison highlights that the survey data are comprised of a representative sample of the nine regions in this study. The income and ethnicity distribution among respondents in the SWISSH survey is similar to populations in these regions, as indicated by the ACS data. There is a slight overrepresentation of higher educated individuals (with a bachelors/graduate degree) and underrepresentation of those with less than high school diploma. Overall, however, the sample is very close to the household profiles of each region.

Table 21 *Pairwise Correlations of Social Vulnerability Index Variables*

	% Poverty	% Unemployment	Income	% No High School Diploma	Aged 65 or Older	Aged 17 or Younger	% With Disability	% Single Parent Households	% Minority	% Limited English	% Crowding
% Poverty	1										
% Unemployment	0.595	1									
	0.000										
Income	-0.553	-0.412	1								
	0.000	0.000									
% No High School Diploma	0.637	0.459	-0.573	1							
	0.000	0.000	0.000								
Aged 65 or Older	-0.291	-0.199	0.212	-0.250	1						
	0.000	0.000	0.000	0.000							
Aged 17 or Younger	0.177	0.178	-0.157	0.255	-0.342	1					
	0.000	0.000	0.000	0.000	0.000						
% With Disability	0.426	0.382	-0.441	0.335	0.315	-0.088	1				
	0.000	0.000	0.000	0.000	0.000	0.000					
% Single Parent Households	0.577	0.486	-0.483	0.535	-0.355	0.505	0.240	1			
	0.000	0.000	0.000	0.000	0.000	0.000	0.000				
% Minority	0.458	0.443	-0.309	0.576	-0.435	0.256	-0.029	0.543	1		
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000			
% Limited English	0.334	0.171	-0.250	0.673	-0.248	0.199	-0.085	0.297	0.565	1	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
% Crowding	0.374	0.171	-0.267	0.545	-0.319	0.286	-0.114	0.285	0.502	0.672	1
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

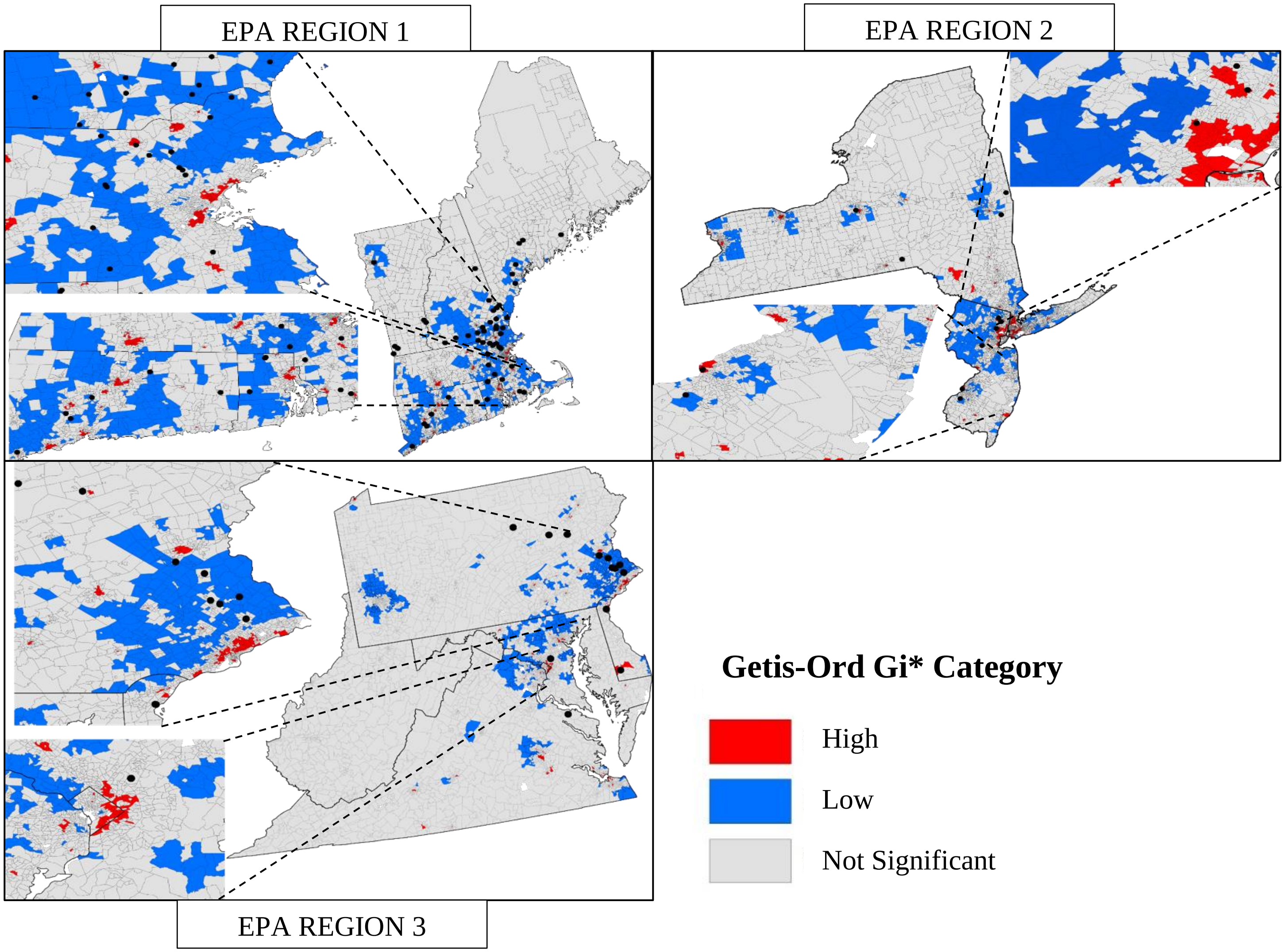

Figure 5 *Spatial Correlation of Social Vulnerability Index using Getis-Ord Gi* Value Across Census Tracts in EPA Regions 1 - 3*

Results of the Getis-Ord G_i^* provide complementary information about spatial clustering and confirm the trends established by the Local Moran's I statistic. The Getis-Ord G_i^* is summarized as high/low cluster analysis and includes the focus tract in its calculation. The G_i^* and local Moran's I complement each other as measures of cluster analysis and are used simultaneously for answering question one of chapter 3: "Are there statistically significant patterns of social vulnerability, as defined by the CDC, around Superfund sites with a PFAS designation? If so, where?"

Table 22 *Tabulation of Getis-Ord G_i^* Cluster Values by PFAS Superfund Type*

	All Data		Within 6-Miles of PFAS Superfund Sites (Military Sites Excluded)	
Getis-Ord G_i^* Categories	Freq.	%	Freq.	%
Not Significant	12,908	74.01	1,050	62.99
High	2,518	14.24	372	22.32
Low	2,073	11.72	245	14.70
No Neighbors	6	0.03	0	0
Total	17,505	100	1,667	100

Results from the Getis-Ord G_i^* confirm the Local Moran's I findings that a higher percentage of Census tracts within 6-miles of PFAS Superfund sites are situated within clusters of high vulnerability compared to the entire study area of EPA regions 1 – 3. Approximately 14.42% of Census tracts are within high social vulnerability clusters across the study area, whereas the percent of high social vulnerability clusters increases to 22.32% when considering Census tracts within 6-miles of non-military PFAS Superfund sites. There is also a lower proportion of Census tracts in low social vulnerability clusters across the entire study area compared to those within 6-miles of non-military PFAS Superfund sites.

Table 23 *Tabulation of the Proportion of Local Moran's I Cluster Category Values in Figure 4 Focusing on Census Tracts within 1-, 3-, 6-, and 10- miles of PFAS Superfund Sites*

Buffer Distance	1-mile		3-miles		6-miles		10-miles	
Moran Categories	Freq.	Percent	Freq.	Percent	Freq.	Percent	Freq.	Percent
Not Significant	49	56.32	408	64.05	1050	62.99	1934	63.24
High-High	27	31.03	154	24.18	365	21.90	735	24.04
Low-Low	8	9.20	68	10.68	231	13.86	361	11.81
Low-High	0	0.00	1	0.16	7	0.42	13	0.43
High-Low	3	3.45	6	0.94	14	0.84	15	0.49
Total	87	100.00	637	100.00	1667	100.00	3058	100.00

In the third dissertation paper, a 6-mile buffer was selected for the Local Moran's *I* cluster analysis based on evidence in the literature (Noonan et al., 2009). However, as discussed in the limitations of chapter 3, the modifiable aerial unit problem (MAUP) necessarily presents challenges to ensuring reliable results. To summarize, MAUP is both a scale problem associated with choices of the level of data aggregation, as well as a boundary problem, whereby varied configurations of spatial units of analysis may yield different results (Fotheringham & Wong, 1991). However, it is possible to garner insight into boundary effects of MAUP by evaluating subsets of the Local Moran's *I* Census tract data at various buffer zones from Superfund sites. As a compliment to table 17, table 23 provides a proportional breakdown of local Moran's *I* values from figure 4, with each column using a different subset of Census tracts. As a reminder, the local Moran's *I* value for the study area is 0.569, the Z-value is 127.26, the pseudo p-value is

0.001, and these data were calculated with 999 permutations. While using the Local Moran's *I* data from chapter 3, each subset of Census tracts is selected depending on whether they fall within 1-, 3-, 6-, and 10- miles of a Superfund sites. Multiple buffer zones were tested to determine whether or to what extent the proportion of Local Moran's *I* category values vary depending on how far Census tracts are from PFAS Superfund sites. This table generally suggests that clusters of vulnerability comprise a larger percentage of Census tracts the closer a neighborhood is to a PFAS Superfund site. The highest proportion of high-high clusters occur within one mile of PFAS Superfund sites at 31% of Census tracts, which is approximately 21.8% higher than the percentage of low-low clusters at this distance. Increasing the buffer distance to 3 miles, the proportion of high-high tracts falls to approximately 24.2% compared to 10.7% being low-low (a difference of approximately 13.5%). The results of the 6-mile buffer, which are reported in the main text of chapter three, are consistent with the trend of a decreased proportion of high-high tracts as distances from PFAS Superfund sites increase, with a decreased gap between the proportion of high-high and low-low tracts (in this case a difference of 8.04%). Overall, this trend starts to reverse around the 10-mile buffer, which is a larger distance than typically used in EJ research associated with Superfund sites (Ashby et al., 2020; Banzhaf et al., 2019; Noonan et al., 2009). Therefore, this large buffer may be capturing more information beyond Superfund site location or potentially capturing effects of multiple Superfund sites simultaneously. Overall, this sensitivity analysis shows that while MAUP seemingly plays a role in the findings of the Local Moran's *I* cluster analysis results of chapter three, the outcome is consistent with the hypothesis of this chapter: closer spatial proximity to PFAS Superfund sites is associated with several measures of social vulnerability.

__Table 24__ Tabulation of Getis-Ord G_i^* Cluster Category Values Across Buffer Distances

	1- mile		3- miles		6- miles		10- miles	
G_i^* Categories	Freq.	Percent	Freq.	Percent	Freq.	Percent	Freq.	Percent
Not Significant	49	56.32	408	64.05	1050	62.99	1934	63.24
High	27	31.03	155	24.33	372	22.32	748	24.46
Low	11	12.64	74	11.62	245	14.70	376	12.30
Total	87	100.00	637	100.00	1667	100.00	3058	100.00

Similar to the Local Moran's *I* sensitivity testing for the spatial cluster analysis, the same method was applied to understand the impacts of MAUP on the Getis-Ord G_i^* results. Cluster results in table 24 parallel those of the Local Moran's *I* (table 23). As the buffer distances around PFAS sites increase, the proportion of Census tracts considered within high vulnerability decreases until the 6-mile buffer distance. The proportion of tracts within high vulnerability clusters peaks at approximately 31% at a 1-mile buffer, reduces to approximately 24.33% and 22.32% at the 3- and 6-mile buffer distances respectively. However, Census tracts within high vulnerability clusters increase again as the buffer distance increases from 6- to 10-miles. Here, the proportion of tracts in high vulnerability clusters is 24.46%. When the buffer distance is extended to 10 miles, it is hypothesized that with so many Census tracts included, a large proportion of metropolitan areas Census tracts are included within the buffer zones. It is therefore likely that several countervailing trends affect the results, including an urban/rural divide. Overall, findings from both the Local Moran's *I* and Getis-Ord G_i^* sensitivity analysis supports chapter three's main findings that neighborhoods surrounding PFAS Superfund sites have higher levels of overall vulnerability than the average of the EPA regions 1 – 3 study area.

Table 25 *Sensitivity Test: Multivariate Logistic Regression Original Model with Additional Unemployment Variable*

VARIABLES	Marginal Effects	Odds Ratio
EPA Region 1	0.1458***	3.7066***
	(0.0098)	(0.2643)
EPA Region 2	0.0516***	1.7839***
	(0.0065)	(0.1236)
Population Density	0.0000***	1.0000***
	(0.0000)	(0.000)
% Unemployment	0.0012*	1.0146*
	(0.0006)	(0.0078)
% Poverty	0.0009***	1.0105***
	(0.0003)	(0.0033)
% Single Parent Households	0.0012***	1.0141***
	(0.0004)	(0.0047)
% Minority	0.0008***	1.0095***
	(0.0001)	(0.0014)
% Limited English	0.0024***	1.0287***
	(0.0004)	(0.0055)
% Crowding	-0.005***	0.9425***
	(0.0008)	(0.0093)
% With Disability	-0.0033***	0.9612***
	(0.0005)	(0.0058)
Superfund sites without known PFAS within buffer	0.0348***	1.4387**
	(0.0163)	(0.2180)
	Pseudo R^2 = 0.0615	
	N = 17,023	

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Unemployment was hypothesized to factor into the potential exposure levels of PFAS Superfund sites as well as the other social vulnerability variables selected in the principal analysis of chapter three. After adding unemployment as a covariate to the initial regression tested, results show that levels of unemployment are not statistically different (using $p \leq 0.05$ as a threshold) in Census tracts within 6-miles of PFAS Superfund sites compared to Census tracts in the rest of the study area. To test whether the final model in chapter three (equations 9 and 10) was statistically different when the percent unemployment variable was added, a likelihood ratio was tested. The likelihood ratio test yielded $\chi^2 = 3.53$ and $p > \chi^2 = 0.06$, which is not statistically significant (using $p \leq 0.05$ as a threshold). Considering this result, and that the unemployment variable was correlated with several other variables in the analysis including poverty (positively correlated with a 0.6 correlation coefficient), unemployment was not included in the final model.

Table 26 *Variance Inflation Factor Test for PFAS Superfund Site Logistic Model*

Variable	VIF	1/VIF
EPA Region 1	1.36	0.734979
EPA Region 2	2.01	0.49829
Population Density	2.12	0.471872
% Poverty	4.63	0.215778
% Single Parent Households	4.87	0.205488
% Minority	4.81	0.207878
% Limited English	2.96	0.337276
% Crowding	3.10	0.322659
% With Disability	3.99	0.250755
Superfund sites without known PFAS within buffer	1.03	0.967164
Local Moran's *I* Value of Low-Low	1.12	0.88929
Local Moran's *I* Value of High-High	2.05	0.48684
Census Tract Area (Square Mile)	1.12	0.895832
Mean VIF = 3.09		

A variance inflation factor (VIF) test was used as a post-estimation to determine the level of multicollinearity in several specifications of regression models. In the final logistic regression model in chapter three (equations 9 and 10). Since the VIF for each variable is less than 5 and the mean VIF model value is 3.09, this test suggests that while some variables were slightly correlated with one another, the level of correlation was relatively low. Thus, it may be concluded that multicollinearity is not a major source of concern among variables for the logistic regression model (equations 9 and 10) in chapter three.

Table 27 *Sensitivity Analysis for Logistic Regression of Probability of PFAS Superfund Sites (Marginal Effects)*

VARIABLES	1-Mile	3-Mile	6-Mile	10-Mile
EPA Region 1	0.0125***	0.0695***	0.1254***	0.1476***
	(0.0041)	(0.0079)	(0.0096)	(0.0098)
EPA Region 2	0.0047**	0.0234***	0.0500***	0.0523***
	(0.0022)	(0.0048)	(0.0062)	(0.0065)
Population Density	0.0000***	0.0000***	0.0000***	0.0000***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
% Poverty	0.0000	-0.0001	0.0009***	0.0011***
	(0.0001)	(0.0002)	(0.0002)	(0.0003)
% Single Parent Households	0.0002***	0.0009***	0.001***	0.0013***
	(0.0001)	(0.0002)	(0.0003)	(0.0004)
% Minority	0.0001**	0.0002***	0.0006***	0.0009***
	(0.0000)	(0.0001)	(0.0001)	(0.0001)
% Limited English	0.0002**	0.0012***	0.0016***	0.0021***
	(0.0001)	(0.0003)	(0.0004)	(0.0004)
% Crowding	0.0001	-0.0008*	-0.0032***	-0.0049***
	(0.0001)	(0.0005)	(0.0007)	(0.0008)
% With Disability	-0.0002	-0.0012***	-0.003***	-0.0031***
	(0.0001)	(0.0003)	(0.0005)	(0.0005)
Superfund sites without known PFAS within 6-mile buffer	0.0078	0.0258**	0.0176	0.0353**
	(0.0057)	(0.012)	(0.0142)	(0.0163)
	Pseudo R^2 = 0.077	Pseudo R^2 = 0.056	Pseudo R^2 = 0.061	Pseudo R^2 = 0.088
	N = 17,031	N = 17,031	N = 17,031	N = 17,031

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The modifiable areal unit problem is particularly severe in multivariate analysis, as evidenced in studies associated with various disciplines including transportation (Horner & Murray, 2002; M. Zhang & Kukadia, 2005), physical geography (Dark & Bram, 2007), and environmental justice (Noonan et al., 2009; Sui, 2004). Several studies demonstrate that a change in scale and areal unit definition for data aggregation in spatial regression analysis may result in a change in efficiency, magnitude, statistical significance, and in some cases flip the direction of parameter estimates in unpredictable ways (Arbia & Petrarca, 2011; Jelinski & Wu, 1996; M.

Zhang & Kukadia, 2005). Logistic regressions from chapter 3 were re-estimated at the 1-, 3- , 6-, and 10-mile buffer distances yielding both marginal effects (table 27) and odds ratios (table 28). These buffer calibrations correspond to the buffer ranges in the spatial cluster analysis for the Local Moran's I and Getis-Ord G_i^* statistics sections.

Results show that while the overall results of the logistic regression analysis in the main section of chapter 3 hold and the direction of the effect of each variable is consistent across buffer distances, there are differences in magnitude and statistical significance. Figure 6 uses a line graph as a visual representation of the changes in the marginal effects of the logistic regression model as the buffer distance increases from 1-mile to 10-miles. Those regression coefficients that were not statistically significant at the 5% level were included in the graph as having zero magnitude. Therefore, from tables 27 and 28, it is evident that statistical significance tends to be stronger for the buffer zones at least 6-miles from PFAS Superfund sites.

Table 28 *Sensitivity Analysis for Logistic Regression of Probability of PFAS Superfund Sites (Odds Ratios)*

VARIABLES	1-Mile	3-Mile	6-Mile	10-Mile
EPA Region 1	4.6951***	3.9870***	3.8059***	3.7519***
	(1.4805)	(0.4480)	(0.3033)	(0.2668)
EPA Region 2	2.2527***	1.8396***	1.9595***	1.7963***
	(0.7027)	(0.2081)	(0.1521)	(0.1244)
Population Density	1.0000***	1.0000***	1.0000***	1.0000***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
% Poverty	0.9982	0.9985	1.0131***	1.0126***
	(0.0123)	(0.0052)	(0.0034)	(0.0031)
% Single Parent Households	1.0338***	1.0268***	1.0144***	1.0152***
	(0.0120)	(0.0068)	(0.0051)	(0.0047)
% Minority	1.0129**	1.0070***	1.0088***	1.0103***
	(0.0052)	(0.0020)	(0.0014)	(0.0013)
% Limited English	1.0329**	1.0337***	1.0231***	1.0254***
	(0.0149)	(0.0074)	(0.0057)	(0.0053)
% Crowding	1.0292	0.9770*	0.9545***	0.9437***
	(0.0247)	(0.0130)	(0.0099)	(0.0092)
% With Disability	0.9695	0.9669***	0.9581***	0.9636***
	(0.0242)	(0.0092)	(0.0063)	(0.0056)
Superfund sites without known PFAS within 6-mile buffer	2.6443**	1.7783***	1.2631	1.4453**
	(1.2549)	(0.3812)	(0.2196)	(0.2189)
Constant	0.0015***	0.0198***	0.0485***	0.0589***
	(0.0006)	(0.0029)	(0.0049)	(0.0053)
	Pseudo $R^2 =$ 0.056	Pseudo $R^2 =$ 0.056	Pseudo $R^2 =$ 0.061	Pseudo $R^2 =$ 0.088
	N = 17, 031	N = 17, 031	N = 17, 031	N = 17, 031

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

For example, there is at least one coefficient estimate that is not statistically significant ($p \leq 0.05$) at the 1- and/or 3-mile buffer distances for poverty, disability, and crowding. However, at the 6- and 10- mile marks these variables are all statistically significant. Regarding magnitudes, typically the directional effect intensifies as the buffer increases. The poverty rate coefficient is not statistically significant at the 1- and 3-mile buffer distances but becomes significant ($p \leq 0.01$) at the 6-mile buffer with a 1% increase in poverty associated with an increase in the likelihood of a PFAS Superfund site nearby by 0.09 percentage points. This increases to 0.11 percentage points at the 10-mile buffer. Similarly, though the percent of racial and ethnic minorities in communities were statistically significantly ($p \leq 0.05$) associated with the presence of PFAS Superfund sites at the 1- and 3-mile buffers, the magnitude of effects increased with the buffer distance increases. At the 6-mile buffer, a 1% increase in racial and ethnic minorities in a neighborhood is associated with an increase in the likelihood of a PFAS Superfund site nearby of 0.06 percentage points. This increases to 0.09 percentage points at the 10-mile buffer. The coefficient for limited English increases across the 1-, 3-, 6-, and 10-mile buffer distances (from 0.02 to 0.12, 0.16, and 0.21 percentage point increases respectively).

Both marginal effects (table 27) and odds ratios (table 28) of the logistic regression in chapter 3 (equations 9 and 10) are estimated. Unsurprisingly, changes in the magnitude and statistical significance of odds ratios for logistic regression in table 28 across buffer distances parallel marginal effects in table 27. Overall, this regression sensitivity analysis section demonstrates that while MAUP is certainly present in the findings of the model's parameter estimates, leading to a slight overall intensification of the magnitude of parameters as the buffer distance is extended outward from 1- to 10-miles. Notwithstanding, the directional effect for statistically significant coefficient estimates ($p \leq 0.5$) remains constant and these variations are relatively insignificant to the overall findings of chapter three.

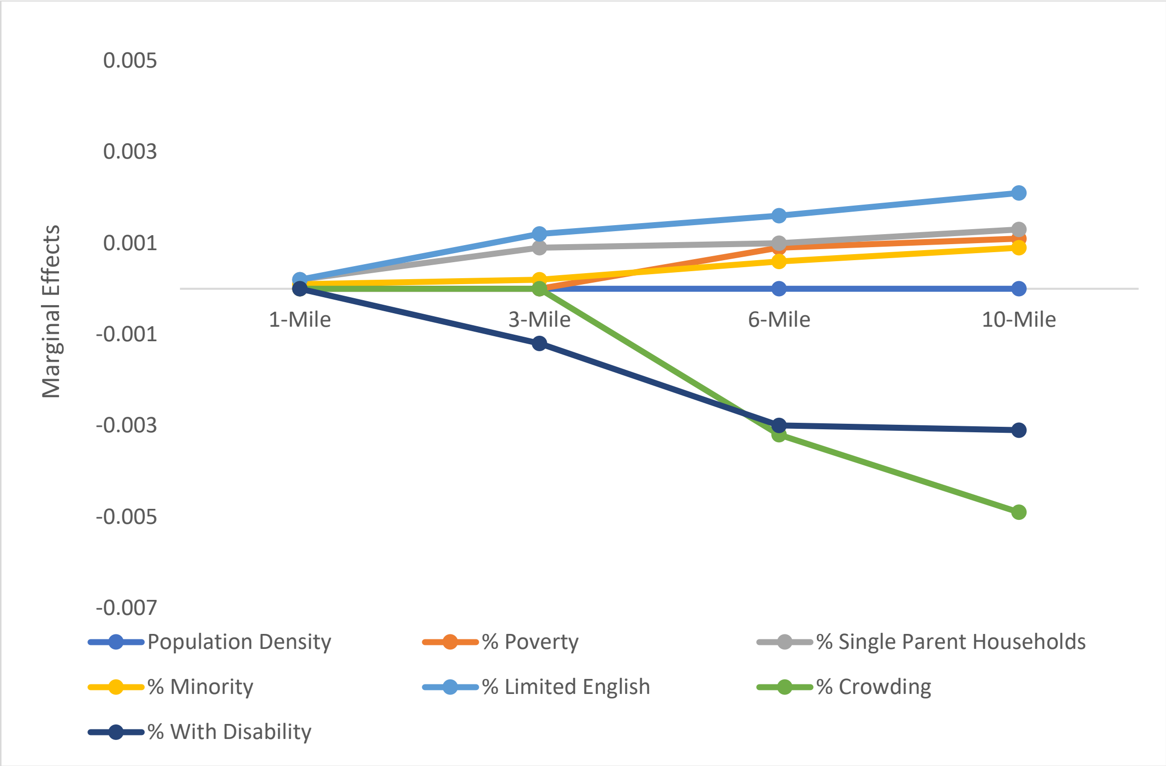

Figure 6 *Variation in Marginal Effects of Logistic Regression - Probability of PFAS Superfund Sites (Marginal Effects) by Buffer Distance*

Figure 6 depicts the coefficient values (those that are not statistically significant at the 5% level or below were recoded to zero) across the buffer distances. It is evident that crowding and disability status both become more negative as the buffer distance increases. Minority status, single parent households, poverty, and limited English coefficients increase as the buffer extends farther, and there is effectively zero effect on population density.

Table 29 *Regression Results for All Superfund Sites and Non-PFAS Superfund Sites*

	No PFAS		All Superfund	
VARIABLES	Marginal Effects	Odds Ratio	Marginal Effects	Odds Ratio
EPA Region 1	-0.0901***	0.639***	0.1230***	2.0296***
	(0.0099)	(0.032)	(0.0093)	(0.1006)
EPA Region 2	0.1986***	2.510***	-0.058***	0.6848***
	(0.0087)	(0.099)	(0.0072)	(0.0333)
Population Density	0.0000***	1.000***	0.0000***	1.0000***
	(0.0000)	(0.000)	(0.0000)	(0.0000)
% Poverty	-0.0016***	0.992***	-0.0007*	0.9955*
	(0.0004)	(0.002)	(0.0004)	(0.0025)
% Single Parent Households	-0.0013*	0.993*	0.0009	1.0059
	(0.0007)	(0.003)	(0.0006)	(0.0038)
% Minority	0.002***	1.010***	0.0027***	1.0172***
	(0.0002)	(0.001)	(0.0001)	(0.0010)
% Limited English	-0.0009	0.995	-0.0013*	0.9918*
	(0.0008)	(0.004)	(0.0007)	(0.0045)
% Crowding	-0.0029**	0.986**	-0.0046***	0.9712***
	(0.0012)	(0.006)	(0.0012)	(0.0076)
% With Disability	-0.0043***	0.979***	-0.0047***	0.9705***
	(0.0007)	(0.004)	(0.0007)	(0.0042)
Superfund sites without known PFAS within buffer	0.2213***	2.982***		
	(0.0115)	(0.181)		
	Pseudo R^2 = 0.155		Pseudo R^2 = 0.062	
	N = 17, 031			

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

While statistically significant trends were found associating elevated social vulnerability in communities near non-military PFAS Superfund sites, table 29 provides a first look at these trends for all Superfund sites in the study area as well as for Superfund sites with no known PFAS contamination. Note that in the initial regression, an indicator variable was included to represent the presence of non-PFAS Superfund sites nearby. For the ‘No PFAS’ regression, this indicator variable was changed to having sites with PFAS nearby. Further, when all Superfund sites were included in the regression, this variable was dropped entirely. This comparative analysis shows that while several vulnerability factors are slightly associated with nonmilitary

PFAS Superfund sites in chapter three, these trends are not necessarily associated with Superfund sites as a whole across the study area. Nor are these effects necessarily robust to selecting Superfund sites not found to have PFAS contamination (SCEPW, 2019). All models in table 29 find that neighborhoods within 6-miles of Superfund sites are associated with higher levels of racial and ethnic minority status and decreases in crowding and disability status. However, some opposing trends emerge across models depending on the type of Superfund site analyzed. For instance, while percent poverty status is positively associated with nonmilitary PFAS Superfund sites, there was a negative association found between neighborhoods surrounding all Superfund sites in the study area as well as Superfund sites with no PFAS found. Further, while neighborhoods surrounding Superfund sites included in chapter three were associated with marginally higher levels of single parent households, this result was not statistically significant ($p \leq 0.05$) across all Superfund sites. Additionally, statistical significance ($p \leq 0.05$) was not met when exclusively non-PFAS Superfund sites are selected. This analysis shows that environmental justice implications surrounding highly polluted sites is dependent on the type of Superfund site, and non-military PFAS sites have comparatively higher associations with neighborhood social vulnerability.

__Table 30__ Ordinary Least Squares Regressing Years of Superfund Site Designation on Vulnerability Characteristics and Geographic Control Variables

VARIABLES	**Number Years of Superfund Site Activity**
EPA Region 1	196.314***
	(54.143)
EPA Region 2	0.124***
	(0.033)
Population Density	1.000***
	(0.000)
% Poverty	1.008
	(0.014)
% Single Parent Households	1.030
	(0.021)
% Minority	0.957***
	(0.005)
% Limited English	1.055**
	(0.024)
% Crowding	0.962
	(0.036)
% With Disability	1.021
	(0.023)
Superfund sites without known PFAS within buffer	2.873*
	(1.831)
Constant	0.0000***
	(0.0000)
	R^2 = 0.249
	N = 6,621

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

As an extension to the logistic regression analysis investigating whether the indicators of vulnerability are associated with close proximity to PFAS Superfund sites (equations 9 and 10), it was hypothesized that the vulnerability effects associated with PFAS Superfund sites may be affected by the duration of the Superfund site designation. A new model and functional form is required to examine this hypothesis since the age of the Superfund site is perfectly correlated with the existence of a Superfund site. Therefore, it is not possible to regress the probability of the existence of a Superfund site on the age of the Superfund site. A separate ordinary least squares regression was estimated with age of the closest Superfund site (to each Census tract within 6-miles of a Superfund site) regressed on the social vulnerability variables, and control variables in equations 9 and 10. Findings suggest that EPA Region 1 has the most Census tracts near the longer-lasting PFAS Superfund sites. Additionally, the age of PFAS Superfund sites is associated with an increased likelihood of the presence of other non-PFAS Superfund sites nearby. This suggests a compounding effect between older PFAS Superfund sites and having other Superfund sites nearby. Regarding social vulnerability indicators, the proportion of racial and ethnic minorities, and limited English proficiency were both found to be positively associated with a longer duration of PFAS Superfund site presence within 6-miles from the Census tract. For instance, among Census tracts within 6-miles of PFAS Superfund sites, on average a one percent increase in neighborhood racial and ethnic minorities, Superfund sites are older by 0.96 years, and a 1% increase in those with limited English proficiency are associated with older Superfund sites by 1.055 years. Therefore, while an increased likelihood of a PFAS Superfund site nearby is positively associated with neighborhood vulnerability, the length of time Superfund sites have been present may compound these effects. Since PFAS is not yet regulated by CERCLA and the findings of known PFAS contamination at Superfund sites were not announced to the public until 2018 (SCEPW, 2019), the public was not likely aware of the presence of PFAS at these sites until then. This means PFAS contamination in isolation was not likely to affect population characteristics prior to 2018. Further analysis could evaluate the effects of social and demographic changes upon PFAS contamination announcements related to Superfund sites.

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