Post Disaster Private Well Water Contamination with Geosocial Network: A Case Study of Post Hurricane Harvey

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ABSTRACT

The prevalence of natural hazards and extreme climatic events highlights the critical importance of disaster recovery for communities. In this study, we examine the impact of Hurricane Harvey on private well water in Texas and explore the relationship between the contamination of well water, stewardship behavior, and: demographic and social capital characteristics. We develop a multi-level regression model that shows bonding and linking social capital index, median house income, owner-occupied houses percentage, and the percentage of households speaking only English correlate with people's vulnerability to unsafe drinking water supplies. We validate the results through a partial dependence framework built upon a random forest model. Our study provides valuable insights to address issues of fairness and vulnerability in society and foster resilience and preparedness in the face of shocks and hazards

INTRODUCTION

Private wells provide drinking water to millions of people in the United States, particularly residents of rural areas. Hurricanes and flooding can have devastating effects on communities that rely on well water for their daily needs. Heavy rains and strong winds can damage wells and water systems, causing contamination and making the water unsafe to drink. Floodwaters can also inundate and contaminate groundwater, making it difficult or impossible to access clean drinking water. In 2017, Hurricane Harvey caused significant damage to water wells and systems in Texas, leaving many communities without access to clean drinking water. Harvey hit Texas near Port Aransas causing severe damage, and then a rain band developed over Fort Bend and Brazoria Counties and spread to Harris County, causing flash flooding due to heavy rainfall rates. Floodwaters contaminated wells with bacteria, viruses, and other harmful substances (Pieper et al. 2021; US Department of Commerce NOAA 2017). In 2018, Hurricane Florence caused severe flooding in North Carolina, damaging many private wells and contaminating groundwater with bacteria and other pollutants. Many residents were left without access to safe drinking water for weeks (Quist et al. 2022). Bacteria in the water can cause health issues and pose a significant risk to the well-being of impacted communities. It leads to an increase in waterborne illnesses such as E. Coli, Legionnaires' disease, and other illnesses (Pandey 2014). However, treating contaminated water can economically burden vulnerable populations, especially the ones in low-income and BIPOC communities (Vanderslice 2011)

Social capital can be an important factor to promote the resilience of private well water infrastructure (Aldrich 2010). Prior research has shown that social capital can play a significant role in the resilience of infrastructure during and after shocks (Aldrich 2012; Aldrich and Meyer 2014; Roque, Pijawka, and Wutich 2018). Private wells, which are not regulated by the Safe Drinking Water Act, rely on the actions of individual well owners to maintain and protect the safety of the water supply. Thus, social capital, related to connections, norms, and trust, may be critical in facilitating stewardship and cooperation among private well owners.

Despite its importance, the role of social capital in water infrastructure vulnerability has received limited attention. For private well owners who lack strong social networks, particularly in rural areas where distances between properties can be significant, environmental problems may be of high severity. Also, a lack of trust or shared norms among private well owners can also inhibit collective action that could drive policy solutions to address well water contamination and other threats to the safe water supply.

This article investigates the contamination rates of private wells in the aftermath of Hurricane Harvey and how social capital influenced the contamination outcomes. Our study particularly focuses on the role of the social capital as captured through an index already validated by previous studies (SoCI) (Aldrich and Meyer 2014; Kyne and Aldrich 2020), on resilience and recovery efforts. By comprehensively examining the intricate interplay of factors contributing to vulnerability and resilience, we aim to promote creating more equitable and sustainable communities better equipped to deal with future disasters.

LITERATURE REVIEW

Flooding and its caused private well contamination have been widely studied in the scientific community. Prior research indicates that floodwater contains a higher concentration of viruses than river water, with Hepatitis A being the most abundant virus found in floodwater, and Norovirus G2 in flooded groundwater. Groundwater contamination likely comes from flood events as microbial contamination was found both near and away from septic tanks. Private wells in flooded areas were tested and found to be contaminated with viruses, thereby increasing the risk of viral infections resulting from either the contamination of drinking water sources or direct exposure to floodwaters (Phanuwan et al. 2006). Furthermore, past studies show that private well users are at a higher risk of infection due to the lack of legislative regulation, and various factors such as demographics and social capital can affect the risk of private well contamination and flooding (Andrade et al. 2018).

Minority populations from disadvantaged neighborhoods are often found to be more vulnerable to the effects of disasters (Deng et al. 2021; Li et al. 2022). Low-income and minority communities frequently face disproportionately high pollutant exposures, which can negatively impact their health (Schaider et al. 2019).

The role of social capital in preparation, endurance, and recovery when facing natural disasters has been examined (Babcicky and Seebauer 2015). On the one hand, research has shown households with strong personal networks and higher levels of social capital experience faster recovery from natural disasters such as floods (Sadri et al. 2018). Tammar, Abosuliman, and Rahaman (2020) found that communities with high levels of social capital were better equipped to prepare for, respond to, and recover from disasters due to the benefits of information sharing, resource mobilization, and collective action. On the other hand, social capital can also be negatively impacted by floods as it may lead to households being less inclined to take preventative measures, thereby diminishing their perceptions of flood risk. The assumption of ample social support downplays the danger, resulting in households being less inclined to take preventative measures (Babcicky and Seebauer 2015).

Overall, despite the potential benefits of social capital in responding to and recovering from floods and their associated well water contamination, there is a lack of research exploring, verifying, and quantifying its impact. This study aims to address this gap.

METHOD

Table 1. Variables and their definitions

Categories	Variables	Definition
Demographics	% White	White people percentage
	% Minority	Asian, Black, Hispanic percentage
	% More race	Multi-ethnic people percentage
	Median household income	Median household income
	% Occupied	Occupied housing percentage
	% Owner occupied	Occupied housing ownership percentage
	% Native	Native born percentage
	% Foreign born	Foreign born percentage
	% Speak Only English	People who only speak English percentage
	Population	Count of population
Social capital index	Bonding	Homogeneous connections between similar residents
	Linking	Connections of regular citizens to those in power
	Bridging	Heterogeneous connections through institutions such as civic organizations

Data. In this study, we include variables from two categories. They are summarized below, and the full list and definitions can be found in Table 1.

Demographic information: These variables provide information about the demographic characteristics of a population, such as the percentage of people who are minority or White, the percentage who are foreign-born, and the rates of home ownership. Demographic information is often used to control for confounding factors and to better understand the relationships between other variables.

Social capital: Social capital refers to the resources and connections that people have from their social networks (Fraser, Page-Tan, and Aldrich 2022). Bonding social capital refers to connections between people who are similar in some way, such as having a shared ethnicity or religion. Bridging social capital refers to connections between people who are different in some way, such as having different social or economic backgrounds. Linking social capital refers to connections between people who have different levels of power or influence, such as connections between politicians and their constituents (Kyne and Aldrich 2020).

Our outcome variable is the percentage of the private well with total coliform tested positive (%Total Coliform from here on) in Texas. The information was gathered through three university and local health department campaigns of well testing from August 2017 to June 2018, and over nine thousand data points were collected in the 41 disaster counties. For more details, see (Pieper et al. 2021).

Models. We develop two models to explore the relationships between the variables and outcome. They collectively help us explore the impact of social capital and demographics on water well contamination rate. The first model is a Bayesian regression model which estimates a probability distribution for regression model parameters using Bayesian probability theory. It has the advantages of incorporating prior knowledge, handling outliers, and allowing for complex models (Permai and Tanty, 2018). Its flexibility is especially useful in studies like ours involving multiple levels of data. Particularly, the Markov Chain Monte Carlo (MCMC) is used for its ability to estimate complex posterior distributions efficiently. A Markov chain proposes new model parameters and accepts or rejects them based on the posterior distribution, exploring the distribution accurately. Samples obtained from the chain estimate posterior properties. (Andrieu et al. 2003) In this study, the MCMC method allows for efficient and accurate estimation of the posterior distribution, and thus can make statistical inferences and estimate the expected effects of demographic and Social capital index (SoCI) variables on the outcome total coliform tested positive rate.

Additionally, we develop a partial dependence analysis in conjunction with random forest to understand how each variable in the model affects the model's overall predictions. By examining partial dependence plots for each variable, one can gain insight into how changing the value of a given variable affects the model's output, which can be useful for interpretation and decision-making. Partial dependence analysis evaluates how the average outcome of a regression model changes when a single variable is altered. Specifically, we select a variable of interest, set its value to be constant across all data instances, and vary it over a range of feasible values. The resulting outcomes are then averaged across all data instances, providing an understanding of how the variable influences the model's predictions (Friedman 2001).

RESULTS AND DISCUSSIONS

In our first MCMC Bayesian regression model, we employ only demographic information as the independent variable and %Total Coliform as the dependent variable. The model has identified three variables that exhibit a significant association %Total Coliform, namely, *median household income*, *the percentage of owner-occupied housing units*, and *the proportion of people who only speak English*. The coefficients obtained from the MCMC model for these variables represent the anticipated change in the %Total Coliform for a one-unit increase in the respective independent variable, with all other variables held constant. For instance, based on the model results, a one-unit increase in median household income corresponds to an average decrease of 0.20 in the %Total Coliform. On the other hand, a one-unit increase in the percentage of owner-occupied housing units is associated with an average increase of 0.37 in the %Total Coliform. Similarly, a one-unit increase in the percentage of people who only speak English corresponds to an average decrease of 0.19 in %Total Coliform, with all other variables held constant.

Table 2. Summary Statistics for MCMC Models

	Demographic Model			Demographic and SoCI Model		
Important variables	Estimate	Lower-89% CI	Upper-89% CI	Estimate	Lower-89% CI	Upper-89% CI
Median household income	-0.20	-0.41	0.01	-0.12	-0.35	0.12
% Owner Occupied	0.37	0.12	0.60	0.30	0.05	0.55
% Speak Only English	-0.19	-0.39	0.02	-0.27	-0.53	-0.01
Bonding	-	-	-	0.22	-0.01	0.46
Bridging	-	-	-	0.08	-0.14	0.31
Linking	-	-	-	-0.09	-0.29	0.11

Second, we add the SoCI variables into the MCMC model. The results are shown in Table 2. SoCI shows certain relationships with %Total Coliform, but they are not statistically significant. We also found that the R^2 value is relatively low (0.32).

Subsequently, a random forest model was utilized in conjunction with partial dependence analysis to isolate the effect of SoCI and investigate its impact. The outcomes of this analysis are presented in Figure 1. We observed a significant improvement in R^2 value, increasing from 0.32 to 0.82. The findings from Figure 1 also illustrate distinct trends in the impact of SoCI indices on %Total Coliform, elucidating a positive association of bonding SoCI and negative correlation of linking SoCI with %Total Coliform.

As mentioned before, bonding SoCI denotes the degree to which individuals are connected to each other through strong bonds of shared identity and similarity. A positive estimate for this attribute indicates that societies with higher levels of bonding may experience a higher proportion of total coliform contamination. The heightened bonding among individuals within a community could be advantageous, offering them a sense of collective action, support, and belongingness. Nevertheless, excessive bonding may lead to less diversity and race similarity, which may foster insularity and exclusion of outsiders. Here is may lead to less new information being shared and accepted, and outside expertise not being a regular source of guidance for handling potential contamination.

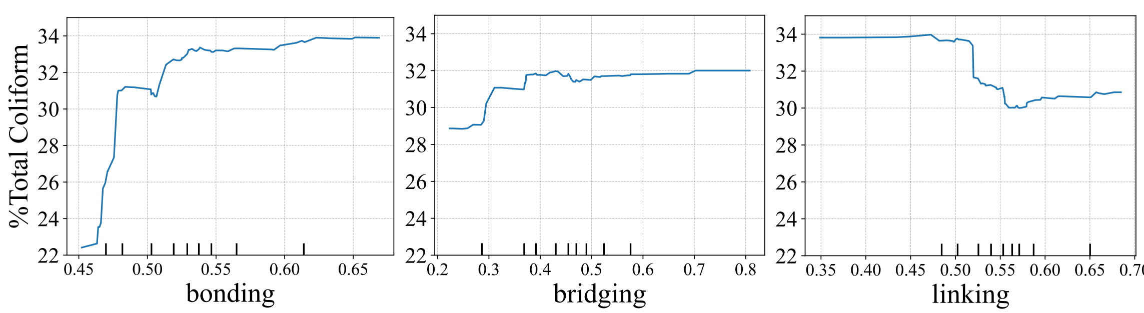

Figure 1. Partial dependency explanation of variable impact on well contamination rate.

The linking index denotes the extent of connections between community members and governmental decision-makers. A negative correlation with this variable suggests that communities with more robust linkages tend to exhibit a smaller proportion of total coliforms testing positive. This pattern implies that communities with strong ties to politicians and decision-makers are potentially better prepared to handle threats like floods, as they are more likely to receive and accept information and assistance concerning environmental contamination. Several regions with high total coliform percentages have been identified, such as Jersey Village, Katy, Cypress, and Houston in Harris County, Aransas Pass in San Patricio County, and Fulshear in Fort Bend County. These cities are marked by a lower percentage of English-speaking residents and a comparatively smaller linking index.

CONCLUSION

This study aims to examine the effects of Hurricane Harvey on private well water in Texas, with a focus on identifying various demographic and social capital factors that can influence individuals' vulnerability to unsafe drinking water. The findings provide critical insights that can enhance community resilience in the face of flooding. Specifically, policy makers should prioritize measures that foster linking social capital in communities and promote diversity to mitigate the potential negative impacts of bonding social capital, particularly in terms of race similarity. Achieving this could involve incentivizing community engagement in disaster preparedness and recovery efforts, fostering government-community partnerships, and gradually building more diverse communities. Additionally, the government should facilitate access to resources and information for groups with lower median household incomes, higher rates of owner-occupied homes, and non-English speakers. This can be accomplished through the provision of English language assistance, dissemination of educational materials in multiple languages, and improvement of infrastructure to ensure access to clean drinking water. By implementing these recommendations, more equitable and resilient communities can be established, which are better equipped to address the challenges posed by natural disasters.

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REFERENCES

Aldrich, Daniel P. 2010. "Fixing Recovery: Social Capital in Post-Crisis Resilience." Journal of Homeland Security Aldrich, Daniel P. *Building Resilience: Social Capital in Post-Disaster Recovery*. Chicago, IL: University of Chicago Press, 2012.

Aldrich, Daniel P., and Michelle A. Meyer. 2014. "Social Capital and Community Resilience." *American Behavioral Scientist*, *59*(2), 254–269. https://doi.org/10.1177/0002764214550299.

Andrade, L., J. O'Dwyer, E. O'Neill, and P. Hynds. 2018. "Surface Water Flooding, Groundwater Contamination, and Enteric Disease in Developed Countries: A Scoping Review of Connections and Consequences." *Environmental Pollution (Barking, Essex: 1987)* 236 (May): 540–49. https://doi.org/10.1016/J.ENVPOL.2018.01.104.

Andrieu, Christophe, Nando De Freitas, Arnaud Doucet, and Michael I. Jordan. 2003. "An Introduction to MCMC for Machine Learning." *Machine Learning* 50 (1–2): 5–43. https://doi.org/10.1023/A:1020281327116/METRICS.

Babcicky, Philipp, and Sebastian Seebauer. 2017. "The Two Faces of Social Capital in Private Flood Mitigation: Opposing Effects on Risk Perception, Self-Efficacy and Coping Capacity." *Journal of Risk Research* 20 (8): 1017–37. https://doi.org/10.1080/13669877.2016.1147489.

Deng, Hengfang, Daniel P Aldrich, Michael M Danziger, Jianxi Gao, Nolan E Phillips, Sean P Cornelius, and Qi Ryan Wang. 2021. "High-Resolution Human Mobility Data Reveal Race and Wealth Disparities in Disaster Evacuation Patterns." *Humanities and Social Sciences Communications* 8, no.1. https://doi.org/10.1057/s41599-021-00824-8.

Fraser, Timothy, Courtney Page-Tan, and Daniel P. Aldrich. 2022. "Social Capital's Impact on COVID-19 Outcomes at Local Levels." *Scientific Reports* 12 (1). https://doi.org/10.1038/S41598-022-10275-Z.

Friedman, Jerome H. 2001. "Greedy Function Approximation: A Gradient Boosting Machine." *The Annals of Statistics* 29, no. 5 https://doi.org/10.1214/AOS/1013203451.

Kyne, Dean, and Daniel P. Aldrich. 2020. "Capturing Bonding, Bridging, and Linking Social Capital through Publicly Available Data." *Risk, Hazards & Crisis in Public Policy* 11 (1): 61–86. https://doi.org/10.1002/RHC3.12183.

Li, Weiyu, Qi Wang, Yuanyuan Liu, Mario L. Small, and Jianxi Gao. 2022. "A Spatiotemporal Decay Model of Human Mobility When Facing Large-Scale Crises." *Proceedings of the National Academy of Sciences of the United States of America* 119 (33): e2203042119. https://doi.org/10.1073/PNAS.2203042119/SUPPL_FILE/PNAS.2203042119.SAPP.PDF.

Pandey, Pramod K., Philip H. Kass, Michelle L. Soupir, Sagor Biswas, and Vijay P. Singh. 2014. "Contamination of Water Resources by Pathogenic Bacteria." *AMB Express* 4 (1): 51. https://doi.org/10.1186/S13568-014-0051-X.

Permai, Syarifah Diana, and Heruna Tanty. 2018. "Linear Regression Model Using Bayesian Approach for Energy Performance of Residential Building." *Procedia Computer Science* 135 (January): 671–77. https://doi.org/10.1016/J.PROCS.2018.08.219.

Phanuwan, Chanetta, S. Takizawa, K. Oguma, H. Katayama, A. Yunika, and S. Ohgaki. 2006. "Monitoring of Human Enteric Viruses and Coliform Bacteria in Waters after Urban Flood in Jakarta, Indonesia." *Water Science and Technology: A Journal of the International Association on Water Pollution Research* 54 (3): 203–10. https://doi.org/10.2166/WST.2006.470.

Phillips, Nolan E, Brian L Levy, Robert J Sampson, Mario L Small, and Ryan Q Wang. 2021. "The Social Integration of American Cities: Network Measures of Connectedness Based on Everyday Mobility Across Neighborhoods." *Sociological Methods & Research* 50 (3): 1110–49. https://doi.org/10.1177/0049124119852386.

Pieper, Kelsey J, C Nathan Jones, William J Rhoads, Mcnamara Rome, Drew M Gholson, Adrienne Katner, Diane E Boellstorff, and R Edward Beighley. 2021. "Microbial Contamination of Drinking Water Supplied by Private Wells after Hurricane Harvey." *Environ. Sci. Technol* 55: 8392. https://doi.org/10.1021/acs.est.0c07869.

Quist, Arbor J.L., Mike Dolan Fliss, Timothy J. Wade, Paul L. Delamater, David B. Richardson, and Lawrence S. Engel. 2022. "Hurricane Flooding and Acute Gastrointestinal Illness in North Carolina." *The Science of the Total Environment* 809 (February): 151108. https://doi.org/10.1016/J.SCITOTENV.2021.151108.

Roque, Anais Delilah, David Pijawka, and Amber Wutich. 2018. "The Role of Social Capital in Resiliency: Disaster Recovery in Puerto Rico." *Hazards & Crisis in Public Policy* 9 (2). https://doi.org/10.1002/rhc3.12187.

Sadri, Arif Mohaimin, Satish, V Ukkusuri, Seungyoon Lee, Rosalee Clawson, Daniel Aldrich, Megan, et al. 2018. "The Role of Social Capital, Personal Networks, and Emergency Responders in Post-Disaster Recovery and Resilience: A Study of Rural Communities in Indiana" *Natural Hazards* 90, no. 3: 1377–1406. https://doi.org/10.1007/s11069-017-3103-0.

Schaider, Laurel A., Lucien Swetschinski, Christopher Campbell, and Ruthann A. Rudel. 2019. "Environmental Justice and Drinking Water Quality: Are There Socioeconomic Disparities in Nitrate Levels in U.S. Drinking Water?" *Environmental Health: A Global Access Science Source* 18 (1): 1–15. https://doi.org/10.1186/S12940-018-0442-6/TABLES/5.

Tammar, Abdurazag, Shougi Suliman Abosuliman, and Khan Rubayet Rahaman. 2020. "Social Capital and Disaster Resilience Nexus: A Study of Flash Flood Recovery in Jeddah City." *Sustainability 2020, Vol. 12, Page 4668* 12 (11): 4668. https://doi.org/10.3390/SU12114668.

Vanderslice, James. 2011. "Drinking Water Infrastructure and Environmental Disparities: Evidence and Methodological Considerations." *American Journal of Public Health* 101 (Suppl 1): S109. https://doi.org/10.2105/AJPH.2011.300189.

US Department of Commerce, NOAA. "Major Hurricane Harvey - August 25-29, 2017." National Weather Service. https://www.weather.gov/crp/hurricane_harvey.