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Determinants of Water System Management

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DETERMINANTS OF WATER SYSTEM MANAGEMENT

by

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DETERMINANTS OF WATER SYSTEM MANAGEMENT

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Water system management is complex, involving state, local, and federal regulations and impacting people from a wide variety of socioeconomic backgrounds. Systems in the developing and industrialized worlds both face challenges in managing water systems. Much research has been completed regarding associations of water system violations and system factors, and there has been an increased attention to issues of environmental justice – how water system violations affect communities of color, impoverished communities, and rural communities. Currently no studies have focused on the associations between socioeconomic factors and water system management violations. The goal of this research was to ascertain the significant determinants of water system management.

Two analyses were conducted to attain this goal: a nation-wide statistical analysis of management violations and individual case studies for two Nebraska, USA and two Madagascar water systems. The binomial logistic regression analysis used community-level socioeconomic and water system characteristics to determine the likelihood of a management violation. The case studies further explored the significant factors determined during the statistical analysis for applicability and review of additional determinants.

The statistical results agree with published studies, while the case study presents areas for further research. The systems most likely to have a violation during the study period were surface water systems; systems with higher Black/African populations; or rural, middle income Latino populations. Communities with a greater percentage of people with a bachelor's degree showed a decrease in violations, while communities with higher levels of poverty showed an increase in violations. Population movement into a community was associated with a decrease in violations. The state where the system was located showed significant correlation with the number of management violations. The case study suggests two additional areas that impact water system management: availability and affordability of additional water sources and the presence of trained labor and staffing within the community.

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Chapter 1: Introduction and Objectives

Section 1.1: Introduction

Public water systems in the United States supply 39.0 billion gallons of water per day (Maupin, 2018). These water supply systems are designed to provide clean and safe water for drinking, washing, commercial, and industrial uses – free from bacteria, organic, and inorganic contaminants. When safe water is not delivered to the consumer, the system is not operating as intended, and thus, has failed. Specific violations include failure to meet drinking water standards, failure to report to state and federal agencies, failure to communicate with the water users, or failing to meet sanitary standards.

To provide continual safe drinking water, operational and maintenance effort must be put into the systems. Water utilities in the United States spent $113 billion dollars in 2017 on water supply and wastewater treatment facilities, and 96% of these funds came from a state or local funding source (Congressional Budget Office, 2018). Nearly three quarters, 72%, of these funds are put towards operation and maintenance costs for the systems, and 28% of funds are obligated towards capital improvements. The United States Environmental Protection Agency (EPA) and the United States Department of Agriculture – Rural Development (USDA-RD) provide additional funding sources for water system improvements. The EPA's Drinking Water State Revolving Fund (DWSRF) has provided funding assistance to 15,425 projects from 1997 to 2019 totaling $41.0 billion dollars (EPA, 2019). USDA-RD has provided $13.9 billion dollars for 5,825 water and wastewater projects from 2009 to 2017 (USDA-RD, 2017).

Yet, here in the United States, with the abundance of funding, systems fail to provide safe, clean drinking water to consumers. Greater than 1 of every 2 community water systems reported a violation from 2017 to 2020 (EPA, 2020). These violations include health violations, monitoring and reporting violations, public notification, and other violations. A health violation is the exceedance of drinking water quality standards. The EPA has set limits for more than 90 contaminants, both chemical and microbial, acute (e.g., coliforms or nitrate) and chronic (e.g., arsenic or uranium). A system incurs a monitoring and reporting (MR) violation when it does not collect sampling data or fails to report the results of the test to the reviewing agency. When the system does not notify the consumers under the requirements of the consumer confidence report rule or the public notification rule, this is considered a public notification (PN) violation. In 2019, of the 148,311 public water supply systems, 1 in 4 systems had an MR violation, and 1 in 10 had a public notification or other violation. Additionally, 1 in 17 systems had a health violation, and 1 in 73 systems had an acute health violation. Whether by management or by health violation, both categories place the end user at risk.

The failure to deliver safe, clean drinking water is not limited to the United States, however. According to the World Health Organization (WHO), in 2019, 785 million people lacked basic drinking water services (WHO, 2019). In 2016, 1.9 million deaths, or 1.5% of all deaths worldwide, were due to inadequate access to clean water, adequate sanitation, or poor hygiene practices. However, while the mortality (death) rate due to diarrheal diseases has decreased, morbidity (disability, sickness) has remained relatively unchanged (UNICEF & WHO, 2019). From 1980 to 1990, during the International Drinking Water

Decade, hundreds of water and sanitation projects were implemented across the globe in developing countries. Yet by 1995, 70% of these projects were no longer in operation, and by the year 2000, only 1 in 8 projects was still in service (Lucena et al., 2010).

The management and operation of a public system has an impact on each of the water users. Unsafe drinking water may lead to disease and disability or force users to look for a different source of drinking water. Water with poor taste, odor, and color issues lowers the quality of living within a community. Unfortunately, those most affected by inadequate water system management are often the poor, marginalized, or under-represented, regardless of location around the globe (Evans & Kantrowitz, 2002).

The ultimate intent of this research is to develop a response to the following questions: Why do some systems operate effectively and comply with drinking water standards when others fail to do so?

Section 1.2: Objectives

A holistic answer to this question cannot be ascertained in one research project, but this research will set a course for future study. This area of research starts by evaluating the significance of socioeconomic factors as they relate to the management and operation of a system. The goal of this research is to evaluate the influence of socioeconomic factors on water system management using community characteristics and compliance data. In pursuit of this goal, two research objectives were defined and are outlined below:

- Conduct a binomial regression for the occurrence of a PNO or MR violation.
- Further refine the regression results through two comparative case studies: one in the United States and one in Madagascar.

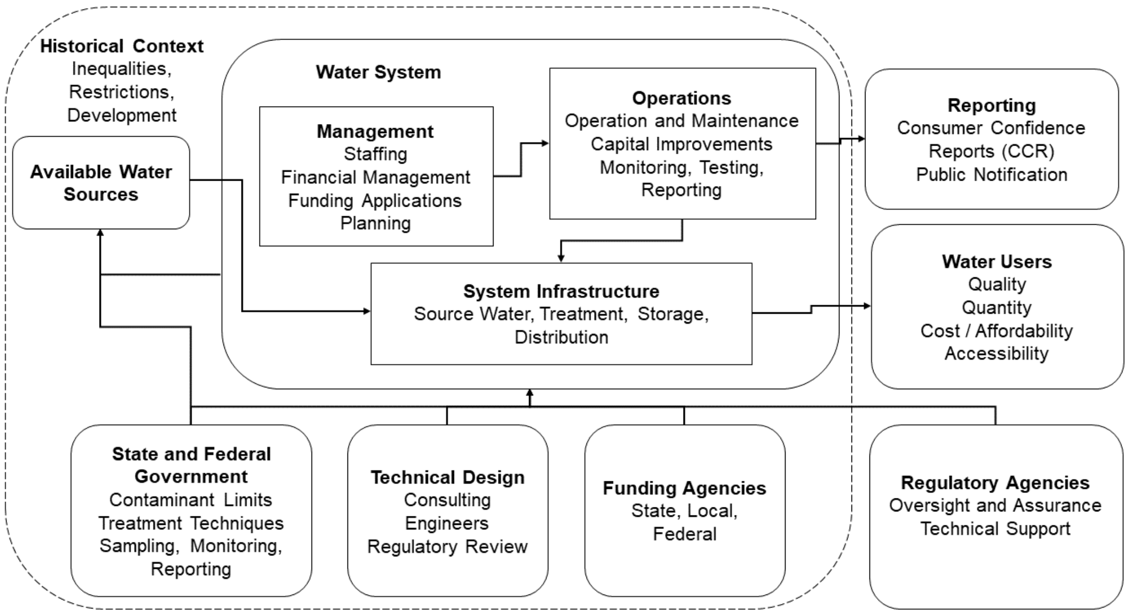
Chapter 2: Literature Review

Section 2.1: Water System Regulation and Management

The United States Environmental Protection Agency (EPA) is responsible for the regulation of drinking water through the Safe Drinking Water Act (SDWA), setting safe Maximum Contaminant Limits (MCLs) for organic, inorganic, and other chemical compounds. Additional Secondary Maximum Contaminant Limits (SMCLs) are set for aesthetic qualities, including taste, odor, color, and clarity. The EPA delegates authority and regulation of water systems to individual state governments. These governing authorities receive the water system operating reports, perform inspections, and review plans and specifications for compliance.

The ability of a water system to adequately manage and operate in accordance with regulations is determined by numerous internal and external factors (Baietti et al., 2006). Internal and external technical, managerial, and financial (TMF) factors determine the water system’s ability to respond to changing regulation (Balazs et al., 2011; Cromwell et al., 1997; Rahman et al., 2010). Internal factors include system infrastructure, management, and operations. External factors that impact the autonomy of the water system to make decisions include labor markets, access to technical and financial resources, policy and regulatory frameworks, and availability of natural resources. In addition to present-day factors, historical marginalization, oppression, and development has led to inequal service to communities (Drabo, 2011; Montag, 2019). The relationships between internal and external factors are illustrated in the following figure.

Figure 1: Water System Factors (Adapted from VanDerslice 2011)



Determinants of water system and project sustainability in developing countries are similar to the factors within a U.S. context, including internal and external factors (Campos, 2008; Enéas da Silva et al., 2013; McConville & Mihelcic, 2007). The framework proposed by McConville & Mihelcic includes sociocultural respect, community participation, political cohesion, economic sustainability, and environmental sustainability applied throughout the life cycle of the project, from needs assessment through operation and maintenance. Many socioeconomic factors impact the long-term acceptance and operation of a system including social sustainability (sociocultural respect, community participation and political cohesion), economic sustainability, and environmental sustainability (McConville & Mihelcic, 2007). Specific management factors include community participation, governance, tariff payment, accounting transparency, financial durability, repair service, and system function (Schweitzer & Mihelcic, 2012).

The emphasis for international water system management and for industrialized communities are slightly different. The framework for international water system management emphasizes community acceptance and participation. The emphasis of U.S. water system research focuses primarily on technical staffing and water system management by a select group of people.

Section 2.2: Water System Violations

Water system violations fall into two categories: health-based and operational. Health based violations include acute health violations and non-acute health violations. Operational violations include monitoring, reporting and public notification. Monitoring and reporting violations are the most common violations and these violations can obscure, hide, or lead to overlooking health based violations (Oxenford & Barrett, 2016; Rubin, 2013; Wallsten & Kosec, 2008). Furthermore, MR and PN violations are indicative of a lack of technical, managerial, or financial capacity of a system (Cromwell et al., 1997). Additionally, among deficiencies noted during regulatory site visits, management was the second most common deficiency. These deficiencies include a lack of planning documents, emergency response plans, monitoring protocols, and operational and maintenance documents (Oxenford & Barrett, 2016). A caveat is noted for MR violations: the number of MR violations may be elevated due to multiple MR violations for a single test (i.e. volatile organic, synthetic organic, and inorganic tests) (Oxenford & Williams, 2014).

Section 2.3: Statistical Methods

Current research has used various statistical methods to investigate the connections between socioeconomic factors and system violations. These range from summary statistics (Oxenford & Barrett, 2016), Chi-squared analysis (Rubin, 2013), ANOVA (Marcillo & Krometis, 2019), probit analysis (Allaire et al., 2018; Rahman et al., 2010), and negative binomial regression (Kirchhoff et al., 2019; Oxenford & Williams, 2014; Statman-Weil et al., 2020; Switzer & Teodoro, 2017; Wallsten & Kosec, 2008; Wren Montgomery et al., 2018). The violation data are not normally distributed and exhibit a high level of skew to the right. Thus, a linear regression analysis is not appropriate for determining statistical significance. A binomial regression approach (had violation / did not have violation) minimizes the impact of multiple violations for the same sampling event and is consistent with prior research.

The unit of analysis (e.g., county or city) and the breadth of water systems included (e.g., a single state or nationwide study) effects whether significant association is found. Studies with smaller units of analysis and a greater breadth are more likely to find significant associations (Baden et al., 2007). Thus, only community level characteristics will be used for the analysis, where available.

Section 2.4: Socioeconomic & System Factors

System size has a significant impact on the number of violations. Small (less than 500 people) and very small (less than 3,300 people) systems have a greater number of monitoring and reporting or public notification violations than larger systems. This is true for national analysis (Oxenford & Barrett, 2016; Schaider et al., 2019; Wallsten & Kosec, 2008), and state analysis (Marcillo & Krometis, 2019; Rubin, 2013).

The research does not agree on the relationship of population served and the number of health violations. Switzer and Teodoro showed a negative correlation between health violations and total population served (logged) ($C = -0.1069$, $p < 0.01$) (Switzer & Teodoro, 2017). Kirchhoff et al. showed no correlation between population served and health violations ($C = 0.0000$, $P = 0.0627$) in the state of Connecticut (Kirchhoff et al., 2019). Rahman et al. observed a positive correlation between population served and number of MCL violations for Arizona water systems between 1993 and 2004 ($C = 0.2498$, $P < 0.05$) (Rahman et al., 2010).

Switzer and Teodoro showed a negative correlation between health violations and percentage of the population with a bachelor's degree ($C = -0.0099$, $p < 0.01$), while demonstrating a positive correlation with the percentage of population with a high school degree ($C = 0.0006$) (Switzer & Teodoro, 2017).

No research regarding the association between community mobility and water system management violations was found.

Correlation between violations and income or poverty is dependent upon the interaction effects applied, and what kind of violations are being investigated. While Switzer and Teodoro showed a negative correlation between health violations and percentage of the population below the poverty line ($C = -0.0067$, $p < 0.05$), Allaire et al. did not find a statistically significant correlation between total violations and median household income (Allaire et al., 2018; Switzer & Teodoro, 2017). Additionally, percent poverty was associated with -2.2% decrease in the likelihood of nitrate levels greater than 5.0 mg/L (Schaider et al., 2019). Looking only at monitoring and reporting violations, Wallsten and Kosec showed a positive correlation between monitoring and reporting violations and increases in income ($C = 0.009$, $P < 0.01$) (Wallsten & Kosec, 2008). Statman-Weil et al. showed a significant negative association for total violations and percent below the poverty line in the state of Pennsylvania, while the same analysis did not find a significant association with health violations, suggesting a decrease in management violations within impoverished communities (Statman-Weil et al., 2020).

Minority communities and low-income communities face increased exposure to pollution, through institutional barriers (Heaney et al., 2011; Johnson & Bullard, 2000). Allaire et al. observed an increase in total violations correlated to the percentage of population that was non-white ($C = 0.081$, $P < 0.01$) (Allaire et al., 2018).

The results of prior research show mixed results for violation association with Black/African populations. As noted previously, the inclusion of income interaction effects changes the statistical significance of results. The percentage of a community's Black population and likelihood of health violations were negatively correlated ($C = -0.0058$, $P < 0.05$), when viewed alone, while the interaction between Black and percentage in poverty showed a slight positive correlation ($C = 0.0003$, $P < 0.05$) (Switzer & Teodoro, 2017). Non-Hispanic, Black populations unit increases were correlated with a -4.3% decrease in probability of nitrate exceedances (Schaider et al., 2019).

As with Black/African populations, including an income factor shifts the correlation direction for Latino populations. Latino populations and health violations were slightly negatively correlated (C = -0.0001) when viewed alone, while the interaction between Latino and percentage in poverty showed a slight positive correlation (C = 0.0002, $p < 0.01$) (Switzer & Teodoro, 2017). Latino population unit increases were associated with a 1.9% increase in probability of having a nitrate level greater than 5.0 mg/L (Schaider et al., 2019).

Monitoring and reporting violations are higher in rural areas than in urban areas. Wallsten and Kosec showed a statistically significant decrease in monitoring and reporting violations as the percent of the county with urban population increased (C = -0.202, $P < 0.01$) (Wallsten & Kosec, 2008). Marcillo and Krometis showed isolated rural communities had greater numbers of MR violations than systems located in an urban core or small town ($P < 0.01$) (Marcillo & Krometis, 2019).

Section 2.5: State Effects

Oxenford and Barrett observed that among public notification violations in 2013, four states (Pennsylvania, Wisconsin, Texas, and West Virginia) had greater than 3,000 PN violations, an additional five states (North Carolina, Missouri, Connecticut, New Hampshire, Maine) had approximately 1,000 violations, while the remaining 41 states had fewer than 500 violations (Oxenford & Barrett, 2016).

Section 2.6: Source Water

The research is not conclusive about the effect of source water on the number of system violations. Wallsten and Kosec showed fewer monitoring and reporting violations for groundwater systems (C = -1.114) than surface water systems (C = -0.734) (Wallsten

& Kosec, 2008) while Marcillo and Krometis showed very small surface water systems had fewer monitoring and reporting violations than groundwater or groundwater under direct influence water sources ($P << 0.01$) (Marcillo & Krometis, 2019). Allaire et al. found a statistically significant ($P < 0.05$) increase in total violations for systems with a surface water source ($C = 0.178$) (Allaire et al., 2018).

Rahman et al. did not find a statistically significant difference between groundwater and surface water systems for the number of MCL violations (Rahman et al., 2010). In another study, the overall percentage of groundwater systems (77.1% of all CWS systems) and surface water systems (22.9% of all CWS systems) with violations did not differ from the percent of systems as a whole, however, groundwater systems with violations serve a much smaller percentage of the population than surface water systems with violations (Rubin, 2013).

Section 2.7: Significant Determinants

To understand which determinants have the greatest impact on water system management it is important to review not only which factors are statistically significant, but which factors show the highest correlation. For Switzer and Teodoro's study, the highest coefficients belonged to the following factors: lagged violations (i.e., had a violation the prior year), $C = 0.7969$; groundwater supply, $C = -0.6686$; purchased water supply, $C = -0.5783$; new system, $C = -0.2222$; logged population served, $C = -0.1069$; and then population with bachelor's degree, $C = -0.0099$. The research done by Allaire et al. showed the highest coefficients as lag violations, $C = 1.090$; surface water source, $C = 0.178$; system density, $C = 0.090$; followed by percent non-white, $C = 0.081$. The percentage non-white had a higher coefficient than system size (medium or large) and whether the system private ownership (Allaire et al., 2018). Kirchhoff et al. found the greatest coefficient was the state coefficient, C = 1.2140; followed by groundwater source, C = 1.1350 (Kirchhoff et al., 2019). The most significant factors associated with likelihood of increased nitrate levels (water source and region) were approximately 72 and 63 times greater than the highest socioeconomic relationship (percent Latino).

Section 2.8: Research Gaps

Research in water system violations has taken many different approaches, from the scope of the analysis, the statistical methods, and the source and use of socioeconomic data. Much of the research is devoted to health based or MCL violations only (Allaire et al., 2018; Schaider et al., 2019; Switzer & Teodoro, 2017), or does not include many socioeconomic factors (Kirchhoff et al., 2019; Wallsten & Kosec, 2008; Wren Montgomery et al., 2018). Furthermore, a number of studies used county level socioeconomic data (Allaire et al., 2018; Schaider et al., 2019). Other studies have only reviewed a single state (Marcillo & Krometis, 2019; Rahman et al., 2010; Statman-Weil et al., 2020). A multi-year nationwide study reviewing management violations using city level socioeconomic data has not been completed.

This thesis aims to add additional dimension to the existing research on water system determinants through the addition of a case study to review and further explain the regression analysis and significant independent variables. This thesis incorporates community level data – including rural and urban factors, socioeconomic factors – into a binomial regression analysis and a case study to determine significance of socioeconomic factors on water system management. This study is most similar in form to Switzer and Teodoro's 2017 study, which included a binomial regression analysis of health violations from 2010 to 2013 on national water system data and included city-level ACS data. This study aims to follow a similar path, with a few differences. First, the regression analysis will be performed on management violations (PN and MR). Second, the most recent ACS 5-year estimates, completed in 2019, will be used as the source of socioeconomic determinants. For this analysis, the selection of water systems was limited to small and very small systems. The unit and scope of analysis have a great influence over the results of a regression analysis, and the scope of this analysis was limited to focus the results to these specific systems (Statman-Weil et al., 2020; VanDerslice, 2011). Additionally, system ownership categories were limited to local government, private/public, and Native American. Federal, state, and private ownership categories were excluded from the analysis. The intent is to use socioeconomic data reflective of specific places or communities, and the excluded ownership categories do not have an associated place and thus are not reflective of the socioeconomic data.

Chapter 3: Data and Methods

Section 3.1: Data Sources

This study included information obtained through publicly available databases. Data sources included the EPA Enforcement and Compliance History Online (ECHO) database; the U.S. Census Bureau American Community Survey (ACS) 5-year estimates (2014-2019); and the United States Department of Agriculture (USDA) 2013 Rural – Urban Continuum Classification (RUCC). The EPA and ACS data are available at the community level, while the USDA RUCC data was available at the County level.

Water System characteristic data was obtained from the EPA's database. The following table shows the characteristics included for each system. It is noted that the ECHO data was available by fiscal year (October 1 – September 30), so data was downloaded from October 1, 2014 – September 2020. Data was further refined to include Community Water Systems, generating 52,412 unique PWS systems. System size and population served were taken from the most recent record. City, county, and state identifiers were added to the ECHO records from the EPA records.

Violation data from the ECHO database was processed into four categories: Public Notification & Other Violations (PNO), Monitoring and Reporting Violations (MR), Acute Health Violations (AH), and Health Violations (H). The total number of violations for each system was added to the database, though only MR and PNO violation will be used for the regression analysis. If a system had no violations during the period, values of 0 violations were input.

Table 1: ECHO Water System Characteristics

PWS ID	System Name
State	County
City	Number of years system was active during period
Water Source:	Groundwater, Surface water
Total violations	Public Notification & Other Violations
Monitoring and Reporting Violations	
Acute health violations	Non-acute violations
EPA Region:	Regions 1 - 7
System Size:	Very Small, Small, Medium, Large, Very Large
Owner Type:	Federal, State, Local Government, Native American, Public/Private

The American Community Survey (ACS) is an ongoing survey by the U.S. Department of Commerce to compile population and socioeconomic data for the 10-year period between the U.S. Census. The surveys obtain additional community information not included on the census form. These community characteristics are produced as an estimate for the geography and have an inherent margin of error, 90% confidence intervals are available for the data. Data profiles are provided in the forms of 1-year and 5-year estimates, with the most recent 5-year estimate ending in the year 2019. These profiles include social, economic, housing, and demographic characteristics.

Community characteristics were obtained from the U.S. Census website for the selected characteristics shown in the following table from the 2019 ACS 5-year estimates. Using the Census API, data was queried for individual places: city, town, and village. Income was reclassified into low, middle, and high income compared to the national average. Low income was classified as income less than 2/3 of the national median household income (MHI) from the dataset. High income has an income greater than 150% of the national MHI. Middle income falls between these two limits.

Table 2: 2019 ACS 5-year Estimate Socioeconomic Characteristics

Median Household Income (MHI)	Percentage Asian
Median Age	Percentage Black
Total Population	Percentage White
County Population	Percentage Native American
Percentage with Bachelor's	Percentage Latino
Percentage with Graduate	Percentage Same County
Percentage with High School or equiv.	Percentage Same House
Percentage with less than High School	Percentage Owner Occupied Housing
Percentage Some college	Housing Costs as percentage of monthly income

County-level RUCC data was obtained from the USDA, including classifications for metro and non-metro counties. The classifications are shown in the table below.

Table 3: RUCC Classifications

Metro counties:
Counties in metro areas of 1 million population or more
Counties in metro areas of 250,000 to 1 million population
Counties in metro areas of fewer than 250,000 population
Urban counties:
Urban population of 20,000 or more, adjacent to a metro area
Urban population of 20,000 or more, not adjacent to a metro area
Urban population of 2,500 to 19,999, adjacent to a metro area
Urban population of 2,500 to 19,999, not adjacent to a metro area
Rural Counties:
Completely rural or less than 2,500 urban population, adjacent to a metro area
Completely rural or less than 2,500 urban population, not adjacent to a metro area

Section 3.2: Database Merge & System Selection

The purpose of this research is to determine the community characteristics that influence the management of water systems. For this reason, it was important to precisely link the ACS data to the PWS data. As noted previously, the ECHO database includes the city served, which was used to link the ACS data to the PWS data. Additional city information was supplemented through the SDWIS Federal Reports Advanced Search (EPA, 2017). For PWS systems which included "County" in their system name, SDWA information was not merged to the record, giving priority to link the ACS information by city or village identifiers. The 1,743 systems that did not match ACS data information were discarded.

For this analysis, the selection of water systems was limited to small and very small systems, and system ownership categories were limited to local government, private/public, and Native American.

Section 3.3: Regression Analysis Methods

A negative binomial regression was used to determine the likelihood of a system violation using IBM® SPSS® 27. The analysis used the presence of a PNO or MR violation as the dependent variable and system and socioeconomic factors as the independent variables.

The final model covariates were chosen by a forward step conditional method if they were statistically significant at a level of $p < 0.10$ (Hosmer & Lemeshow, 2000). Outliers were eliminated based on a Z-scores greater than 3.29 or less than -3.29 or a Cook's distance greater than 1 (Tabachnick, 2006). Multicollinearity was reviewed using the table outputs from SPSS®. Correlation categories were determined if the absolute value of the score was as follows: low (0.25-0.50), moderate (0.50-0.75), and high (0.75-1.0).

Various interaction effects were tested during development of the model, including categorical and scale variables. The final interaction effects included in the model were the interaction between race (Asian, Black, American Indian, Latino), MHI (categorized as low, medium, and high), and rurality (reclassified into metro, urban, and rural).

The reference category for state effects was Tennessee, as the mean and median number of violations for the state was nearly the same as the national mean and median. Therefore, comparisons shown for state effects are nearly the same as compared to the national average for PNO and MR violations.

Section 3.4: Case Study Selection

The two case studies were selected based on available data and familiarity with state regulations. For the U.S. case study, two communities were selected from the state of Nebraska, chosen for their proximity to each other and the regression analysis results. One selected community was incorrectly predicted to have a management violation and one was correctly predicted to have a management violation. Information for each community was obtained through the state drinking water watch (DWW) website, including number of wells, number of violations, and number of operational staff. The presence of a wellhead protection program was determined through the Nebraska Department of Environment and Energy (NDEE) website. Water rates and debt levels were obtained through the Nebraska Rural Water Association 2013 water rate publication. Additional information about the community was obtained through the For the Madagascar case study, the Denver professional chapter of Engineers Without Borders (EWB) provided a repository of their documents related to the projects for the two communities.

The case studies were performed by reviewing the regression results and comparing the communities' characteristics to the regression results. Information about the communities not directly related to the regression analysis is used to develop possible reasons for the accuracy or inaccuracy of the regression model.

Chapter 4: Results

Section 4.1: Descriptive Statistics

A total of 12,832 systems were included in the regression analysis. The database included all systems for the period October 2014 to September 2020. Nearly all the systems were active for the entire period (98.2%, n = 12,603). The breakdown of communities by a selection of system factors are shown in the following tables and figures.

Figure 2: System Ownership

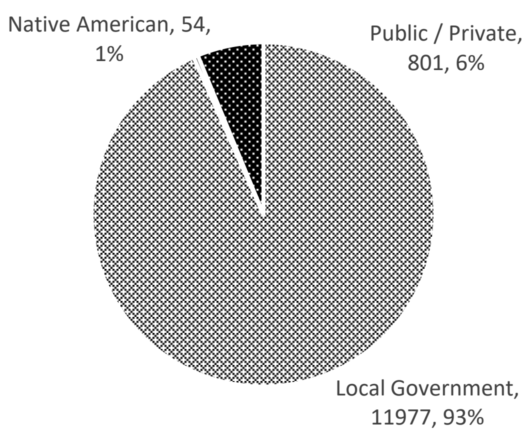


Figure 4: System Size

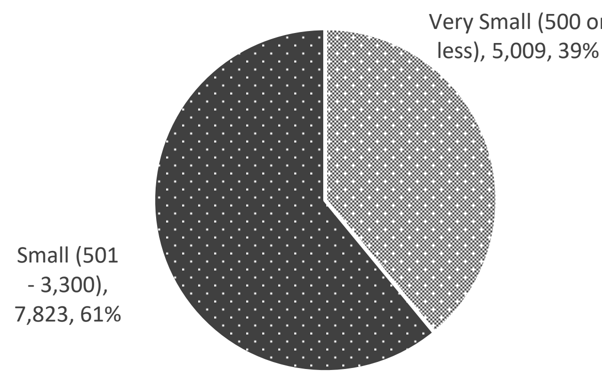


Figure 3: Water Source

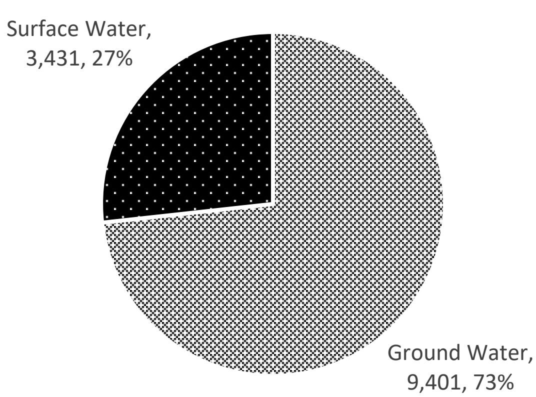


Table 4: System Characteristics

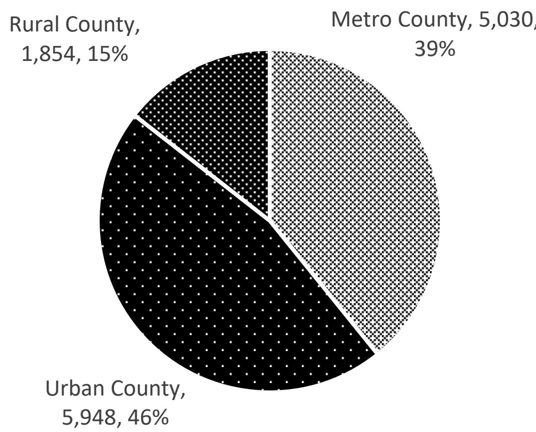
		Number of Systems	Percent of Total
Owner Type	Local Government	11,977	93.3%
	Native American	54	0.4%
	Public / Private	801	6.2%
	Total	12,832	100.0%
System Size	Very Small (500 or less)	5,009	39.0%
	Small (501 - 3,300)	7,823	61.0%
	Total	12,832	100.0%
Water Source	Ground Water	9,401	73.3%
	Surface Water	3,431	26.7%
	Total	12,832	100.0%

As shown, most systems are operated by local government (93.3%, n = 11,977). Slightly less than two-thirds of the systems are classified as small (61.0%, n = 7,823) and the remaining 39.0% (n = 5,009) are very small. Three-quarters of the systems (73.3%, n = 9,401) have groundwater sources.

Table 5: Rural Classifications

	Number of Systems	Percent
Metro County Systems		
Counties in metro areas of 1 million population or more	1,713	13.3%
Counties in metro areas of 250,000 to 1 million population	1,738	13.5%
Counties in metro areas of fewer than 250,000 population	1,579	12.3%
	5,030	39.2%
Urban County Systems		
Urban population of 20,000 or more, adjacent to a metro area	1,150	9.0%
Urban population of 20,000 or more, not adjacent to a metro area	489	3.8%
Urban population of 2,500 to 19,999, adjacent to a metro area	2,568	20.0%
Urban population of 2,500 to 19,999, not adjacent to a metro area	1,741	13.6%
	5,948	46.4%
Rural County Systems		
Completely rural or less than 2,500 urban population, adjacent to a metro area	717	5.6%
Completely rural or less than 2,500 urban population, not adjacent to a metro area	1,137	8.9%
	1,854	14.4%

Figure 5: Metro, Urban, Rural Distribution



Most of the systems are in an urban county (49.2%, n = 5,948) with 39.2% (n = 5,030) located in metro county and 14.4% located in a rural county (n = 1,854). The county classifications fall into either adjacent to a metro area or not adjacent. Most systems were either metro or adjacent to a metro county (69.7%, n = 7,752) while a smaller percentage (30.3%, n = 3,367) were not adjacent to a metro area. For the United States as a whole, the 2010 census reported that 80.7% of the U.S. population lived in urban areas, while 19.3% of the population lived in rural areas (US Census Bureau, 2010).

Table 6: PNO and MR Violation Distribution

Has PNO Violations?	No	9,695	75.6%
	Yes	3,137	24.4%
Has MR Violations?	No	6,638	51.7%
	Yes	6,194	48.3%
Has PNO or MR Violation?	No	5,963	46.5%
	Yes	6,869	53.5%
Has MR and PNO violation?	No	7,738	60.3%
	Yes	5,094	39.7%

Figure 6: PNO Violation Distribution

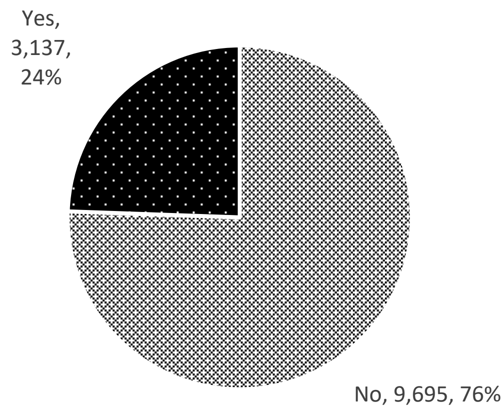


Figure 8: MR or PNO Violation Distribution

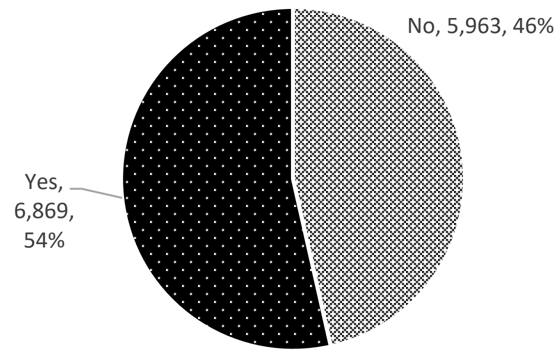


Figure 7: MR Violation Distribution

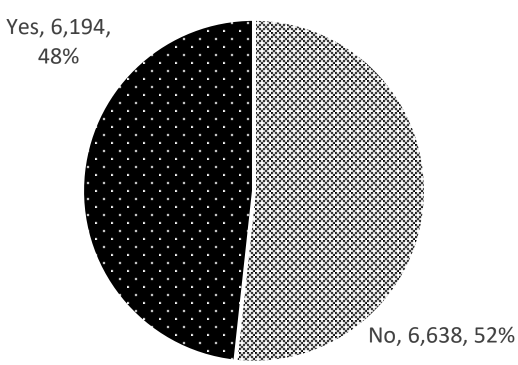
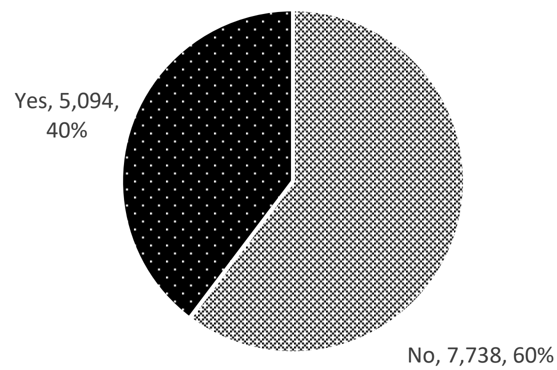


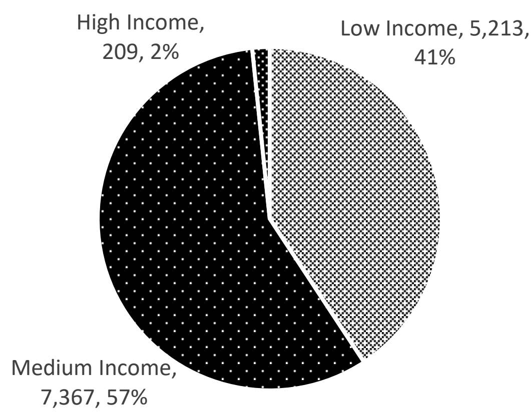
Figure 9: MR and PNO Violation Distribution



One-quarter (24.4%, n = 3,137) of the systems had a PNO violation. Slightly less than half (48.3%, n = 6,194) of systems have an MR violation. The two violation categories comprise just over half of all systems (53.5%, n = 6,869). 675 communities (5.3%) had one or more PNO violations and no monitoring or reporting violations. 39.7% (n = 5,094) of communities with a monitoring and reporting violation also had a PNO violation.

The dataset showed the following characteristics: 40.8% of all systems (n = 5,213) were classified as low-income, 57.6% of all systems (n = 7,367) were classified as middle income) and 1.6% of all systems were classified as high income (n = 209). In the study period, the mean MHI was $65,712. The low-income upper bound is $43,370, and the high income lower bound is $98,568.

Figure 10: Income Distribution



Section 4.2: Regression Analysis

Initial review of correlation coefficients indicate that percent White was highly correlated with percent Asian and percent Black or African. Percent Latino showed moderate correlation with percent Asian and percent Black or African. Percent Black or African showed a high degree of correlation with percent Asian. Percent Latino and percent Black were retained in the model, while percent White and percent Asian were removed from the model. This eliminates the high correlation covariates but does retain a moderate correlation covariate relationship. Low correlation was shown between percent in Poverty, percent home ownership, and percent bachelor's degree. Percent home ownership was removed from the model. Varying degrees of correlation occurred between states; however, this is due to the categorical nature of the covariate. All state effects were included in the model regardless of correlation score.

The model was checked for fit, with the Hosmer and Lemeshow Test resulting in a X^2 score of 2.017 (8 degrees of freedom at $p < 0.05$). It is noted that the Cox and Snell and Nagelkerke R^2 tests were computed at 0.224 and 0.299, respectively. The observed and predicted results and regression coefficients are shown in the following tables.

Table 7: Regression Coefficients

	B	S.E.	Sig.	Exp(B)
Water Source (Groundwater)	-.201	.050	.000	.818
Total Population	.000	.000	.000	1.000
Percent Poverty	.005	.003	.058	1.005
Percent Bachelor's Degree	-.023	.003	.000	.977
Percent In Same County	-.008	.003	.013	.992
Percent Black or African	.004	.002	.027	1.004
Percent Hawaiian Other Pacific Islander by Median Household Income	.000	.000	.000	1.000
Percent Latino * Income Category * Metro / Urban / Rural Category			.006	
Percent Latino (Metro, Medium Income)	-.002	.006	.753	.998
Percent Latino (Rural, Medium Income)	.012	.004	.002	1.012
Percent Latino (Metro, Low Income)	-.002	.006	.793	.998
Percent Latino (Rural, Low Income)	-.004	.002	.118	.996
Constant	.595	.238	.012	1.814

Table 8: Observed & Predicted Results

Observed		Predicted: Has PNO/MR Violation? No	Predicted: Has PNO/MR Violation? Yes	Percentage Correct
Has PNO/MR Violation?	No	3,929	1,988	66.4%
	Yes	1,750	5,036	74.2%
Overall Percentage				70.6%

The regression analysis showed statistically significant results for state effects. The listing of the statistically significant ($p < 0.05$) state effects are shown as odds ratios (OR) in the following table. The states most likely to have systems with PNO or MR violations were Alaska, West Virginia, Arizona, and New Mexico. Each of these states had more than 10 times the national average of PNO / MR violations. The states that were the least likely to have a PNO or MR violation were Mississippi, Minnesota, Alabama, South Carolina, Iowa, Nebraska, South Dakota, Illinois, and Virginia. Each of these states had an odds ratio less than 0.5. During the preliminary model runs, it was determined that state effects increased the model accuracy by more than 10 percentage points, from 59.8% to 70.5%.

Table 9: State Effects

State	**OR**	**State**	**OR**	**State**	**OR**	**State**	**OR**
MS	0.174	IL	0.469	KS	2.592	TX	4.422
MN	0.248	VA	0.494	OR	2.609	PA	7.157
AL	0.298	GA	1.588	ID	2.766	OK	7.2
SC	0.305	OH	1.96	CO	3.397	CT	8.28
IA	0.393	NC	2.211	VT	3.849	NM	13.173
NE	0.400	MT	2.402	LA	3.851	AZ	14.947
SD	0.429	FL	2.495	KY	4.349	WV	27.738
						AK	76.345

Section 4.3: Case Study

The Nebraska communities selected for the case study are both located in western Nebraska and withdraw water from the Ogallala Aquifer. Both systems are in Sheridan County, NE, approximately 15 miles apart. The two communities' socioeconomic and water system characteristics are shown in the tables below.

Table 10: Community Characteristics

Characteristic	Coefficient	Rushville	Gordon	Dataset Mean
Total Population	0	807	1,733	1,263
Percent Black	1.004	0.3%	4.5%	9.0%
Percent Latino	Varies by Category	24.4%	3.2%	10.1%
MHI Category		$34,083 (Low)	$40,000 (Low)	$49,200 (57.7% are Middle)
Percent Bachelor's	0.977	9.1%	18.3%	12.5%
Percent Poverty	1.005	24.2%	23.5%	17.0%
Percent Same County House	0.992	15.2%	9.3%	8.21%
Predicted Likelihood of PNO/MR Violation	-	0.574	0.599	0.533

Table 11: Water System Characteristics

Characteristic	Rushville	Gordon
PNOMR Violations	2	0
Total Health Violations	4	8
PNOMR Violations (1999-2019)	8	0
Health Violations (1999-2019)	8	8
Water Source	Ground Water	Ground Water
# of Active Wells	2	6
Year Last Well Constructed	2011	2003
Site Visit Deficiencies Found (Corrected)	17 (17)	27 (27)

Rushville is the smaller of the two communities, with about one-half of the population of Gordon. The Nebraska Department of Health and Human Services (NeDHHS) Drinking Water Watch (DWW) lists 3 water operators, 1 clerk/treasurer, and a mayor for Rushville, a total of 5 staff. The DWW lists 3 water operators, one 1 clerk, the mayor, a city manager/administrator, and public works director (who is also a water operator), for a total of 6 staff. Both city councils consist of four members and a mayor. The two communities share a school district, with elementary schools located in both cities, and the high school and middle school located in Gordon. The website for Gordon appears to be more updated than the Rushville city website. Water bill pay, council agendas and minutes, city ordinances, and public notifications are posted and available on the Gordon website.

During the study period, Gordon did not have a PNO or MR violation, while Rushville had 2. Gordon had 8 health violations, while Rushville had 4. In review of the DWW violation data, Rushville had 16 violations. 8 of these violations were health-based violations, primarily Total Coliforms. Total Coliform violations are common for the State of Nebraska, as many systems provide untreated, unchlorinated groundwater to their consumers. From 1999-2019, Rushville had 5 monitoring violations, 1 public notification violation, and 2 Consumer Confidence Reporting (CCR) violations. The City of Gordon did not have any PNO or MR violations during the same period but had 7 total coliform violations and 1 E. Coli violation.

The residential water rates for Rushville include a base rate of $22.00 per month and $2.00 per 1,000 gallons (after the first 1,600 gallons included with the base rate). The residential water rates for Gordon include a base rate of $24.50 per month and $1.60 per 1,000 gallons. The debt service was listed as $189,000 for Gordon. No outstanding debts were noted for Rushville.

The Madagascar communities are in the Fianarantsoa Province of Madagascar. The available community characteristics are shown in the following table.

Table 12: Community Characteristics

	Ambalona	Anosimparihy
Total Population	800	1,858
Economy	Subsistence Farming	Agriculture
Community Features	Primary school	Primary and Middle School small medical clinic
Government Structure	Elder council	Gov’t appointed mayor
Electricity	No	No

The Denver Professional Chapter of Engineers Without Borders (EWB) were involved in water projects within these two communities. The projects were completed in partnership with the communities, a local non-government organization (NGO), and the Centennial Colorado Rotary Club. Beginning in 2008, 6 hand pump wells of various designs were constructed in Ambalona over the course of 6 trips. After the initial assessment trip in 2015, two wells with hand pumps were constructed in 2016. Two pumps in Ambalona were damaged during a fire in 2016, approximately 1 month after their installation. The two pumps in Anosimparihy have fallen into disrepair and are no longer in use. The local NGO has dissolved. The Anosimparihy wells are not in service, and it is likely that the Ambalona wells are not in service either. There were some technical challenges regarding the implementation of the wells, including silty clay soils in Ambalona, and Anosimparihy's location on top of a local ridge.

For both communities, the project was implemented using groundwater as a primary source of drinking water. Prior to the construction of the wells, Ambalona used surface water and seeps (springs) as the drinking water sources, both of which were susceptible to contamination. Anosimparihy relied on a hand dug well (occasionally dry) and the Ranomafana River as sources of drinking water. In addition, chlorination drops were readily available within Anosimparihy for treatment of water.

Anosimparihy appears to have a slightly higher per household income than Ambalona. While Ambalona relies primarily on subsistence farming of rice, Anosimparihy grows cash crops such as bananas, coffee, and lychee in addition to rice. Income for both communities is estimated at less than USD$1 per day.

Education level within each community is unknown. A school was established in Ambalona by the NGO and was complete and operation in 2015. A school is present in Anosimparihy as well. In addition to the school, Anosimparihy has a small medical clinic, suggesting a higher level of education within the community. Ambalona had a blacksmith (trained by the NGO) who was able to perform some repairs on the well pump.

Exact diversity demographics are not available for the communities. Anecdotally, the community within Anosimparihy is more transient than the Ambalona community, due to the proximity of the community to the highway.

During the assessment and implementation trips, a water committee was established in each community. This committee was to be responsible for maintenance of the wells and pumps, and to collect water fees for this maintenance. It is understood that just one meeting occurred with the Anosimparihy water committee, while a few meetings occurred with the Ambalona committee, primarily due to the timing and number of trips to each community. Despite the economic differences, the Ambalona water committee established a fee of 1,000 Ariary per month (USD$ 0.26). The nominal fee in Anosimparihy was established at 500 Ariary per month (USD$ 0.13).

Chapter 5: Discussion

Section 5.1: Descriptive Statistics

The number of systems included in the dataset is lower than previous studies, which is to be expected. The smaller sample size excluded medium, large, and very large systems from the analysis in addition to government, private, and state-owned systems. The focused section of systems is expected to provide precise results for small and very small community water systems.

The number of rural communities in the data set is slightly smaller than the U.S. (14.4% versus 19.3%). This difference is likely due to the urban and rural classification happening at a county level, rather than the city level. This may also be due to the exclusion of county and rural water systems from the analysis.

Most communities had either an PNO or MR violation during the study period, with just over half of the communities committing a management violation. The slight favoring of the data toward having a violation is important when considering the accuracy of the model. It would be expected that the model would skew towards positive results (i.e., having a violation).

Section 5.2: Regression Analysis

The model showed an overall accuracy of 70.5%: 66.3% correct (n = 3,924) for no violations and 74.1% (n = 5,030) for having violations. 53.5% of the systems had a violation during the study period, thus the data model would show a skew towards having violations. Prior to the inclusion of state effects, the model only had a 59.8% accuracy, only 6.3 percentage points higher than the dataset mean. Given the low percentage accuracy (not including state effects), it is believed that socioeconomic effects (not including system factors such as water source, system size, etc.) are correlated with water system violations, but are not a cause of violations. The more important factor is what state the system is in, for geographic and regulatory reasons. Each individual state is responsible for the monitoring and enforcement of EPA regulations. As each state implements the EPA regulations, the staff, policies, and programs will have an effect on the number of violations issued within each state in addition to local climate, geography, and weather effects (Kirchhoff et al., 2019). The differences in state regulation include limited funds and staffing, violation response (formal, informal, no action), and methods of enforcement targeting (Kirchhoff et al., 2019). Table 9: State Effects shows the way in which the state regulates water systems has a significant impact on the number of water system violations. Depending on which state the community is in, the likelihood of having a violation ranges 6 times less likely to 76 time more likely than the reference category. This is consistent with prior research which emphasizes the role that states play in regulation and enforcement of water systems (Oxenford & Barrett, 2016).

The model showed a significant decrease in PNO/MR violations for groundwater systems compared to surface water systems. The model showed the odds of a surface water system having a PNO/MR violation compared to a groundwater system are 1.22:1. These results are in concurrence with prior research. This would indicate that the operational complexity of a treatment system (i.e., surface water treatment) does not positively contribute to a system’s ability to adequately notify the public, monitor, and report. It may be expected that a more sophisticated level of treatment technology (such as is typically present in a surface water treatment system), would increase the understanding and compliance with state and federal requirements, but that does not appear to be the case. This difference may also be due to increased violation potential – multiple PNO/MR violations may be handed down for missing a single set of samples.

For small and very small communities, Black/African populations are more likely to receive water from a system with PNO/MR violations. A slight positive increase in violations (OR = 1.004) was associate with a one-percentage increase in African American Population. Through infrastructure disparities, rate affordability, and segregation of services, the black community has been historically oppressed regarding water access and services (Montag, 2019). This is evident from the correlation between PNO/MR violations and black-African populations.

The analysis showed statistically significant effects for middle income, rural Latino people compared to the reference category (high-income, urban areas). A positive correlation was found for rural, middle income Latino populations (OR = 1.012). No other categories showed statistically significant correlations.

One education factor was found to be statistically significant: percent bachelor’s degree. This factor showed a decrease in violations with increase in percentage, OR = 0.977. This is consistent with prior research which showed a decrease with percent bachelor’s (Switzer & Teodoro, 2017).

The relationship between income and management violations varies by definition and depending on the interaction effects applied. Percent unemployment and median household income were found to be statistically insignificant stand-alone covariates for the analysis. An increase in violations was correlated with percent poverty (OR = 1.005). The MHI category was only significant when associated with race and rurality, as discussed previously. The association of increased violations correlating with percent in poverty is concerning, as the average water bill for 1 in 8 (or 11.9 percent) of households nationwide exceeds the EPA's recommended affordability threshold of 4.5% of MHI (Mack & Wrase, 2017). Research suggests that correlations with income and poverty are the result of poor environmental conditions (Drabo, 2011; Johnson & Bullard, 2000). This includes water source quality, and distance to water source. The decreased quality of groundwater, for example, may increase the level of nitrates within a system (Schaider et al., 2019) or distance to gather water may affect women in developing countries (Evans & Kantrowitz, 2002).

A statistically significant correlation was found between number of violations and the percent of the population that lived in the same county as the previous year, showing a decrease in violations (OR = 0.992). It is noted that this factor measures the number of people who moved to a new residence within the same county that they previously lived in. It is not entirely a measurement of population transiency or stability, but a measure of those who moved within the county due to job, house, education, or other reasons. It is not able to be determined if this movement was desirable or undesirable. The negative correlation to MR violations suggests that when a greater number of people move to a community the management of the system benefits.

Section 5.3: Case Study

From the available data, it is not entirely clear what are the differences between the two communities and what are the drivers for compliance with PNO and MR regulations. The two US communities socioeconomic and water system characteristics result in nearly the same likelihood of violation despite significant variation in the socioeconomic characteristics. The systems have a similar percentage of the population in poverty, but vary regarding education, Black and Latino populations, and percent living in the same county. None of these socioeconomic conditions appeared to play a large role in the management of the system. Population may have a role to play, as larger populations will require a more robust civil government to communicate and collect water bills as demonstrated through Gordon's more robust city website. It appears that education and experienced staff will play a role in compliance with regulations, given the lack of violations in Rushville after 2013.

Both communities share similar poverty rates and have the same MHI category (low) but have widely varying socioeconomic characteristics. Gordon has approximately 4.5% of the population with Black or African ethnicity, while Rushville has approximately 0.25%. This percentage increases the predicted likelihood that Gordon has a violation compared to Rushville. The Latino population in Rushville comprises 24.41% of the residents, while in Gordon the percentage is only 3.23%. The regression analysis only showed statistically significant effects for Latino population within rural, medium MHI communities. The effect lowers the predicted score for Rushville. Gordon has a higher percent with bachelor's degree (18.38% versus 9.12%), which decreases the likelihood of a violation. Rushville has a higher percentage of the population that lived in the same county the year prior (15.23% versus 9.25%), which decreases the likelihood of a violation.

While the predicted violation score was nearly the same, Rushville had a violation during the study period while Gordon did not. The city of Gordon did, however, have twice as many total health violations as Rushville (8 compared to 4). In review of the historical violations since 1999, the likelihood of increased violations for Rushville is confirmed. However, it appears that since 2013, significant operational improvements within Rushville have been made to avoid non-compliance and to improve monitoring and reporting.

Without understanding the water usage in each community, it is difficult to determine if the overall water rates have an impact on the management of the system. Water rates for a community are generally set to cover system expenses including capital projects, maintenance and operational costs, and staff salaries. It appears the water rates are very similar, though the overall rate for Gordon may be higher than Rushville. This could be due to existing debt service for the Gordon water system.

Data sources are important when performing a nationwide study. It is noted that Rushville had no violations listed on the state DWW website from 2013 to present, which conflicts with the information in the EPA SDWIS database. Reviewing a longer period of violation data may be helpful in determining and reviewing compliance with PNO and MR violations.

In a review of the members of the committee, the EWB was not able to determine the capability of the Anosimparihy committee to carry out the requirements of the committee. It is thought that the Anosimparihy committee was interested in established a closer source of water, as the safety of the water was improved using chlorination drops. However, in Ambalona, the people forming the committee had a vested interest in maintaining the wells, as no other satisfactory source of water was available. This is confirmed through the establishment of higher fees within Ambalona, despite the community having a lower income.

The application of the case study adds a few dimensions to the regression parameters. The water source variable should be expanded to include available treatment technologies, such as chlorine drops. The presence of treatment may have reduced the incentive for Anosimparihy residents to pay for and maintain the community drinking water system. Further investigation into the community characteristics is recommended to see who is affected by this choice. It is proposed that the socioeconomically disadvantaged (those who cannot afford the chlorine drops) are most affected by the community's lack of adequate water system management. In addition to primary school education, the presence of trained laborers may improve the ability of a community to manage their water system. The local NGO trained a blacksmith how to fix the well pumps. This person's skills were used to repair the pumps after the fire. The diversity component (Black or African or Latino) factor is unable to be commented on, as detailed breakdowns of ethnic status were unknown for these communities.

Chapter 6: Conclusions & Further Research

Drinking water system management is a complex, multi-faceted operation. The challenges associated with adequate monitoring, reporting, and public notification are numerous. This study has sought to understand specific socioeconomic factors and their correlation with water system management. Developing a framework through regression analysis serves as a backdrop for evaluating the socioeconomic factors and communities affected by poor water system management. The analysis presented in this thesis found that state regulation of water systems has a significant effect on the number of PNO and MR violations, in addition to water source. The primary communities effected by poor water system management are medium income rural Latino communities, communities with high Black or African populations, and communities with increased levels of poverty. Communities with increased percent with a bachelor's degree show fewer violations, as do communities with population migration to the community from the surrounding county.

After accounting for state-level effects, the analysis showed statistically significant effects for socioeconomic factors that are less significant in the model than system and state factors. This is consistent with prior research (Allaire et al., 2018; Balazs et al., 2011; Switzer & Teodoro, 2017). This indicates that while certain communities (medium income, rural Latino; Black or African; communities in poverty) are disproportionally affected by poor water system management, these socioeconomic factors are not the cause of poor management.

Due to historical inequalities, under-represented persons are disproportionally affected when a system is managed poorly. Thus, it is important for decision making authorities at the system, state, and federal levels to use their position of authority to provide equitable water access for all people. On an international front, a similar thought prevails. In the community of Anosimparihy, a well project failed, possibly due to the ability for persons to use chlorine drops to disinfect and treat water. It would be expected that the poor within the community that cannot afford the drops would be left without an adequate water source when the well was not maintained. Persons from all sections of society should be brought to the decision-making table to ensure adequate representation. Water system data and socioeconomic data are readily available for the United States, giving an opportunity to research these socioeconomic determinants. In many developing countries, however, water system data is not as readily available.

The analysis presents several areas for research and additional study. In particular, the makeup, longevity, and demographics of elected city officials and water system management staff may be of interest. The operational staff's experience, training, and longevity may also be of interest when determining a system's ability to comply with state and federal requirements. Additional research areas include a review of state management frameworks to determine what enforcement and regulatory frameworks are shared between states with high PNO/MR violations and those with lower PNO/MR violations. Lastly, there are numerous independent variables not included in this analysis that should be considered in future research: if a federally funded or state funded project was recently completed, availability and prevalence of operator training programs, community civic engagement, and water rates.

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