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Factors Associated with Public Water Supply Unreliability

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Abstract: Public water supply unreliability is a problem that causes human hardships and remains common in the United States. In this paper, we attempt to examine the factors associated with public water supply unreliability. We measure public water service unreliability by the issuance of boil water notices (BWNs). By using a Negative Binomial regression model and data from West Virginia community water systems in 2020, we find that water systems that purchase their water from other water systems, have more educated and experienced operators, and serve high-income areas and a higher percentage of Native residents are expected to issue more BWNs. On the other hand, water systems that are small and serve a higher percentage of rural, educated, employed residents are expected to issue fewer BWNs. The findings emphasize the need to move beyond simplistic assumptions about water system reliability and consider the combined influence of technical, socio-economic, and demographic factors.

Keywords: boil water notices; negative binomial regression; water management; water service disruptions; water supply unreliability

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1. Introduction

Access to a reliable public water supply is important for human health and well-being. Public water service is reliable if it is provided in time and with the quality and the quantity required by the user. Although the United States (US) public water supply is generally considered safe and reliable, it has still confronted challenges that have resulted in disparity in the level of service provided to water customers across the country. Such challenges include aging infrastructure, limited financial and human resources, impaired water sources, and high environmental quality expectations. For example, recent studies have shown that many public water systems (PWSs) struggle to provide a reliable water service to millions of water customers in many parts of the U.S. [1–3].

Investigating the factors affecting the performance of PWSs and the disparity in water service reliability has been a topic of interest in various fields, such as economics, public health, and environmental justice. However, previous research on the determinants of water supply unreliability has only focused on the water quality component, where researchers mainly used Safe Drinking Water Act (SDWA) violations as a proxy for unreliability [4]. In this study, we examine the factors affecting public water supply unreliability by using a new way to measure service reliability that combines both water quality and quantity. This measure is the number of boil water notices (BWNs) issued by PWSs, which can be used as an indicator of problems in public water supply.

In the U.S., a BWN is a tool used by PWSs or local (county) health departments to communicate health and environmental risks related to drinking water to customers. It acts as a precautionary measure that is issued as a response to the identification or suspicion of the presence of microbial contaminants within the water distribution system. Most of the BWNs are issued due to water main breaks that often result in disruption in water service for many customers [5]. BWNs can be communicated by using different methods, including local news outlets, radio, newspapers, or door tags. They instruct water customers to boil all water used for three to five minutes before drinking, cooking, preparing food, brushing teeth, and making ice. Public water supply issues related to BWNs are generally considered short-term problems, but in rare cases, they can last for years [6].

Public water service disruptions related to BWNs can result in significant health and economic costs for residents, businesses, and communities [7,8]. For example, areas that experienced more BWNs were found to have lower residential property prices, higher bottled water sales, lower student achievement, and a higher number of emergency room and urgent care visits [9–12]. Therefore, the identification of predictive variables for BWN occurrences is important, since such information can be used to improve our understanding of human health risk, exposure, and management, as well as risk communication and perception among stakeholders.

The rest of this article is organized as follows: The next section reviews the literature on the determinants of water supply unreliability, where we focus on studies that used SDWA violations as a measure of public water supply unreliability. Then, we describe the materials and methods used in this study, where we provide information on the study area, data, and statistical methods used in the study. After that, the results are presented and discussed. Finally, the article ends with conclusions.

2. Literature Review

The unreliability of water supply is a very real problem in large parts of the world, developed and developing alike. The problem is multifactorial or multifaceted, and it comes from a multitude of sources [13,14]. It can take the form of insufficient water supply, infrastructure failures (pipe ruptures, pump failures, and transformer failures), equipment failures, leaky pipes, pressure management, operational problems, water quality problems, and contamination. Some studies have focused on the factors that contribute to unreliability in public water systems. These factors could be grouped into technical, financial, administrative, environmental, demographic, cultural, social, economic, and political factors.

Many water systems use old pipes and facilities that are more likely to fail [6,15]. Poorly designed or constructed infrastructure can result in more failures and water quality issues [16]. The size of the system is a major determinant of unreliability, generally with interruptions being more profound and frequent in smaller systems compared with larger systems [1,17]. Pressure management within water distribution networks is a critical aspect of their operation and maintenance, posing a significant challenge, particularly in the context of large and intricate systems [18].

Underinvestment and insufficient funding for maintenance exacerbate infrastructure problems, increasing the risk of unreliability [9,19]. Inefficient management practices and shortages of qualified water system operators increase the risk of operational blunders and inadequate monitoring, generating more problems and thus increasing the risk of unreliability [20]. Highly institutionalized and fragmented governance structures can undermine water management, generating more problems and risking reliability [21].

Climate change and associated extreme weather events can disrupt water availability and increase contamination, increasing the risk of unreliability [22]. Different water sources generate different bases of vulnerability to contamination and other problems, potentially increasing the risk of unreliability [13,23]. Surface water sources are generally more vulnerable to contamination [6,23], while groundwater sources tend to be more stable and reliable [6,13]. Source water protection is important for maintaining water quality, reducing treatment costs, and ensuring public water supply reliability [24].

The geographic location influences water supply unreliability, with remote and rural communities often facing more difficulties in maintaining reliable water supply due to logistical constraints [17,25]. Disclosure of information to the public and consumers' awareness could be used as important tools to maintain the reliability of public water supply [26,27]. Socioeconomic factors can play a role in the reliability, or lack thereof, of public water systems [28,29]. Environmental justice issues are connected to unreliable public water supply, as low-income, racial, ethnic minority, BIPOC (Black, Indigenous, and People of Color), and First Nations communities often bear a disproportionate burden of water insecurity [13,20,27,30–33]. The entity responsible for operating the water system (e.g., local government or utility) is a key factor influencing water supply unreliability [17].

3. Materials and Methods

3.1. Study Area

The study area for this research encompasses the state of West Virginia, which is located among the Appalachian Mountains in the eastern part of the United States. West Virginia was selected as the study area because it is one of a few states that have publicly available BWN data. There are 55 counties in West Virginia, comprising 401 places, 232 incorporated places (77 cities, 148 towns, 6 villages, and 1 corporation), and 169 census-designated places (CDPs) [34]. Charleston is the capital and most populous city in West Virginia. Figure 1 shows a map of West Virginia and its largest cities in terms of population. According to the U.S. Census Bureau [35], the total population in West Virginia was about 1.8 million, and mostly white (93%). In the same year, per capita income was USD 31,462, and 18% of the population were living under the poverty threshold.

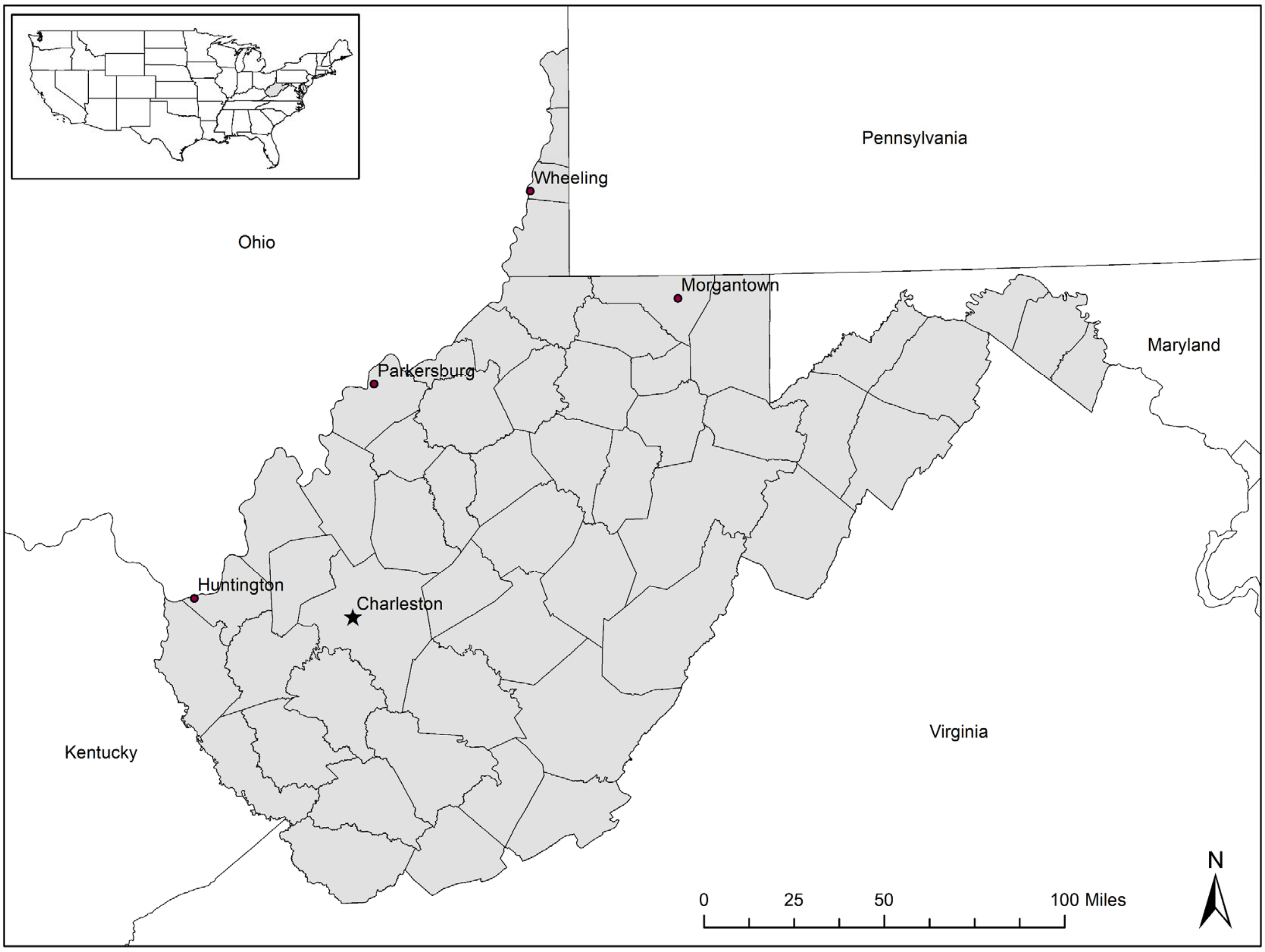

Figure 1. A map of the State of West Virginia.

The state has 417 community water systems serving about 1.53 million people (85% of the state's population) [36]. The remaining 250,000 people are served by private water systems (i.e., wells, cisterns, or springs) [37]. In 2023, the State of West Virginia ranked 31st in terms of the average number of Safe Drinking Water Act (SDWA) violations per community water system [38]. The West Virginia Infrastructure and Jobs Development

Council [39] has estimated current and future funding needs for water and sewer infrastructure in West Virginia to be about USD 2.3 billion and USD 13.9 billion, respectively. However, only about 9% of the current funding needs have been committed. Finally, about 4% of West Virginia's population are being served by inadequate water systems in terms of technical, managerial, and financial capabilities [37].

3.2. Data

We relied on four sources of data. The first one was the West Virginia Office of Environmental Health Services (OEHS) data portal for information about BWNs [40]. The second and third ones were the West Virginia Drinking Water Viewer (DWV) and the Environmental Protection Agency's Safe Drinking Water Act Information System (SDWIS) for information about water systems [36,41]. The fourth one was the U.S. Census American Community Survey (ACS) for socio-economic and demographic information on the served areas [42]. All these data were collected for the year 2020 for all active community water systems (CWSs) that served residential areas in West Virginia (388 CWSs). We provide a brief description of the data and variables included in the analysis of this study.

3.2.1. Boil Water Notices

We measure water supply unreliability by using the number of BWNs issued by public water systems. The OEHS data portal provides information on all BWNs in West Virginia. For each notice, the provided information includes the public water system identification code (PWSID); the system name; the public health sanitation district where the notice was issued (there are five districts in West Virginia); the county name; the dates when the BWN was issued and lifted; reasons for the notice; and details about the BWN, which usually include the affected areas or street names and number of customers affected. We collected all the BWNs issued between 1 January and 31 December in 2020 (1897 BWNs) and linked them to their respective water system to obtain CWS count of BWNs.

3.2.2. Water System Characteristics

Water system characteristics play an important role in public water supply reliability. We attempted to control for such characteristics by using different variables from the DWV and SDWIS datasets, including water source type, availability of water source protection, size, certification level of water system's operator, ownership type, water system's age, and number of facilities. These variables were obtained for each CWS and linked to the BWN dataset by using the PWSIDs.

3.2.3. Socio-Economic and Demographic Characteristics

Socio-economic and demographic characteristics of the served area can influence public water supply reliability. We controlled for these characteristics by using census data at the county level where the CWS provides its services. For socio-economic characteristics, we included per capita income, employment, and education. For demographic characteristics, we included the percentage of residents living in rural areas, and the percentage of Black, Native, and Hispanic residents.

3.2.4. Descriptive Statistics

Table 1 shows the descriptive statistics for the variables considered in the analysis. The average number of BWNs a CWS in West Virginia issued in 2020 was about five BWNs. The maximum number of BWNs was 676. In addition, Figure 2 shows the distribution of BWNs across West Virginia's counties.

Table 1. Summary statistics—data at community water system (CWS) level.

Variable	Description	Mean	Std. Dev.	Min	Max
Boil Water Notice Variables (Dependent Variables)					
BWNs	Number of boil water advisories issued	4.89	37.38	0	676
BWN Event	1 = if CWS issued a BWN, 0 = otherwise	0.40	0.49	0	1
Water System Characteristics					
Age	Age of the system based on the activity starting date	44.16	18.14	1	85
Groundwater	1 = if the CWS uses groundwater as a primary water source, 0 = otherwise	0.33	0.47	0	1
Purchased	1 = if the CWS uses purchased water as a primary water source, 0 = otherwise	0.47	0.50	0	1
Protection	1 = if CWS source water is protected, 0 = otherwise	0.57	0.50	0	1
Operator	The certification category of the CWS operator (1 = less experienced; 5 = most experienced)	1.99	1.08	1	5
Facilities	Total number of facilities related to the CWS	11.95	16.87	2	295
Small	1 = if the CWS serves less than or equal to 500 people, 0 = otherwise	0.25	0.43	0	1
Private	1 = if the CWS is owned privately, 0 = otherwise	0.18	0.39	0	1
Socio-Economic and Demographic Characteristics					
Income	Per capita income (USD 2020 inflation-adjusted)	25,432.65	4274.99	15,150	36,722
Education	Percent of the population 25 years and over with a bachelor's degree or higher	17.62	6.58	6.8	43.7
Employed	Percent of population 16 years and older who are employed	47.18	8.36	24.4	62.5
Rural	Percent of population living in rural areas	71.57	26.79	22.03	100
Black	Percent of Black or African American population	9.04	4.61	3.49	20.90
Native	Percent of Native American population	0.17	0.05	0.06	0.36
Hispanic	Percent of Hispanic or Latino population	1.64	1.28	0.42	7.17
Observations = 388					

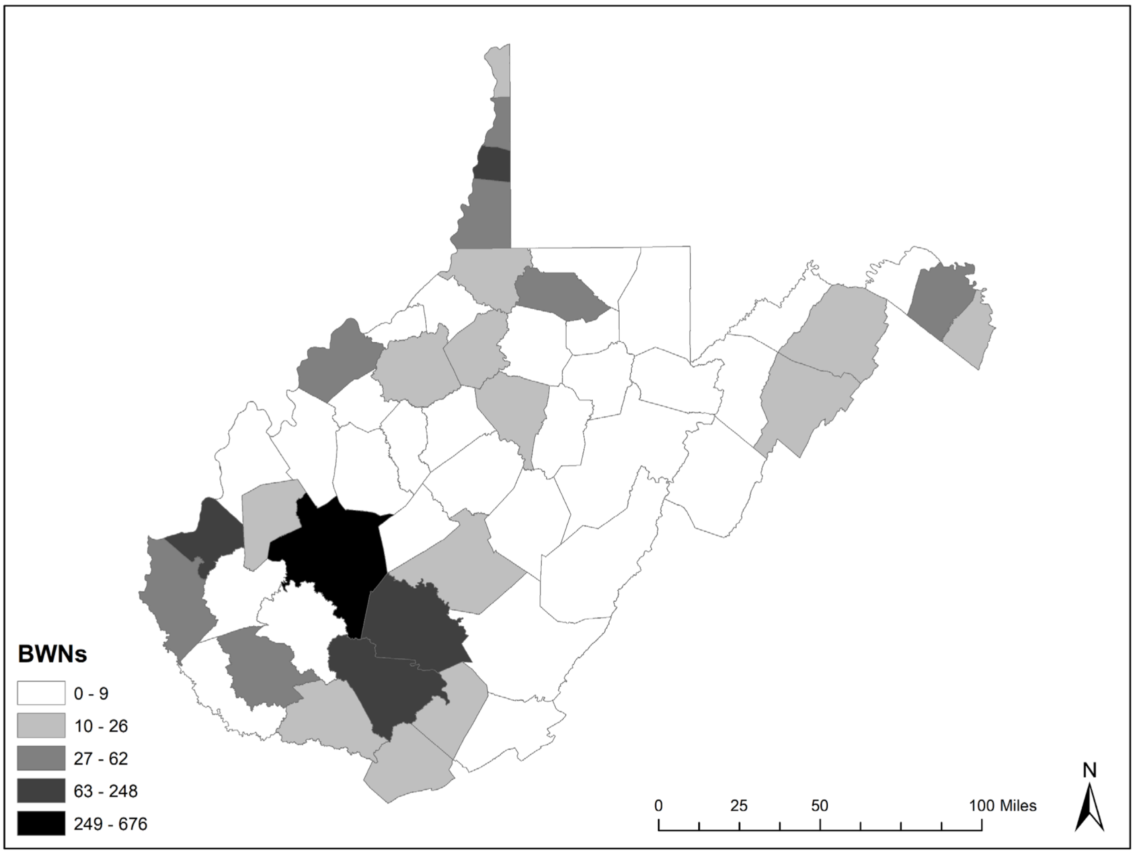

Figure 2. Total number of boil water advisories (BWNs) in West Virginia's counties in 2020.

Table 2 shows the frequencies of the observed BWN numbers. Of particular concern for the empirical analysis is the high number of observations where CWSs reported no BWNs. In our data, 60% of observations have no BWNs. A high number of observations with zero events may require an appropriate empirical methodology. Therefore, we investigate this issue further in the next section.

Table 2. Observed frequency of the community water systems' boil water notices in 2020.

Observed Counts (BWNs)	Frequency	Percent
0	232	59.79
1	55	14.18
2	36	9.28
3	14	3.61
4	5	1.29
5+	46	11.90
Total	388	100

3.3. Methods

We used count data regression techniques because our dependent variable was the number of BWNs a CWS issued in a year. That is, the dependent variable is a non-negative integer, with most of the data being concentrated on a few small discrete values, as shown in Table 2. In such contexts, count data models (sometimes called models of event counts) are widely used [43]. There are different variants of count data regression models, where each has its own assumptions. The most popular one is the Poisson regression model. However, one disadvantage of the Poisson model is that it assumes that the mean and the variance are both equal (equidispersion property). According to the results of the likelihood ratio test, which examines the null hypothesis that the overdispersion parameter is statistically significantly different from zero, this assumption was not met in our data (LR =1083.08, p-value = 0.000). In such cases, results from the Poisson regression can be inefficient, and Negative Binomial regression models are commonly used instead [28,30,44,45].

A complication may arise when the dependent variable has an excessive number of zero observations. Such data may not be well represented by the Negative Binomial distribution because there are many observations with zeros in the dependent variable, which are not part of the Negative Binomial distribution and instead are subject to a different data-generating process. In such cases, one option is to use the Zero-Inflated Negative Binomial model. Zero inflation is a concern in our context, because 60% of the observations have zero values (see Table 2). However, the bias-corrected Vuong test with BIC correction is -5.01 (p-value = 0.000), indicating that the Negative Binomial regression model is the most appropriate model for our data [46]. Therefore, we stick with the Negative Binomial regression model. Figure 3 shows a flowchart for selecting the appropriate count regression model.

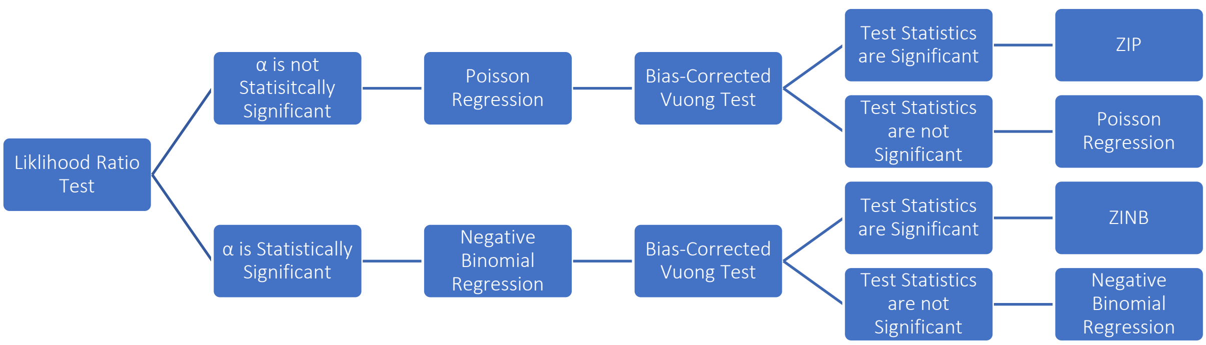

Figure 3. Flowchart for selecting a count regression model (ZIP = Zero-Inflated Poisson Regression; ZINB = Zero-Inflated Negative Binomial Regression).

As a robustness check, we also include a logistic regression. In this regression, we examine the influence of water system, socio-economic, and demographic variables on the probability that a CWS issues at least one BWN.

4. Results

Table 3 shows the results from the Negative Binomial regression models, which estimate the relationship between the frequencies of BWNs and the independent variables. Three models are provided with marginal effects to facilitate interpretations. The first model includes only water system variables, the second adds the socio-economic and demographic variables, and the third includes all variables plus interactions terms of income and demographic variables.

Table 3. Negative Binomial regression results (dependent variable: BWNs).

	Model (1) Coefficients	Model (1) Marginal Effects	Model (2) Coefficients	Model (2) Marginal Effects	Model (3) Coefficients	Model (3) Marginal Effects
Age	0.007	0.008	0.001	0.001	0.001	0.001
	(0.006)	(0.008)	(0.006)	(0.007)	(0.006)	(0.006)
Groundwater	0.376	0.461	−0.046	−0.051	0.047	0.051
	(0.246)	(0.294)	(0.248)	(0.279)	(0.243)	(0.259)
Purchased	1.478 ***	1.814 ***	1.161 ***	1.302 ***	1.053 **	1.125 **
	(0.440)	(0.552)	(0.448)	(0.506)	(0.455)	(0.487)
Protection	−0.038	−0.047	0.127	0.143	0.093	0.100
	(0.215)	(0.264)	(0.208)	(0.233)	(0.208)	(0.222)
Operator	0.859 ***	1.054 ***	0.829 ***	0.929 ***	0.808 ***	0.863 ***
	(0.235)	(0.291)	(0.241)	(0.274)	(0.239)	(0.263)
Facilities	0.043 *	0.052 *	0.032	0.035	0.034	0.036
	(0.023)	(0.030)	(0.025)	(0.028)	(0.025)	(0.028)
Small	−1.278 ***	−1.568 ***	−1.200 ***	−1.346 ***	−1.171 ***	−1.251 ***
	(0.375)	(0.426)	(0.376)	(0.397)	(0.359)	(0.368)
Private	0.225	0.276	0.221	0.247	0.246	0.262
	(0.262)	(0.318)	(0.271)	(0.302)	(0.268)	(0.284)
Ln (Income)			4.222 **	4.736 **	10.818 **	11.560 ***
			(1.657)	(1.867)	(4.299)	(4.405)
Education			−0.063 *	−0.071**	−0.092 **	−0.098 **
			(0.033)	(0.037)	(0.038)	(0.039)
Employed			−0.074 **	−0.083 **	−0.090 **	−0.097 **
			(0.033)	(0.037)	(0.041)	(0.042)
Rural			−0.021 ***	−0.024 ***	−0.018 ***	−0.019 ***
			(0.006)	(0.007)	(0.007)	(0.007)
Black			−0.014	−0.015	−0.849	−0.907
			(0.052)	(0.058)	(2.418)	(2.590)
Native			−1.420	−1.593	324.681 ***	346.953 ***
			(2.084)	(2.340)	(119.881)	(123.896)
Hispanic			0.127	0.143	1.100	1.176
			(0.173)	(0.194)	(9.260)	(9.892)
Ln (Income) × Black					0.092	0.098
					(0.239)	(0.256)
Ln (Income) × Native					−32.476 ***	−34.703 ***
					(11.903)	(12.307)
Ln (Income) × Hispanic					−0.116	−0.124
					(0.898)	(0.960)
Ln (alpha)	1.058 ***		0.956 ***		0.910 ***	
	(0.122)		(0.126)		(0.130)	
Constant	−2.823 ***		−38.798 **		−104.565 **	
	(0.634)		(15.546)		(42.324)	
Pseudo R^2	0.140		0.154		0.160	
Observations	388		388		388	

Note: Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

For water system characteristics, across the three models in Table 3, we find that CWSs who purchase their water from other water systems and have more educated and experienced operators are expected to issue more BWNs compared with CWSs that use their own water source and have less educated and experienced operators. Specifically, the marginal effects of these variables in Model (3) indicate that CWSs who purchase water and increase the level of certification of their operators by one level are expected to issue 1.13 and 0.86 additional BWNs, respectively. On the other hand, very small CWSs are expected to issue 1.25 fewer BWNs compared with medium and large CWSs.

For the socio-economic and demographic variables, we find that CWSs that serve high-income areas are expected to issue more BWNs, where a one-percent increase in income results in a 10.82 percent increase in issued BWNs. However, CWSs that serve areas with a higher percentage of the population that are educated, employed, and rural result in decreasing the number of issued BWNs. That is, a 1-percent increase in educated, employed, and rural residents results in 9.2-percent, 9-percent, and 1.8-percent decreases in issued BWNs. Finally, including interaction terms of income and demographics in Model (3) makes the coefficient of Native large and significant, while the interaction with income is negative. This indicates that if the population of Native Americans increases, then the issued BWNs would increase by more than 300%, but when income increases in such minorities, then the issued BWNs would decrease by about 30%. The results from the Logistic regression models in Table 4 are similar to those in Table 3. However, CWS age is positive and significant here, indicating that older water systems (in comparison to newer systems) are more likely to issue a BWN.

Table 4. Logistic regression results (dependent variable: BWN Event).

	Model (1) Coefficients	**Model (1) Marginal Effects**	**Model (2) Coefficients**	**Model (2) Marginal Effects**	**Model (3) Coefficients**	**Model (3) Marginal Effects**
Age	0.017 **	0.004 **	0.013 *	0.003 *	0.016 **	0.004 **
	(0.007)	(0.002)	(0.007)	(0.002)	(0.007)	(0.002)
Groundwater	0.580 *	0.137 *	0.160	0.038	0.152	0.036
	(0.312)	(0.074)	(0.355)	(0.084)	(0.365)	(0.086)
Purchased	0.691	0.164	0.374	0.088	0.331	0.078
	(0.507)	(0.120)	(0.557)	(0.132)	(0.567)	(0.134)
Protection	0.120	0.028	0.225	0.053	0.203	0.048
	(0.234)	(0.055)	(0.239)	(0.056)	(0.246)	(0.058)
Operator	0.380 *	0.090 *	0.285	0.067	0.243	0.057
	(0.230)	(0.054)	(0.246)	(0.058)	(0.243)	(0.057)
Facilities	0.014	0.003	0.014	0.003	0.016	0.004
	(0.014)	(0.003)	(0.014)	(0.003)	(0.015)	(0.004)
Small	−1.205 ***	−0.285 ***	−1.139 ***	−0.269 ***	−1.120 ***	−0.264 ***
	(0.345)	(0.080)	(0.354)	(0.082)	(0.361)	(0.084)
Private	0.317	0.075	0.154	0.036	0.226	0.053
	(0.327)	(0.077)	(0.341)	(0.081)	(0.350)	(0.082)
Ln (Income)			3.652	0.863	12.905 ***	3.038 ***
			(2.240)	(0.528)	(4.751)	(1.116)
Education			−0.089 **	−0.021 **	−0.138 ***	−0.033 ***
			(0.041)	(0.010)	(0.045)	(0.011)
Employed			−0.055	−0.013	−0.073	−0.017
			(0.040)	(0.009)	(0.046)	(0.011)
Rural			−0.020 ***	−0.005 ***	−0.020 ***	−0.005 ***
			(0.007)	(0.002)	(0.008)	(0.002)
Black			0.014	0.003	0.822	0.194
			(0.067)	(0.016)	(2.896)	(0.682)
Native			−1.002	−0.237	443.096 ***	104.315 ***
			(2.464)	(0.582)	(156.686)	(36.845)
Hispanic			0.156	0.037	−5.489	−1.292
			(0.234)	(0.055)	(12.605)	(2.969)
Ln (Income) × Black					−0.068	−0.016
					(0.286)	(0.067)
Ln (Income) × Native					−44.135 ***	−10.390 ***
					(15.559)	(3.659)
Ln (Income) × Hispanic					0.531	0.125
					(1.221)	(0.288)
Constant	−2.474 ***		−33.429		−125.671 ***	
	(0.794)		(21.209)		(46.712)	
Pseudo R^2	0.096		0.124		0.144	
Observations	388		388		388	

Note: Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5. Discussion

Public water supply unreliability is a problem that causes human hardships and is still common in the U.S. This study delves into the myriad factors influencing public water supply unreliability in West Virginia, as measured by the frequency of BWNs. Despite having 417 CWSs serving a significant majority (85%) of the inhabitants, the state faces a critical funding gap in maintaining adequate water infrastructure, with only 9% of the necessary funding having been secured and 4% of the population receiving water from systems that lack technical, managerial, and financial capabilities [36,37]. While aging infrastructure and lack of investment are often cited as primary causes in the literature [6], this study demonstrates that other factors play significant roles. The results reveal relationships between water system characteristics (i.e., age, water source, protection, operator experience, facilities, size, and ownership), socio-economic factors (i.e., income, employment, and education), and demographic composition of the served areas (i.e., percentage of residents living in rural areas and percentage of Black, Native, and Hispanic residents) and the frequency of BWNs.

The findings challenge some common assumptions. Contrary to the expectation that purchasing water from larger systems would enhance reliability as the wholesale providers are responsible for water quality and treatment [1,45,47], our results reveal a positive association between purchased water and BWN frequency. Some studies found mixed results (e.g., purchased water was found to be correlated with an increase in health-based violations alongside a decrease in coliform violations [48], or it reduced the likelihood of certain types of violations while increasing the likelihood of others [49]). This suggests that the impact of this factor may vary depending on the violation type and the water system context. Moreover, the positive relationship between operator certification and BWNs diverges from the assumption that greater expertise translates into improved reliability. A possible explanation is that more qualified operators are employed by inherently complex systems facing greater challenges or that they exhibit more stringent reporting practices. In contrast, other studies revealed that a substantial portion of advisories were issued in systems where a need for additional operator training was identified [13,23]. A negative coefficient for the "Small" variable indicates that smaller water systems are less likely to experience disruptions compared with medium and large systems. Large systems, often serving urban areas, may be more susceptible to disruptions due to the complexity of their infrastructure and higher water demand. Smaller systems often have simpler infrastructure and distribution networks, making them easier to manage and maintain. This can lead to quicker identification and resolution of issues, reducing the need for BWNs. Conversely, many studies found that smaller systems generally exhibit greater vulnerability to service disruptions compared with larger systems due to the reliance on untreated surface water, limited access to funding, challenges related to personnel and capacity, and aging infrastructure [1,13,17,28]. Another divergence from the literature and assumptions is that higher-income areas experience more BWNs, which challenges the common perception of water insecurity being primarily an issue for low-income communities. This may be attributable to the higher water demand or increased resident awareness and reporting.

Aligning with the literature, the results underline the persistent environmental justice issues surrounding access to safe and reliable water, highlighting the need for targeted interventions and policy measures. The disproportionate burden of water insecurity on minority communities, particularly Native American populations in our study, echoes the findings of prior research. Research has shown a correlation between the percentage of Black [30] and Hispanic [29,30,50] residents, People of Color [33], poor and minority communities [27], Appalachian counties [6,10], indigenous communities [25], and First Nations communities [13,20,31,32] and the frequency of SDWA violations. Some studies indicated that race/ethnicity effects may be contingent upon socioeconomic status (e.g., income, education, and poverty line) [30,47].

This study contributes to the literature by using a new way to measure public water supply unreliability and highlighting the complex interplay of factors. The findings emphasize the need to move beyond simplistic assumptions about water system reliability and consider the combined influence of technical, socio-economic, and demographic factors. The study also raises some questions for further research. The unexpected relationships identified in our study, such as those involving purchased water, operator certification, system size, and income, open new avenues for investigation and call for a deeper understanding of the mechanisms driving BWN occurrences. Future research could also explore alternative data sources or methods to validate the findings and address measures of unreliability other than BWNs. Sustainability indices, which are based on performance criteria encompassing, in addition to reliability, resiliency and vulnerability, may present a more comprehensive assessment [18,51]. More studies are needed to assess the effectiveness of various policy interventions and management strategies in improving water supply reliability and to explore innovative financing mechanisms, new technologies, and data-driven approaches to improving water system management.

6. Conclusions

To tackle water supply unreliability, we need an integrated and collaborative approach because various factors lead to it and they all need to be considered. While investing in new infrastructure is certainly essential, it is not enough to deliver fair and sustainable water management. The public water supply unreliability issue is a multicausal matter. It arises from many different factors: aging infrastructure, insufficient investment, ineffective pressure management, poor management practices, environmental conditions, and socio-political context. The vulnerability of the water source is a crucial aspect that needs to be considered carefully in the selection of an integrated strategy suitable for managing a safe and reliable water supply for the population. This includes better management practices; development of source water protection plans; investment in operator training and capacity development; addressing the fiscal constraints plaguing a large number of water systems today; ramping up water infrastructure modernization; partitioning and improving the pressure regime in water distribution systems; focusing on disadvantaged communities and advancing the goals of environmental justice in water management; developing meaningful community engagement and participation in decision-making processes; understanding the underlying root causes and drivers of unreliability; building efficient and accountable governance structures; increasing awareness among the public and encouraging responsible use attitudes and behaviors; and building public–private partnerships among water utilities, local government agencies, water research organizations, and communities. By addressing the drivers of unreliability and implementing solutions that are capable of tackling these systemic causes, we can work towards ensuring access to safe and reliable drinking water for all communities.

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