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Prevalence of private drinking water wells is associated with salmonellosis incidence in Maryland, USA: An ecological analysis using foodborne diseases active surveillance network (FoodNet) data (2007–2016)

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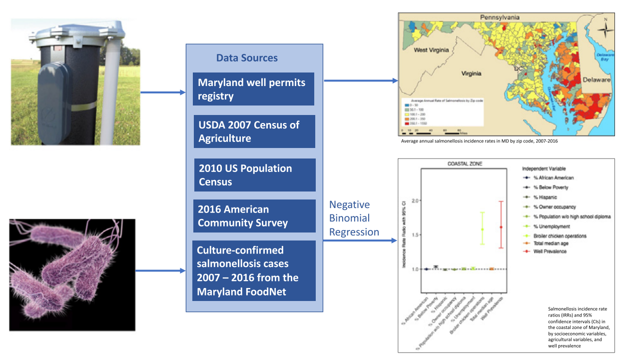
HIGHLIGHTS

- *Salmonella* is a leading cause of bacterial foodborne illness in the US.
- Approximately 19% of MD residents rely on private wells as their water source.
- Well prevalence is associated with salmonellosis in MD coastal zones.
- Agricultural and socioeconomic factors impact salmonellosis in coastal zones.

GRAPHICAL ABSTRACT



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ABSTRACT

Salmonellosis is a leading cause of foodborne illness worldwide. *Salmonella* infections have most often been associated with food-related risk factors, including the consumption of eggs and poultry. Recently, socioeconomic, agricultural and environmental factors, including drinking water source, have also been shown to influence the risk of salmonellosis. However, there are few data evaluating the association between consuming private well water and risk of *Salmonella* infections. Here, we examined the association between the prevalence of private drinking water wells and the incidence of salmonellosis in Maryland. Culture-confirmed salmonellosis case data (2007–2016) were obtained from the Foodborne Diseases Active Surveillance Network. Cases were linked by zip code with data from the Maryland well permits registry, the 2010 U.S. Census, the 2016 American Community Survey, and the USDA Agricultural Census. Well prevalence and salmonellosis incidence rates were calculated by zip code, and associations were evaluated using negative binomial regression models. From 2007 to 2016, a total of 8850 salmonellosis cases were reported in Maryland. Annual incidence rates ranged from 12.98 to 17.25 per 100,000 people. Prevalence of private wells in a zip code was statistically significantly associated with salmonellosis incidence at a statewide level (Incidence Rate Ratio [IRR] = 1.62; 95% Confidence Interval [CI] = 1.35, 1.93) and in the coastal zone of Maryland (IRR = 1.61; 95% CI = 1.31, 1.99). The presence of broiler

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Foodborne illness
FoodNet

chicken operations and the percentage of people living below the poverty level were also significantly associated with salmonellosis incidence at the zip code level in the coastal zone. To our knowledge, these are the first U.S. data to characterize the relationship between private drinking water wells and the risk of salmonellosis using an ecological study design. Our findings provide support for *Salmonella* testing of private wells in Maryland, as well as strengthening private well water regulations and improving the education of homeowners on well maintenance.

1. Introduction

Salmonella is a leading cause of gastroenteritis worldwide (Kirk et al., 2015). Globally, it is estimated that there are over 78 million cases of salmonellosis annually, resulting in over 28,600 deaths (Kirk et al., 2015). In the U.S., over 1 million cases of acute gastroenteritis caused by infection with nontyphoidal *Salmonella* spp. occur annually, including an estimated 19,500 hospitalizations and more than 375 deaths (Scallan et al., 2011). Infection with nontyphoidal *Salmonella* often causes mild self-limited illness, including diarrhea, fever and abdominal cramping 12–72 hours after infection (Dekker and Frank, 2015). However, much more serious sequelae including osteomyelitis, pneumonia, meningitis and death may occur, especially among immunocompromised individuals or those with underlying medical conditions such as sickle cell anemia (Crump et al., 2015; Dekker and Frank, 2015; Pond, 2005).

Nontyphoidal *Salmonella* is transmitted predominantly by commercially-produced food contaminated by animal feces, such as meat, eggs, poultry products and fresh produce (Batz et al., 2012; Braden, 2006; Hanning et al., 2009; Painter et al., 2013; Patrick et al., 2004). Transmission to humans has also occurred through contact with animals, particularly reptiles, and contact with animal environments (Hoelzer et al., 2011). Recently, waterborne transmission of *Salmonella* to humans has also been demonstrated (Ashbolt, 2004; Leclerc et al., 2002). *Salmonella* spp. can enter the aquatic environment directly in the feces of infected humans or animals, or indirectly, such as through untreated sewage discharge or agricultural runoff (Levantesi et al., 2012). *Salmonella* has also been detected in different types of natural aquatic environments such as rivers, lakes, coastal waters, and in contaminated ground water (Haley et al., 2009; Martinez-Urtaza et al., 2004; Levantesi et al., 2010; Wilkes et al., 2009). Moreover, *Salmonella* has been demonstrated to remain viable in freshwaters for longer than many other enteric bacteria (Chao et al., 1987), thereby increasing the probability of environmental exposure to humans.

Municipal drinking water and untreated spring water have also been associated with salmonellosis outbreaks in the U.S. (Berg, 2008; Farooqui et al., 2009; Kozlica et al., 2010). In 2008, an untreated supply of spring water stored in a small unprotected reservoir was recognized as the source of *Salmonella* infection in a rural community in Tennessee (Kozlica et al., 2010). An outbreak of salmonellosis was reported in Colorado when *Salmonella* in animal feces contaminated a storage reservoir in the public water system that supplies drinking water to the city of Alamosa (Berg, 2008). The outbreak resulted in 442 reported illnesses, 122 of which were laboratory-confirmed, and one death (Berg, 2008). Contaminated drinking water sourced from community wells also has been implicated in outbreaks of salmonellosis (Farooqui et al., 2009).

Private well water remains the sole source of drinking water for approximately 14% of the U.S. population (Maupin et al., 2014). While the quality of municipal drinking water systems is protected under the Safe Drinking Water Act, homeowners with private wells are responsible for ensuring the safety of their own drinking water (U.S. Environmental Protection Agency, 1974). In Maryland, approximately 19% of the population (over 1 million people) relies on private wells for home consumption (Maupin et al., 2014), which includes water for drinking, cooking, bathing, washing, toilet flushing and other needs. Although *Salmonella* infections have been previously associated with consumption of contaminated and untreated water, very few studies have investigated private domestic well water sources as risk factors for salmonellosis.

A Turkish study of 40 groundwater samples from private wells detected *Salmonella* in 15% of the samples tested (Özler and Aydın, 2008). In Nigeria, *Salmonella* serotype Typhi and Paratyphi were detected in private well water, and microbial water quality was found to be positively correlated with the waterborne diseases detected within the study area (Oguntoke et al., 2009). In a Taiwanese study, Li et al. (2009) determined that the consumption of groundwater from private wells was an independent risk factor for a number of confirmed cases of infection with *Salmonella choleraesuisis* (Li et al., 2009). In the U.S., a matched case-control study of almost 300 children in Washington state found that infection with *Salmonella* was associated with the use of private wells as sources of drinking water (Odds Ratio [OR] = 6.5; 95% CI = 1.4, 29.7), and with the use of residential septic systems (OR = 3.2; 95% CI = 1.3, 7.8) (Denno et al., 2009).

Recent studies have also shown that agricultural and community-level socioeconomic factors can impact rates of salmonellosis. Shaw et al. (2016) determined that multiple agricultural factors were associated with salmonellosis incidence rates, and these relationships varied by state (Shaw et al., 2016). For example, the presence of broiler chicken operations, dairy operations and cattle operations in a zip code was associated with significantly higher rates of infection with at least one serotype in states that are leading producers of these animal products. In Georgia, Maryland, and Tennessee, all of which are leading broiler chicken producing states, rates of *Salmonella* infection were 48%, 58% and 46% higher respectively in zip codes with broiler chicken operations compared to those without these operations (Shaw et al., 2016). These same states also saw higher rates of *Salmonella* infections in zip codes characterized by greater rurality (Shaw et al., 2016). Additionally, other recent studies have directly implicated animal feeding operations with regard to contamination of surface water and groundwater with *Salmonella* (Haley et al., 2009; Jenkins et al., 2006; Maurer et al., 2015), which could be a potential exposure pathway for contamination of private wells.

Given that a significant proportion of the Maryland population relies on groundwater from private wells, and that *Salmonella* is known to persist in many different water sources, we hypothesized that homeowners in Maryland who rely on groundwater from private wells may face an increased risk of salmonellosis. We utilized an ecological approach to investigate the association between the prevalence of wells and salmonellosis incidence at the zip code level using surveillance data on *Salmonella* infection from 2007 to 2016. Since previous studies have indicated that coastal communities face a higher risk of *Salmonella* infection (Jiang et al., 2015; Simental and Martinez-Urtaza, 2008), we examined the relationship between the prevalence of wells and salmonellosis incidence in coastal and non-coastal areas in Maryland.

2. Methods

2.1. Salmonella case data

We obtained *Salmonella* case data between 2007–2016 from the Maryland Foodborne Diseases Active Surveillance Network (FoodNet). The Maryland FoodNet is one of 10 sites that participate in the Centers for Disease Control and Prevention (CDC) FoodNet program. The FoodNet program conducts active, population-based surveillance for infections caused by nine bacterial and protozoal pathogens "commonly transmitted through food", including *Salmonella* (CDC, n.d.; Henao et al., 2015). As with all active surveillance systems concerning pathogens "commonly transmitted through food", source attribution (i.e. the process of estimating the source of the illness, whether it is a specific food, water, another beverage, a fomite, etc.) is very challenging, and in many instances the origin of the infection is not identified. Therefore, cases picked up by this surveillance system could originate from multiple source types including food, water and fomites. We restricted our analyses to culture-confirmed cases of *Salmonella* infection that occurred in Maryland between 2007-2016. A salmonellosis case was an individual whose biological specimen (stool, blood, or other) was culture-confirmed for the presence of *Salmonella*, regardless of symptoms or date of onset. Both sporadic cases and those associated with outbreaks were included. For each salmonellosis case, we also obtained limited demographic data (e.g., age, gender, race/ethnicity) and each case's zip code at the time of diagnosis.

2.2. Socioeconomic data

We obtained population data from the 2010 U.S. Census of Population and Housing by 5-digit zip code tabulation area (ZCTA) (U. S. Census Bureau, n.d.). We also obtained socioeconomic variables from the 2010–2016 American Community Survey (5-year estimates) by 5-digit ZCTA using the American Fact Finder Service (U. S. Census Bureau, 2014). We selected socioeconomic variables based on previous research (Shaw et al., 2016; Krieger et al., 1997; Zappe Pasturel et al., 2013), including % of the population that identifies as African American, % of the population that identifies as Hispanic, % of houses occupied by their owners, % of the population living below the poverty level, % of the population that is ≥25 years without high a school diploma, and % of the population that is unemployed.

2.3. Animal feeding operations data

We obtained animal feeding operation data in Maryland from the 2007 U.S. Census of Agriculture, National Agricultural Statistics Service (NASS) (United States Department of Agriculture (USDA), n.d.), which was the only year for which data were available at the zip code level. Specifically, we obtained data on the number of animal operations with sales by zip code for broiler chickens, turkey, aquaculture, sheep or goats, hogs, and dairy or beef cattle. These data were utilized to create dichotomous presence/absence variables for each type of animal feeding operation.

2.4. Private well data

The Maryland homeowner well permits registry was obtained from the Maryland Department of the Environment (MDE). The registry consisted of a tab-delimited file of 446,781 residential wells, some of which had an associated latitude and longitude coordinate (362,075 wells). The only locational information provided for the other permit records were the names of the town and street nearest to the property that contained the well (84,706 wells). Zip codes were retrieved for records with valid latitude and longitude coordinates or valid Maryland town and street addresses using Google's Geocoding application programming interface (API) (Google Developers, 2018).

Custom parsers were written to query the API for each record's zip code using either the latitude and longitude coordinates or the town and street name. Only wells with both a valid town and street name were queried to ensure accuracy (19,621 wells). The zip codes for each record were verified to be among the 619 registered Maryland zip codes. After completing the query process and removing incorrect records, valid zip codes were obtained for a total of 374,162 private wells in Maryland. To calculate well prevalence by zip code, data on the number of houses per zip code in Maryland was obtained from the 2012–2016 American Community Survey (5-year estimates) via the American Fact Finder Service (U. S. Census Bureau, 2014).

2.5. Maryland coastal and non-coastal zones

Maryland is located in the Mid-Atlantic region of the continental United States and is comprised of 24 counties (including Baltimore City) that are divided into two distinct zones by the Chesapeake Bay. The counties in the Atlantic coastal plain (known as the Eastern Shore) lie to the east of the Bay where some border the Atlantic Ocean. The counties to the west of the Bay comprise the Appalachian and Piedmont areas of the state (Maryland Department of Natural Resources (DNR), n.d.; Maryland Geological Survey, n.d.). We used definitions from the Maryland Department of Natural Resources to classify the 24 counties as being a part of the coastal or non-coastal zone as shown in Fig. 1 (Maryland Department of Natural Resources (DNR), n.d.). The Maryland coastal zone extends from three miles out in the Atlantic Ocean to the inland boundaries of the 16 counties and Baltimore City that border the Atlantic Ocean, Chesapeake Bay and the Potomac River up to the District of Columbia. This zone encompasses two-thirds of the state's land area and is home to almost 70% of Maryland's residents (Maryland Department of Natural Resources (DNR), n.d.). The remaining 7 counties are classified as the non-coastal zone. Given that the counties of the coastal zone have a greater number of homes with wells, differing geologies compared to those in the non-coastal zone, and contain the majority of the chicken farms in the state, and given that previous studies have indicated that coastal communities face a higher risk of *Salmonella* infection (Jiang et al., 2015; Simental and Martinez-Urtaza, 2008), we examined the relationship between the prevalence of wells and salmonellosis incidence by coastal and non-coastal areas in Maryland.

2.6. Descriptive analyses

We calculated *Salmonella* incidence rates per 100,000 population by year for the State of Maryland using population estimates from the 2010 U.S. Census (U. S. Census Bureau, n.d.). Cases that were potentially associated with international travel (1550 cases (17.5%)) were then excluded from further descriptive and inferential analysis. These cases were removed since travel outside of the United States was found to be a significant risk factor for salmonellosis in previous studies (Johnson et al., 2011; Tighe et al., 2012). We then determined a prevalence rate of wells per zip code (the well prevalence variable) using the Maryland homeowner well permits registry and data on the number of houses per zip code from the 2012–2016 ACS via the American Fact Finder Service (U. S. Census Bureau, 2014). Well prevalence per zip code was calculated by dividing the number of wells per zip code by the number of houses per zip code. *Salmonella* case count data (excluding cases associated with international travel) were then linked with the socioeconomic, animal feeding operation, and well prevalence data by zip code and 5-digit ZCTA. A choropleth map of salmonellosis incidence rates by zip code was created to illustrate the distribution of salmonellosis across the state. We performed all mapping using ArcGIS version 10.3 (ESRI, 2016) (ESRI, Redlands, CA).

2.7. Statistical models

We developed regression models to evaluate associations between well prevalence, socioeconomic and agricultural factors, and salmonellosis incidence at the zip code level. First, any salmonellosis cases for which zip codes were missing or incorrect were excluded from the analysis, along with those cases associated with international travel. We then evaluated collinearity among all independent variables of well prevalence, SES factors, and agricultural factors to avoid using highly

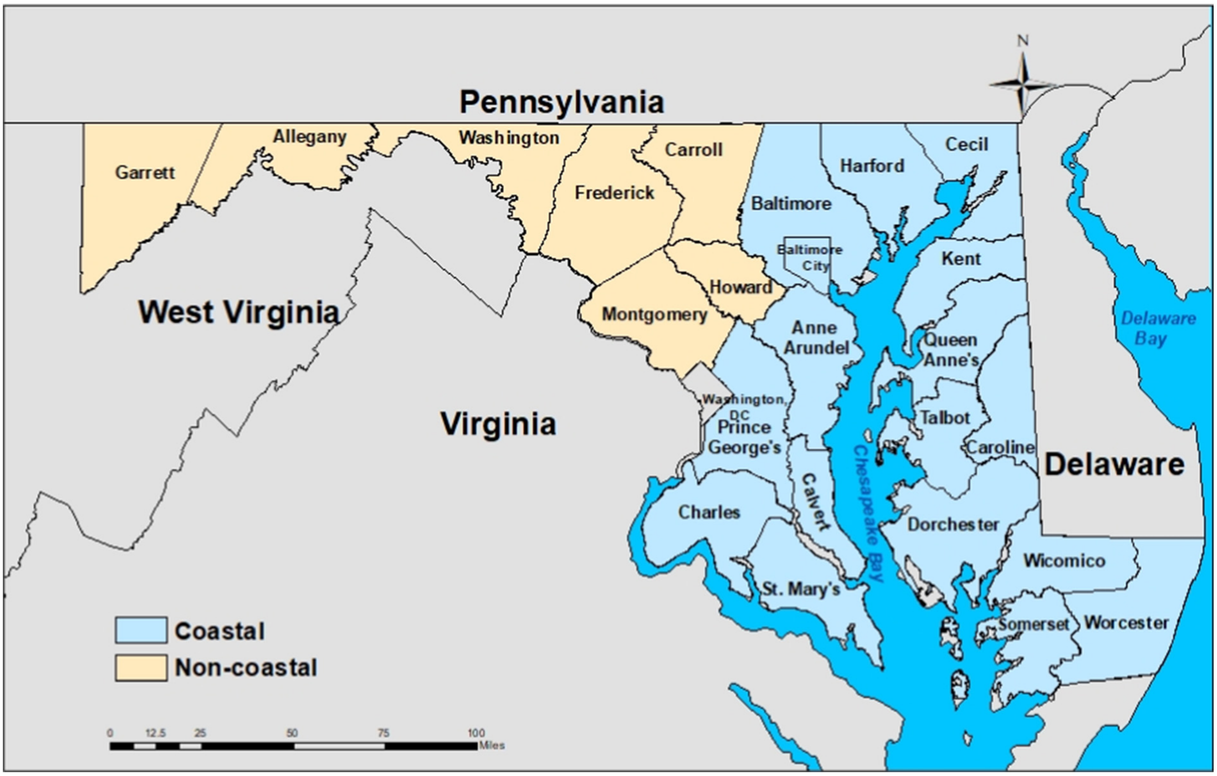

Fig. 1. Map of Maryland indicating coastal and non-coastal counties.

correlated variables in the multivariate regression model. A variance inflation factor of 4 (equivalent to a tolerance level 0.25) was used to indicate excessive collinearity among the variables (O'Brien, 2007) (Supplemental Tables 2 and 3).

Regression models typically employed for count data were compared and the negative binomial regression model provided the best fit for the dataset. The final model included well prevalence and agricultural, demographic and socioeconomic variables at the zip code level. We ran a statewide regression model, a univariate regression model between well prevalence and incidence of salmonellosis stratified by county, and univariate and multivariate regression models by coastal/non-coastal zone. Only the well prevalence variable and the independent variables that were significantly associated with salmonellosis incidence at the zip code level for each zone by univariate analysis were included in the multivariate regression models of that zone. We performed all modeling using SAS version 9.4 (SAS Institute, Cary, NC) (SAS Institute, 2014), and used *p*-values of ≤0.05 to assess statistical significance. We used R version 1.0.153 (Vienna, Austria) (R Core Team, 2017) to create bar charts and whisker plots of the multivariate analyses.

3. Results

3.1. Maryland salmonellosis cases, 2007–2016, and incidence rates

A total of 8926 cases of culture-confirmed *Salmonella* infections were reported to the FoodNet active surveillance system in Maryland between 2007 and 2016. A total of 8850 cases (99.1%) had valid zip codes.

The majority of cases were between the ages of 20–59 (42.23%), White (50.47%), and Non-Hispanic (74.54%) (Table 1). Most cases were sporadic infections (81.36%), while 4.95% of cases were associated with outbreaks, and 13.69% were of unknown type. Over 200 unique *Salmonella* serotypes were identified among all cases of infection. Approximately 21.28% were identified as Enteritidis, 6.25% as Typhimurium, 5.53% as Newport, and 3.57% as Javiana. An additional 23.68% were other unique serotypes, and 34.43% were unknown serotypes.

The average annual incidence rates of salmonellosis in Maryland between 2007 and 2016 are illustrated in Fig. 2. The lowest annual incidence rate for this 10-year period of 13.19 per 100,000 people was recorded in 2009, and the highest annual incidence rate of 17.64 per 100,000 people was recorded in 2010 (Fig. 2). The choropleth map (Fig. 3) visualizes the spatial distribution of average annual salmonellosis incidence rates by zip code in Maryland. *Salmonella* infection rates are highest within the coastal zone of Maryland, particularly along the Eastern

Table 1
Demographic characteristics of Salmonellosis cases reported to the Maryland FoodNet program, 2007–2016.

Variable	No. (%)
Age, years	
0–4	1939 (21.91)
5–9	714 (8.07)
10–19	928 (10.49)
20–59	3737 (42.23)
≥ 60	1468 (16.59)
Unknown	64 (0.72)
Race	
African American	2579 (29.14)
White	4467 (50.47)
Other Race	1804 (20.38)
Ethnicity	
Hispanic	619 (6.99)
Non-Hispanic	6597 (74.54)
Unknown or missing	1634 (18.46)
International travel	
Yes	1550 (17.51)
No	6123 (69.19)
Unknown	1550 (17.51)
Disease type	
Sporadic	7200 (81.36)
Outbreak	438 (4.95)
Unknown or missing	1212 (13.69)

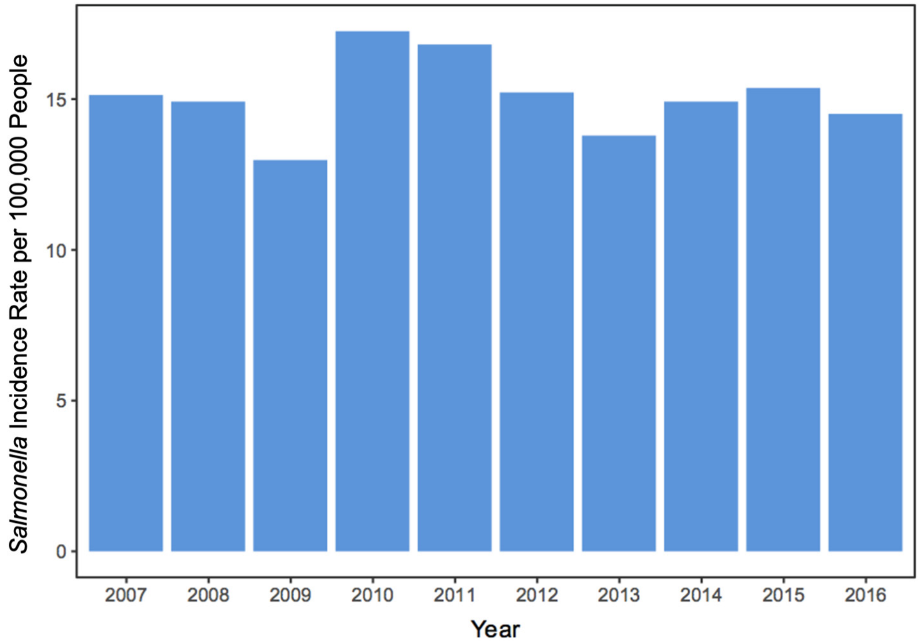

Fig. 2. Incidence rates of salmonellosis per 100,000 people in MD, 2007–2016.

Shore. This region is characterized by the presence of high numbers of broiler chicken operations that may play a role in the relationship between salmonellosis incidence rates and the risk factors investigated in this study.

3.2. Maryland Private Wells

The Maryland county with the most wells was Anne Arundel county with 53,192 wells, while the county with the least number of wells was Baltimore City with 153 wells (Fig. 4). However, well prevalence (the number of wells per number of houses in each county) was highest in Somerset county (0.967) and lowest in Baltimore City (0.0006) (Fig. 4). Most wells in the state are located within the coastal zone, a region characterized by limestone, sandstone and shale (Reger and Cleaves, 2008; Vokes, 1957).

3.3. Statewide multivariate analysis

Overall, we observed a significant positive association between well prevalence and increased salmonellosis incidence at the zip code level (Incidence Rate Ratio [IRR] = 1.62, 95% Confidence Interval

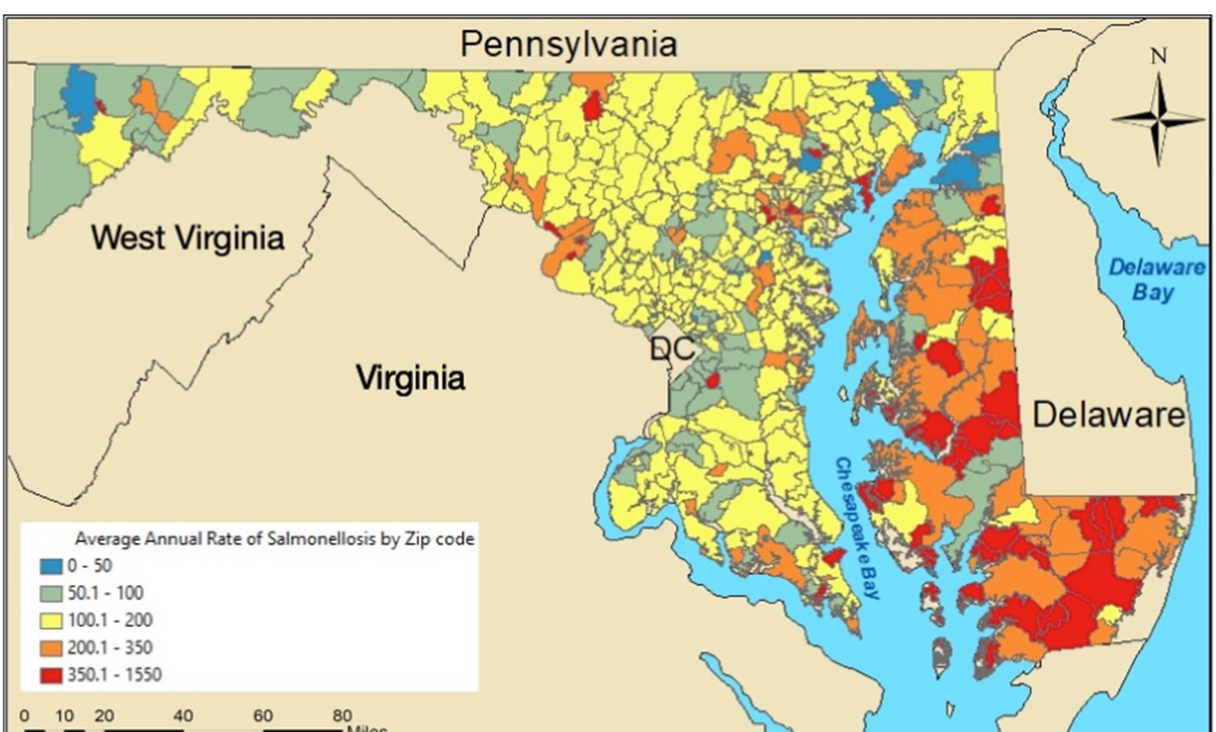

Fig. 3. Average annual salmonellosis incidence rates in MD by zip code, 2007–2016.

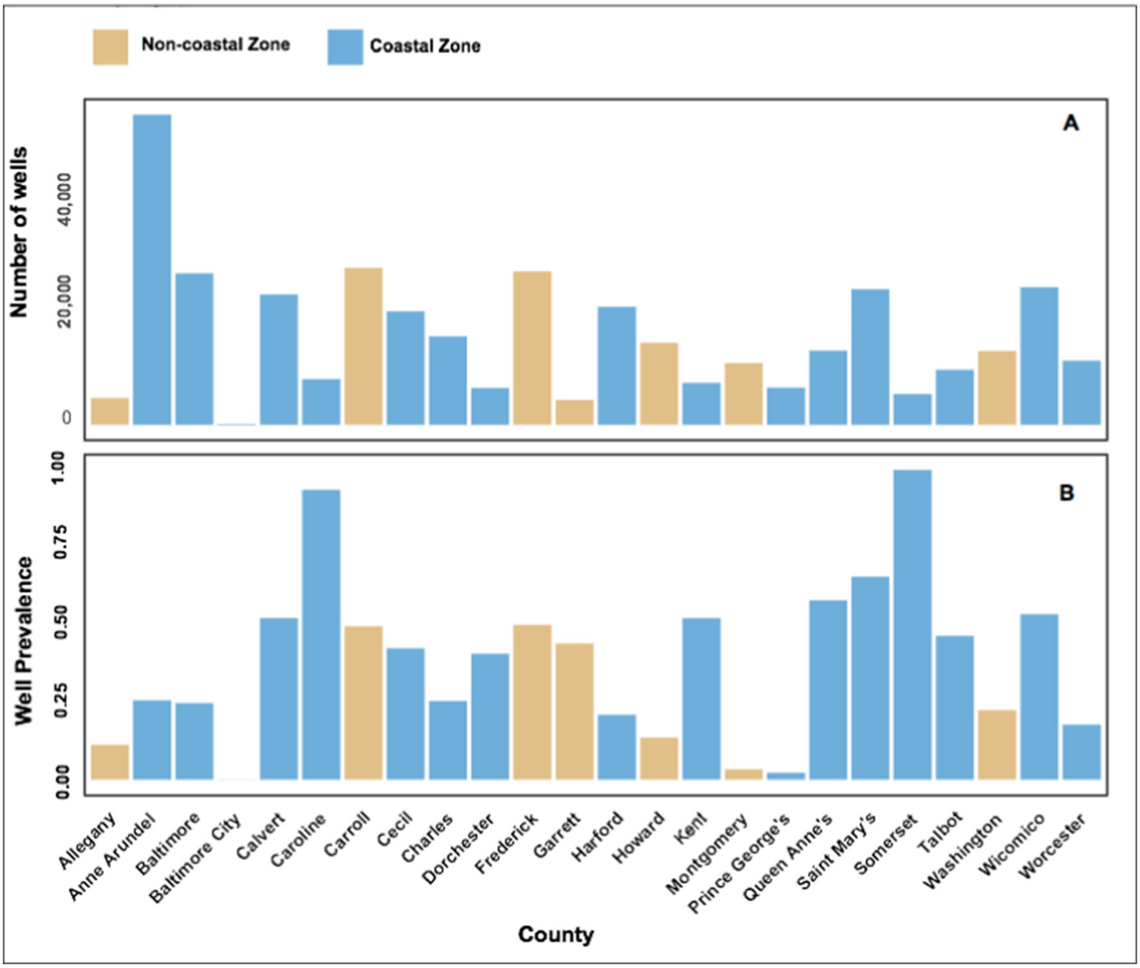

Fig. 4. Number of wells (panel A) and well prevalence (panel B) by county and zone in Maryland.

[CI] = 1.35, 1.93) (Table 2). Agricultural and socioeconomic factors were also found to influence salmonellosis incidence at the zip code level. In zip codes that contain broiler chicken operations, the incidence rate of salmonellosis was 1.47 times that in zip codes that do not contain broiler chicken operations (IRR = 1.47, 95% CI = 1.29, 1.66). In zip codes characterized by the presence of cattle operations, the incidence rate of salmonellosis was lower than that of zip codes that do not contain cattle operations (IRR = 0.84; 95%CI = 0.74, 0.95). Salmonellosis incidence was also higher in zip codes characterized by higher percentages of the population living below the poverty level (IRR = 1.03; 95%CI = 1.02, 1.04).

Table 2
Incidence rate ratios (IRR) and 95% confidence interval (CI) for salmonellosis in Maryland (2007–2016).

Variables		IRR[a]	IRR 95% CI
Well prevalence		1.62	(1.35, 1.93)
Cattle operations	Absent	1.00	(Reference)
	Present	0.84	(0.74, 0.95)
Broiler chicken operations	Absent	1.00	(Reference)
	Present	1.47	(1.29, 1.66)
Hog operations	Absent	1.00	(Reference)
	Present	0.94	(0.73, 1.22)
Turkey operations	Absent	1.00	(Reference)
	Present	0.88	(0.75, 1.03)
Median age, years		1.01	(0.99, 1.01)
% African American		1.00	(0.99, 1.00)
% Hispanic		0.99	(0.99, 1.01)
% Owner occupancy		0.99	(0.99, 1.00)
% Residents below poverty		1.03	(1.02, 1.04)
% Population ≥ 25 years without high school diploma		1.00	(0.99, 1.01)
% Unemployment		1.01	(1.00, 1.03)

Note: IRR = incident rate ratio; CI = confidence interval.
[a] Adjusted after controlling for other independent variables in the multivariate regression model.

3.4. Stratified analysis

Given that well prevalence was a significant predictor of salmonellosis incidence at the zip code level in the statewide model, we decided to examine the relationship by geographic region in Maryland, specifically in coastal vs. non-coastal counties. Additionally, a previous study indicated that coastal communities in Maryland face a higher risk of *Salmonella* infection due to extreme temperature and precipitation events (Jiang et al., 2015). Following a univariate analysis of well prevalence and other independent variables and incidence of salmonellosis stratified by coastal/non-coastal zone, we observed that well prevalence was a significant predictor of an increased incidence of salmonellosis in the coastal zone only. We then built a multivariate model for only the coastal zone to investigate the association between well prevalence and salmonellosis incidence, controlling for other significant factors (Supplemental Table 1).

In the coastal counties, we observed that well prevalence was significantly associated with an increase in salmonellosis incidence after controlling for agricultural and socioeconomic variables (IRR = 1.61, 95% CI = 1.31, 1.99) (Fig. 5). Agricultural and socioeconomic factors at the zip code level were also associated with salmonellosis incidence in coastal counties (Fig. 5). For instance, salmonellosis incidence was higher in zip codes that contained broiler chicken operations

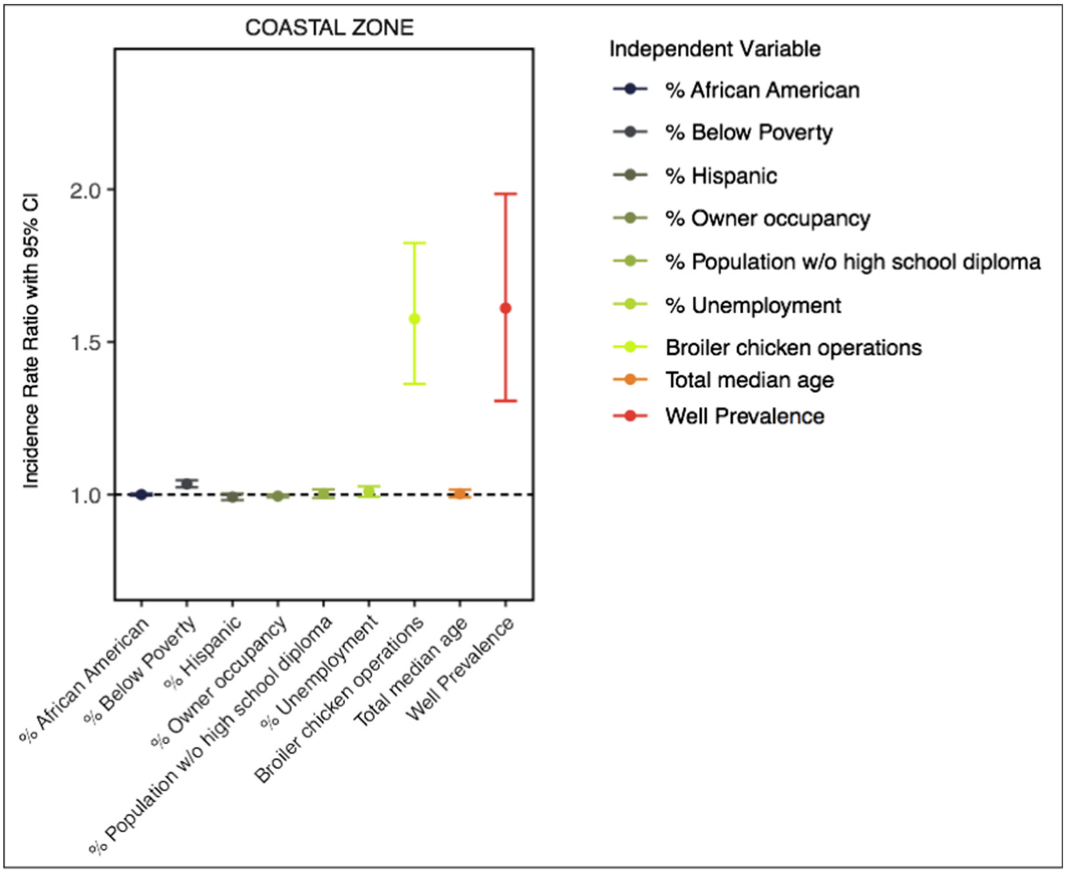

Fig. 5. Salmonellosis incidence rate ratios (IRRs) and 95% confidence intervals (CIs) in the coastal zone of Maryland, by socioeconomic variables, agricultural variables, and well prevalence.

(IRR = 1.58, 95% CI = 1.36, 1.82). Zip codes characterized by a higher percentage of the population living below the poverty line also had increased incidence rates of salmonellosis (IRR = 1.02; 95% CI = 1.01, 1.04).

4. Discussion

Our findings suggest that the prevalence of private drinking water wells within a zip code is associated with an increased risk of salmonellosis in the coastal counties of Maryland (IRR = 1.61, 95% CI = 1.31, 1.99) (Fig. 5). Our data also confirm that other environmental factors, including proximity to large-scale broiler chicken facilities, can also influence salmonellosis incidence. To our knowledge, this is the first U.S. ecological analysis to characterize the relationship between private drinking water wells and the risk of salmonellosis, an illness that is typically viewed as foodborne.

From 2007 to 2016, a total of 75,304 cases of confirmed salmonellosis were reported to the CDC FoodNet program across all ten participating sites (CDC, 2018). In comparison with other sites during the same ten-year period, the overall incidence rate of salmonellosis in Maryland is the fourth highest (15.3 per 100,000 population), followed by California (15.77 per 100,000 population) and New Mexico (17.44 per 100,000 population). The site with the highest rate of *Salmonella* infection during this period was Georgia (24.06 per 100,000 population).

The association between well prevalence and the risk of salmonellosis was observed in our statewide multivariate model (Table 2) and in the multivariate model for the coastal zone of Maryland (Fig. 5). However, well prevalence was not found to be significantly associated with salmonellosis incidence in the non-coastal zone by univariate analysis (Supplemental Table 1), and as such a multivariate model for the non-coastal zone was not performed. It is possible that the differences we observed between the coastal zone and the non-coastal zone may be attributed to the differing geologies underlying each of these areas, which could influence potential groundwater contamination events.

In addition to well prevalence, the presence of broiler chicken farms in a zip code was also significantly associated with an increase in the risk of salmonellosis in the statewide model (IRR = 1.47, 95% CI = 1.29, 1.66), and in the coastal counties of Maryland (IRR = 1.58, 95% CI = 1.36, 1.84). The Eastern Shore of Maryland, which is located within the coastal zone, produces close to 300 million broiler chickens annually (United States Department of Agriculture (USDA), 2016). Broiler chicken operations produce an estimated 5.5 tons (446 cubic feet) of waste per 1000 birds (Carr et al., 1990), totaling over 1.6 million tons of waste produced by broiler operations in Maryland. This waste is typically applied to land and other agricultural fields, leading to potential contamination of nearby water supplies (Burkholder et al., 2007). You et al. (2006) demonstrated that *Salmonella* can persist for up to 405 days in soil after manure is applied to a field, thereby posing a risk of contamination of groundwater (You et al., 2006).

The Maryland Department of the Environment allows animal feeding operations within the state to discharge into surface waters of the state following the issuance of a permit (MDE, n.d.-a). There are 610 broiler chicken farms (non-laying hens) within the state and an additional 5 farms that consist of laying hens, all of which have a permit to discharge wastewater into waters of the state (MDE, n.d.-b). Permits are only required of farms which have 37,500 chickens or greater, meaning that broiler operations with less chickens exist in the state without permits, making them difficult to quantify and their locations difficult to assess (MDE, n.d.-a). All of the permitted broiler chicken farms and four of the farms with laying hens in the state of Maryland are located within the coastal counties (MDE, n.d.-b). Given that animal feeding operations have been previously implicated in contamination of surface water and groundwater with *Salmonella* (Haley et al., 2009; Jenkins et al., 2006; Maurer et al., 2015), broiler facilities could play a role in the relationship between well prevalence and salmonellosis risk observed in this study.

Our multivariate regression model also provided evidence that socioeconomic factors are associated with an increase in salmonellosis incidence. We found that as the percentage of people living below the poverty line in a zip code increased, so did the risk of salmonellosis (IRR = 1.04; 95% CI = 1.02, 1.05). A previous study using national FoodNet data from 2004 to 2010 also found that higher poverty levels in zip codes were associated with higher rates of *Salmonella* infection in Maryland, New Mexico and Tennessee (Shaw et al., 2016). Other research previously identified a positive association between poverty levels and salmonellosis incidence rates in a nationwide county-level study using data from the National Notifiable Diseases Surveillance System (Chang et al., 2009). However, this study also found that another variable commonly used to assess poverty, the percentage of the adult population that is unemployed, was negatively associated with salmonellosis incidence rates at the county level.

Our study found that the percentage of unemployed individuals within a zip code was positively associated with the risk of salmonellosis; however, it was not significant (IRR = 1.010, 95% CI = 0.99, 1.03). A recent Danish study found that that the risk of *Salmonella* infection was not primarily associated with poverty, but rather with increasing socioeconomic status (Simonsen et al., 2008). Other studies have found similar contrasting results regarding the associations between indicators of socioeconomic status and incidence of enteric diseases (Newman et al., 2015; Rosenberg Goldstein et al., 2016; Zappe Pasturel et al., 2013).

There are notable strengths of our study. We used a decade of illness surveillance data from the Maryland FoodNet program to conduct our study, ensuring that we had a large number of salmonellosis cases from which to draw our conclusions. In addition, FoodNet has the advantage of being an active surveillance network, thereby avoiding some of the inconsistencies and heavy underreporting that can characterize passive national surveillance systems.

A limitation of our study is that it was performed on an ecological scale using community-level socioeconomic data at the zip code level rather than individual-level data of the cases. As such our findings cannot be used to infer associations between private wells and salmonellosis at the individual level. Performing the analysis with salmonellosis case data at the zip code level required us to pair these data with data from the U.S. Census and the American Community Survey by ZCTAs. However, zip codes and ZCTAs do not always correlate, resulting in some zip codes for which census data are unavailable. Grubesic and Matisziw (2006) also highlight the discrepancies in matching ZCTA and zip code level data, indicating that using ZCTAs to link geographic data is convenient but can result in relatively large geographic zones with linkages that can lead to imprecise estimates (Grubesic and Matisziw, 2006).

An additional limitation is that while the FoodNet active surveillance system provides reliable data on the cases that are tested and reported to the system, it underestimates disease burden and typically represents a fraction of the total community cases (Majowicz et al., 2010; Mead et al., 1999). Underreporting of foodborne illnesses leading to underestimation of disease burden is also recognized as a problem of laboratory-based illness surveillance systems in other countries (de Wit et al., 2001; Flint et al., 2005; Wheeler et al., 1999). In addition, the Census of Agriculture data were only available at the zip code level for the 2007 Census, and not for subsequent years. It is possible that additional animal feeding operations could have been established in Maryland since 2007, rendering the census data used in this study an underestimate of the true number of operations (United States Department of Agriculture (USDA), n.d.). Finally, it is possible that other variables, not accounted for in our models, including different types of land use such as farms growing fresh produce and sites employing groundwater recharge with recycled water, could have influenced the observed association. For instance, previous studies have demonstrated that contaminated irrigation water can contribute to *Salmonella* contamination of tomatoes and other fresh produce at the land surface (Gu et al., 2018; Micallef et al., 2012); however, it is unclear whether this type of *Salmonella* contamination originating from irrigation water could percolate through soil and ultimately contaminate underlying aquifers. Future studies evaluating this relationship are necessary.

Nevertheless, this is the first study to use an ecological study design to investigate the association between private wells and the risk of salmonellosis in the United States, and it provides a rationale for continuing to evaluate wells as a risk factor for gastrointestinal diseases. Future research in this area could include sampling of private well water for the detection of *Salmonella*, and employing techniques such as Microbial Source Tracking (MST) to determine the likely sources of *Salmonella* contamination, whether human, animal or environmental (e.g., irrigation water utilized at the surface). MST has been previously used in similar studies to characterize the magnitude and incidence of microbial contamination in private wells, and to identify the likely sources of this contamination (Allevi et al., 2013). Moreover, aquifer type, whether confined or unconfined, can contribute to the quality of private well water since the potential for contamination changes with each type. Confined aquifers exist within layers of impermeable rock, while unconfined aquifers are located closer to the earth's surface than confined aquifers, and as such are impacted by external factors and contamination sources much more than confined aquifers (Heath, 1983; Waller, 1988). A spatial analysis of salmonellosis incidence that incorporates aquifer type could illustrate the effect of drilling a well in an unconfined vs. confined aquifer on this illness.

Finally, given that no uniform national laws exist to regulate private wells, more extensive private well monitoring will help identify wells at greater risk of contamination. Increased monitoring can assist public health efforts by streamlining a focus on education and outreach to improve monitoring, maintaining, and treating private wells in communities that rely on them (Lee and Murphy, 2020). In addition to community interventions, federally enforceable regulations and funding for regular well monitoring are needed to support and protect private well owners.

5. Conclusion

We observed an increased risk of salmonellosis associated with increasing well prevalence in coastal counties of Maryland. Other risk factors, such as the presence of broiler chicken operations and the percentage of the population living below the poverty level were also found to be significantly associated with salmonellosis incidence in the coastal zone of Maryland. Our results add to the growing body of international research that has identified drinking water as a potential risk factor for *Salmonella* infection. Our findings provide support for strengthening private well water regulations and for improving education and outreach to private well owners on proper maintenance and testing for their wells.

CrediT authorship contribution statement

Rianna T. Murray: Investigation, Writing – original draft, Writing – review & editing, Visualization, Formal analysis. **Raul Cruz-Cano:** Investigation, Formal analysis, Writing – review & editing. **Daniel Nasko:** Investigation, Formal analysis, Writing – review & editing. **David Blythe:** Investigation, Writing – review & editing. **Patricia Ryan:** Investigation, Writing – review & editing. **Michelle Boyle:** Investigation, Writing – review & editing. **Sacoby Wilson:** Investigation, Writing – review & editing. **Amy R. Sapkota:** Conceptualization, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.147682.

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