Examining the factors related to bacteriological testing of private wells in Southern Ontario

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ABSTRACT

The incidence of infectious waterborne disease in Canada continues to be a public health issue and can be associated with the source of drinking water. Millions of Canadians relying on unregulated private well water are at increased risk of disease. This study examined relationships between well and owner characteristics and the frequency of microbial testing of private wells in two southern-Ontario counties. Using multi-level logistic regression models, testing frequency (i.e., at least once per year vs. less) was modeled, as both self-reported and laboratory-validated, for associations with owner and well characteristics. For the self-reported outcome, a previous adverse test result significantly increased the odds of being classified as a frequent tester, and owners with a well-head more than 16 inches (40.6 cm) above the ground were at significantly higher odds of being classified as frequent testers compared to those with well-heads less than 16 inches above the ground and those below ground level. For the model based on the laboratory-validated outcome, the odds of an owner being a frequent tester significantly varied with the length of occupancy and the occurrence of a previous adverse result. The absence of associations between other well characteristics and testing frequency suggests that well safety education could benefit these communities.

Key words | bacteriological contamination, coliforms, drinking water, Ontario, testing, wells

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INTRODUCTION

Even within developed nations, waterborne infectious diseases constitute a significant cause of morbidity and mortality (Charrois 2010). In North America, these waterborne diseases are conservatively estimated to cause over one million cases of illness per year, of which 1,000 result in death (Krolik *et al.* 2013). In Canada, the risk is most pronounced among residents who lack access to municipal water supplies that are treated and monitored by local governments. Roughly four million Canadians fall into this category, primarily the residents of rural areas (Kreutzwiser *et al.* 2011; Krolik *et al.* 2014; Maier *et al.* 2014). Nationwide, the reliance on private wells for drinking water has, according to one study, puts these residents at approximately 5.2 times greater risk of contracting enteric diseases related to water consumption than those accessing drinking water through municipal systems (Krolik *et al.* 2014).

Consumption of untreated surface water is associated with high rates of infectious disease, and contamination of private well water with surface water has been identified as the greatest risk to well water safety (Simpson 2004; Murphy *et al.* 2016). This risk may be exacerbated by the nearby presence of sources of fecal contamination – animal or human – such as septic tanks and grazing land. Fecal coliforms found in septic tanks, *E. coli* in particular, can be indicators of risk for a variety of enteric diseases, and the spread of these pathogens can be facilitated by heavy rainfall (Arnade 1999; Kreutzwiser *et al.* 2011). Several factors are associated with private well water

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contamination, including the structure, depth, and age of the well (Simpson 2004). Although the need for more research remains, a review of studies concerning the safety of groundwater systems in the United States and Canada found high rates of contamination with enteric pathogens among sampled private wells (Hynds *et al.* 2014).

In rural Ontario, groundwater-supplied private wells are the most common source of drinking water, and the maintenance of water quality and safety is the sole responsibility of the owner (Imgrund *et al.* 2011). Awareness of this responsibility has been found to be lacking among private well owners, especially those who have recently relocated from towns or cities (Ridpath *et al*. 2016). A number of factors have been found to relate to good well maintenance by owners, including knowledge, risk perception, and convenience (Malecki *et al.* 2017). There have been efforts at promoting well testing, but few promotional programs have been evaluated, and there have been few studies aimed at identifying factors specifically related to testing. Those studies that exist have concentrated on social characteristics such as educational background and socio-economic status, as well as individual motivations such as convenience, as predictors of testing (Imgrund *et al.* 2011; Flanagan *et al.* 2016).

Wellington–Dufferin–Guelph Public Health (WDGPH), a local health unit in southwestern Ontario, is mandated by the provincial government to prevent or minimize the occurrence of illness related to drinking water according to the Safe Water Standard (Ontario Ministry of Health and Long-Term Care 2018). The health unit works to inform residents of the risks inherent in drinking groundwater and to promote water quality testing. Previous provincial guidelines recommended that wells should be tested at least three times a year (Ontario Ministry of Transportation 2004), whereas current guidelines simply recommend that private wells be tested 'often' (Public Health Ontario). In cooperation with Public Health Ontario Laboratories (PHOL), the public health unit facilitates free water quality testing by providing residents of the counties of Wellington (including the City of Guelph) and Dufferin (WDG) with sample collection bottles at WDGPH offices that can be filled by well owners with well water and then returned to the health unit and submitted by WDGPH to PHOL for microbiological testing. An exploratory study by WDGPH of spatial patterns of water testing frequency identified at least one area within WDG north of the city of Guelph where a lower than expected proportion of privately owned wells was tested as recommended in at least one year between 2011 and 2015 (Montague *et al.* 2018; Tschritter, unpublished results). Further, data obtained by WDGPH indicate that more than half of private wells were not tested at all, and even fewer were tested at least annually, over this period (Montague *et al.* 2018). In light of the presence of suboptimal testing in the region, the objective of this study was to investigate what factors, including owner demographics and well characteristics, might be associated with testing frequency (based on self-reports and PHOL submissions) among owners of private wells in WDG. This information may prove useful in implementing health promotion and intervention efforts designed to reduce the incidence of waterborne illness among residents of the region with private wells.

METHODS

Data sources

PHOL well water testing data

PHOL provide Ontarians with free water testing services to detect *Escherichia coli* and other coliforms, which have long been used as standard indicator organisms for drinking water quality (Coleman *et al.* 2013).

Records of bacteriological tests of well water from private wells in Wellington and Dufferin counties were obtained from PHOL for the years 2013–2017, inclusive. For the purposes of this study, water sample results indicating the presence of coliforms or *E. coli* (quantifiable or not), or that the presence of coliforms could not be determined due to the overgrowth of non-coliform bacteria, were classified as adverse test results, the latter being included since the safety of the water for drinking remained unknown.

WDGPH well owner survey

In the summer and fall of 2018, WDGPH conducted a survey in the WDG region. The survey was based on a review of the literature, and its purpose being, in addition to collecting information on privately owned wells in the region to facilitate public health services, was to identify factors that might influence the frequency of testing private wells by owners, as well as the factors affecting the risk of bacteriological contamination of private wells. The survey was launched in May 2018. Questions concerned the characteristics of private wells and the practices of well owners related to the testing of their well water. The survey was made available online via the data collection software Qualtrics (Qualtrics Inc., Provo, UT). In addition, hard copies of the survey were made available at well water testing and bottle pickup locations, including WDGPH offices and public libraries, some attached to water testing bottles and some available separately. In an attempt to also recruit well owners who were not frequent testers of their wells, hard copies of the survey, along with information letters that included the URL address of the online survey, were mailed to 2,131 addresses linked to private wells in WDG that had not been tested by PHOL since 2006, according to the PHOL database. These addresses were identified by cross-checking a list of addresses present in a PHOL database of well water test results for WDG water samples tested from 2006 to 2017, against a list of existing wells with usable street addresses within WDG drawn from the provincial Well Water Information System (WWIS, Ontario Ministry of the Environment), with mail-outs being done to all WWIS addresses not in the PHOL database.

As an incentive to complete the survey, all participants were offered the opportunity to enroll in a monthly raffle for a $50.00 gift certificate to participating grocery stores, with information concerning the draw being collected separately from the survey responses in order to protect the privacy of the survey respondents.

For the survey, free and informed consent of the participants or their legal representatives was obtained. The study protocol was approved by the appropriate Committee for the Protection of Human Participants: the Research Ethics Committee of WDGPH, Guelph, Ontario, Canada on 27 March 2018. A copy of the survey is available from the authors upon request.

Statistical analysis

Using the VLOOKUP feature on Microsoft Excel (Microsoft 2014, Redmond), survey responses were matched and linked to the corresponding PHOL testing data by well addresses entered by respondents. The process was manually audited by the lead author M. Ugas, with those matches unable to be completed by Excel being done by hand.

To examine the merged dataset for associations between frequency of testing and independent variables related to well characteristics, owner attitudes, and historical test results from the years 2013–2017, the data were analyzed using multi-level logistic regression models, each including a random intercept for *sub-region* (a variable described in more detail below). Models were constructed for each of two dependent variables: one variable defined based on owner response to the survey and the other on the data recorded by PHOL. For the survey-based outcome, a 'frequent' tester was defined as a well owner who reported in the survey, in response to the question 'How often do you test your well?', that they tested their well water at least once per year. For the laboratory-validated dependent variable, based on records in the PHOL database of testing results, owners of wells for which the laboratory records indicated that they had been tested at least once per year in each year over the five-year study period were considered 'frequent' testers. The historical benchmark of three times per year was not used as it quickly became apparent that very few wells were tested that often, and because the government had ceased to formally recommend it.

The level of agreement between the self-reported and laboratory-validated dependent variables was assessed using Cohen's kappa or a prevalence-adjusted, bias-adjusted kappa (PABAK). If either of the two variables had a prevalence of less than 20% or greater than 80%, or if McNemar's χ^2 statistic assessing the difference in prevalence between the two was significant, then PABAK was estimated (Sim & Wright 2005). If not, Cohen's kappa was estimated instead.

Multi-level univariable logistic regression models with a liberal significance level of 20% (alpha = 0.20) were used to screen independent variables against each of the two binomial outcomes (self-reported and laboratory-validated testing frequency, respectively), for inclusion in subsequent multivariable models. Where appropriate, Spearman rank correlations and phi coefficients were assessed to identify highly correlated independent variables to avoid collinearity issues. If the correlations between two variables exceeded

0.80, the variable with the higher frequency was used for subsequent models.

For each of the two dependent variables, a multivariable multi-level model was then fitted by backward elimination. An independent variable was included in the final multivariable model if it was statistically significant (alpha = 0.05), acted as a confounding variable or was part of a significant interaction. Confounding variables were distinguished from intervening variables based on a causal diagram and were kept in the final model if their removal resulted in a 20% or larger change in the coefficient of a significant variable (Dohoo *et al.* 2012). Based on epidemiological plausibility, we examined the interaction between the variables for adverse test results and water treatment for bacteria. In addition, we tested for interaction among all variables that were included in our final multivariable models.

The variable *sub-region,* which was modeled as a random intercept to account for potential clustering, was created by combining groups of adjacent municipalities, to avoid convergence issues where too few observations existed at the municipal level. This facilitated a more granular level of analysis than would have been possible using counties for the same purpose, as there were only two counties in the study area (Figures 1 and 2).

The assumptions of normality and homoscedasticity for the best linear unbiased predictors (BLUPS) were examined graphically using normal-quantile plots and by examining a scatter plot of the BLUPS against the predicted outcomes for each observation. Pearson residuals were also examined to identify potential outliers.

All statistical analyses were performed using the software program Stata 15 (StataCorp, College Station, TX).

RESULTS

Descriptive statistics

Of the 23 questions in the original survey, 13 were used in the study, since they related to well structure or location, owner characteristics and self-reported testing frequency. In the case of five of these questions, the variables necessitated reclassification to achieve greater power for our subsequent statistical analyses. This involved, for instance, collapsing the 5 options relating to the age of the well ('Under 1 year'; '1–10 years'; '11–35 years'; '36–75 years'; and 'More than 75 years') into 3 larger groupings ('Less than 11 years'; '11–35 years'; and 'More than 35 years'). For all of the questions included in our analyses, the response rates were fairly high, ranging from 84.8% to 100%.

Of the 632 survey records, 358 were successfully matched, by the addresses of the wells as entered by the respondents, to corresponding records of the PHOL testing dataset. For the purpose of our analyses, the remaining 274 surveyed households, for which no identifiable testing data could be found in the 2013–2017 PHOL database, were classified as non-testers for the laboratory-validated outcome. Based on survey responses, 32.2% (193/599) of households tested their water once or more times per year, while only 13.0% reported that they tested at least three times per year. However, based on the PHOL test data, only 16.3% (103/632) tested their water at least once per year and 2.0% at least thrice per year.

The vast majority (93.3%) of households responding to the survey indicated that they used their well water for drinking, but only 26.4% reported treating their water for bacteria and other contaminants (Table 1). According to the PHOL dataset, 16.3% of respondents had received an adverse bacteriological test result in the last five years; 9.7% of those had been reported by PHOL as overgrown with non-coliform bacteria. The majority (82.9%) of respondents reported that surface water drained away from their well (i.e., no water pooling near their wells). Similarly, 85.4% reported that none of the potential sources of bacteriological contamination listed as options on the survey (e.g., septic systems, barn, and sites where manure was stored or spread) were located within 15 meters of their well. Most (91.6%) of the respondents were the owners of the property, and 54.1% had resided at that location for at least a decade. The wells in this study were relatively old – at the time of the survey, only 18.2% were less than 11 years old and 27.6% were older than 35 years – and were also mainly drilled (79.0%). Most (66.7%) were fitted with secure caps (Table 1). With the exception of Shelburne, for which there were no testing data or survey responses, all the municipalities of Wellington and Dufferin counties were represented in the study (Figure 1), with 474 (75.0%) responses from the residents of municipalities in Wellington and 158 (25.0%) from Dufferin.

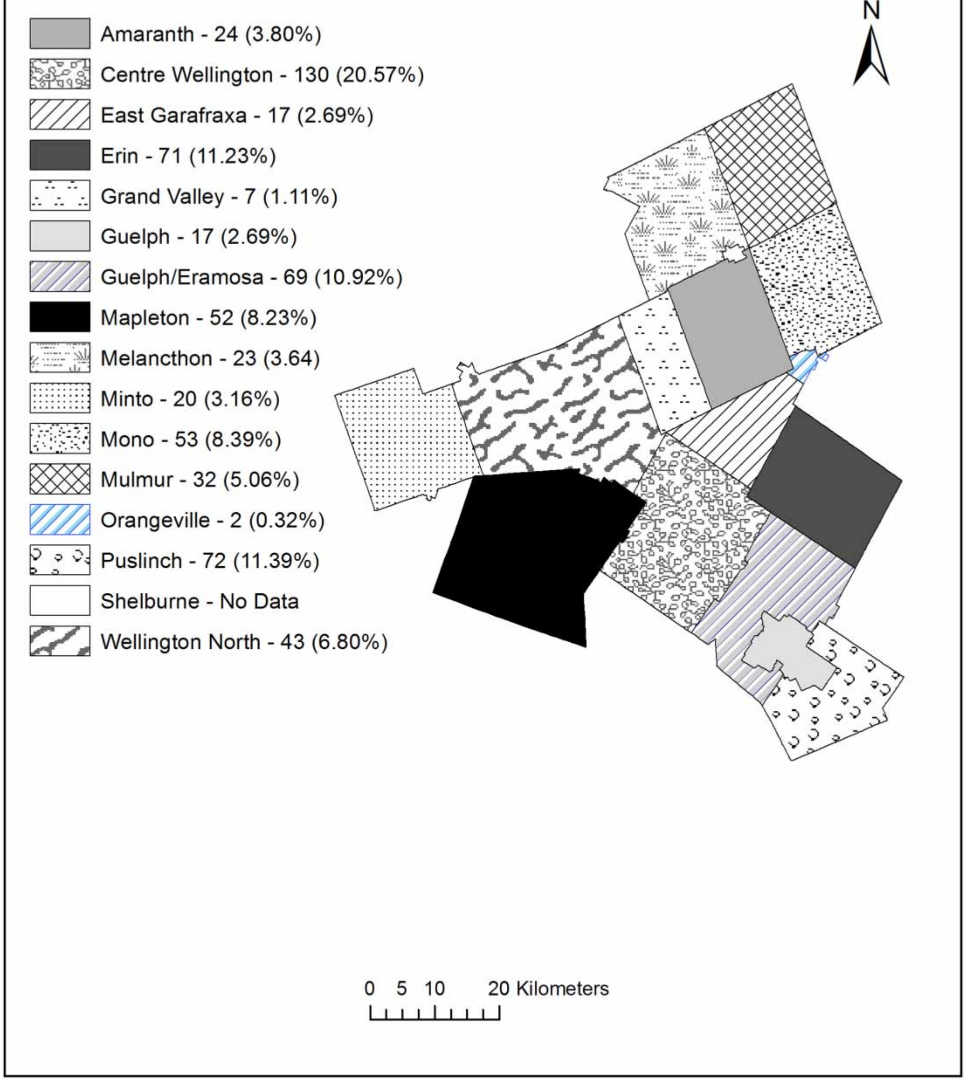

Figure 1 | Municipalities in Wellington (with City of Guelph) and Dufferin, showing the number and percentage of well water survey respondents from each municipality.

Based on a McNemar test, we found that the odds of being classified as a frequent tester were significantly greater when defined based on survey responses than when based on laboratory submissions (McNemar's $OR = 5.18$; 95% CI: 3.26–8.59; $p < 0.0001$). The level of agreement was fair to moderate between the two sources of information concerning testing behavior ($PABAK = 0.55$; 95% CI: 0.48–0.61 p-value: <0.001).

Univariable screening

For the owner-reported testing frequency outcome, the following variables were considered for inclusion in the multivariable model ($p \leq 0.20$): residence status of the survey respondent (e.g., owner of the property or other), water treatment, age of the well, height of the top of the well (well-head) relative to the ground, the presence of runoff, and the well having had at least one previous adverse result over the study period (Table 1). For the laboratory-validated testing frequency outcome, the following variables were considered for inclusion in the multivariable model: years at the property, age of well, presence of runoff, and previous adverse result (Table 1). There was no indication of high correlation among the independent variables based on Spearman rank and phi coefficients.

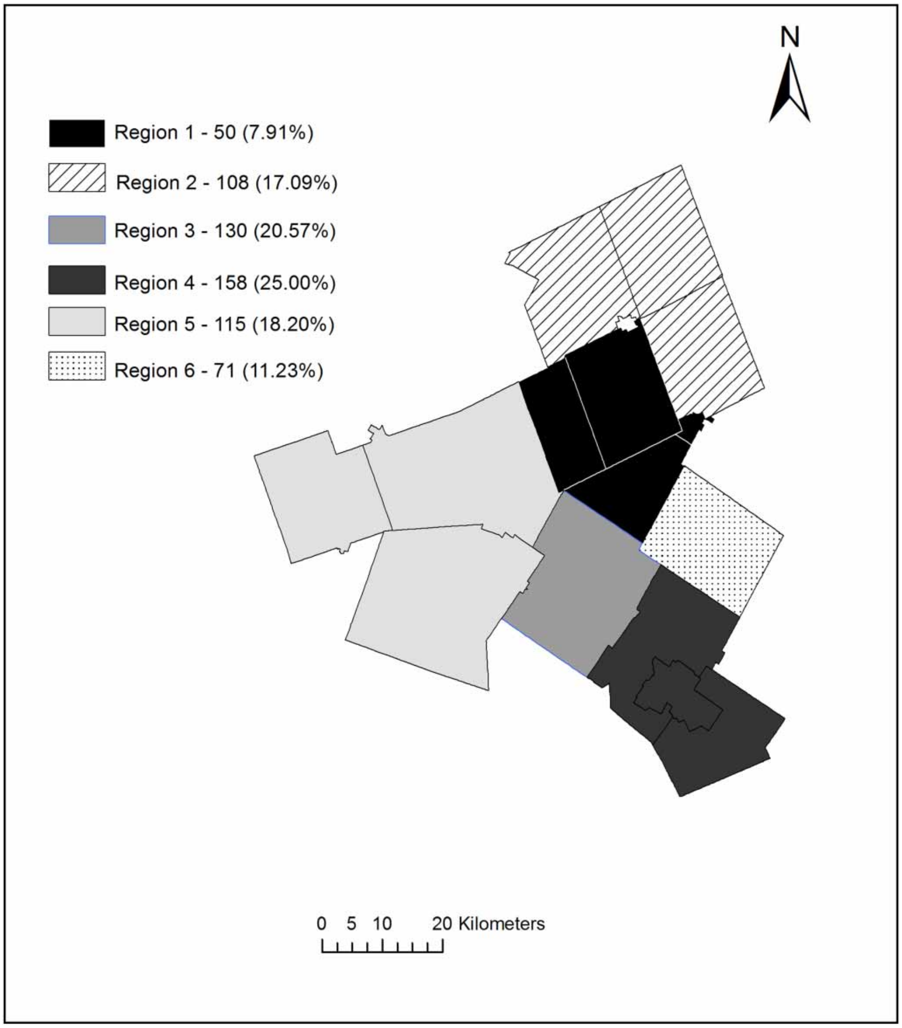

Figure 2 | Sub-regions of Wellington (with City of Guelph) and Dufferin, formed by collapsing groups of municipalities for statistical analysis of study data and represented by the variable sub-region, with the number and percentage of well water survey respondents from each sub-region.

Multivariable regression analysis

In the final multivariable model using the survey-based outcome, a well having had a previous adverse result significantly increased the odds of its having been tested at least once a year (Table 2). In addition, the odds of being tested at this frequency were greater if the well-head was at ground level or at least 16 inches (40.6 cm) above ground than if it was below ground or less than 16 inches above ground level (Table 2). In the final model with the laboratory-validated outcome, whether or not a well had had a previous adverse result was the only variable significantly associated with the odds of being classified as a frequent tester (Table 2). In addition, when this model was fitted without the variable previous adverse result (i.e., an intervening variable between well and owner characteristics and the outcome), only the length of occupancy was significantly associated with being classified as a frequent tester; respondents who had resided on their property for 1–5 years were at significantly greater odds of being classified as frequent testers compared to those who had resided on their property for less than one year or greater than five years (Table 2).

No significant interactions were identified in building the multivariable models. After assessing the BLUPS, each model met the assumptions of normality and

Table 1 | Associations between testing frequency[a] (self-reported and laboratory-validated) and well characteristics and adverse test history, based on univariable multi-level[b] logistic regression using the 2018 survey of well owners in Wellington and Dufferin counties

Predictor variable	Responses	Frequency distribution	$OR_{Self-reported}$ (95% CI)	*p*-Value	$OR_{Lab-validated}$ (95% CI)	*p*-Value
Residence status of survey respondent	632/632			**0.120**		**0.733**
		Homeowner living on the property – 579 (91.6%)	Referent		Referent	
		Not homeowner living on the property – 53 (8.4%)	1.60 (0.89–2.88)	0.120	0.87 (0.39–1.92)	0.734
Years at this property	631/632			**0.380**		**0.007**
		1–5 Years – 155 (24.5%)	Referent		Referent	
		6–10 Years – 97 (15.4%)	0.72 (0.42–1.26)	0.251	0.50 (0.25–0.98)	0.045
		>10 Years – 342 (54.2%)	0.71 (0.47–1.07)	0.101	0.47 (0.29–0.76)	0.002
		<1 Year – 37 (5.9%)	0.94 (0.43–2.07)	0.880	0.26 (0.08–0.91)	0.035
Used for drinking	629/632			**0.331**		**0.919**
		No – 42 (6.7%)	Referent		Referent	
		Yes – 587 (93.3%)	0.71 (0.35–1.43)	0.331	0.96 (0.41–2.22)	0.920
Water treatment	595/632			**0.217**		**0.045**
		Does not treat water – 438 (73.6%)	Referent		Referent	
		Treats water – 157 (26.4%)	1.29 (0.86–1.91)	0.217	1.62 (1.01–2.61)	0.046
Age of well	630/632			**0.188**		**0.193**
		11–35 Years – 248 (39.4%)	Referent		Referent	
		<11 Years – 115 (18.3%)	1.05 (0.65–1.69)	0.853	0.57 (0.29–1.14)	0.111
		>35 Years – 174 (27.6%)	0.64 (0.41–0.99)	0.047	1.00 (0.59–1.68)	0.987
		Unsure – 93 (14.7%)	0.94 (0.56–1.58)	0.823	1.35 (0.74–2.46)	0.325
Type of well	629/632			**0.408**		**0.043**
		Drilled well – 497 (79.0%)	Referent		Referent	
		Dug well – 62 (9.9%)	1.57 (0.89–2.79)	0.121	1.99 (1.05–3.75)	0.034
		Other – 7 (1.1%)	1.11 (0.20–6.22)	0.901	4.27 (0.93–19.7)	0.062
		Unsure – 63 (10.0%)	1.29 (0.74–2.26)	0.373	0.82 (0.38–1.80)	0.626
Depth of the well	628/632			**0.408**		**0.652**
		30–100 feet – 156 (24.9%)	Referent		Referent	
		>100 feet – 269 (42.8%)	1.29 (0.82–2.02)	0.267	1.09 (0.62–1.92)	0.753
		<30 feet – 24 (3.8%)	1.66 (0.65–4.21)	0.288	1.96 (0.70–5.50)	0.203
		Unsure – 179 (28.5%)	0.98 (0.60–1.59)	0.934	1.10 (0.61–2.01)	0.745
Top of the well relative to ground level	628/632			**0.0131**		**0.458**
		16 inches above ground level – 270 (43.1%)	Referent		Referent	
		At ground level – 59 (9.4%)	0.70 (0.38–1.30)	0.255	1.10 (0.54–2.22)	0.798
		Below ground level in an access pit – 98 (15.6%)	0.51 (0.29–0.87)	0.014	0.66 (0.34–1.28)	0.217
		Below ground level and non-accessible – 21 (3.3%)	0.17 (0.04–0.75)	0.020	0.45 (0.10–1.99)	0.291
		<16 inches above ground level – 119 (18.9%)	0.52 (0.32–0.85)	0.009	0.72 (0.39–1.30)	0.275
		16 inches above ground level – 270 (43.1%)	0.71 (0.39–1.32)	0.281	0.56 (0.24–1.30)	0.179

What kind of cap covers the well	617/632			**0.231**		**0.299**
		Cap that is easily removed – 21 (3.4%)	Referent		Referent	
		Cement cover; unsure if sealed – 73 (11.8%)	1.14 (0.38–3.47)	0.807	1.08 (0.31–3.77)	0.902
		Other – 20 (3.2%)	0.71 (0.16–3.13)	0.647	1.98 (0.46–8.57)	0.362
		Sealed or secure cement cover – 42 (6.8%)	1.88 (0.59–6.06)	0.289	1.23 (0.33–4.62)	0.760
		Tight fitting secure cap – 412 (66.8%)	1.20 (0.44–3.24)	0.727	0.81 (0.26–2.50)	0.712
		Unsure because it is buried – 36 (5.8%)	0.48 (0.13–1.80)	0.277	0.39 (0.08–1.97)	0.254
		Wooden/other easily removed material – 13 (2.1%)	*Omitted*	–	*Omitted*	–
Does the surface water drain away	629/632			**0.284**		**0.869**
		No, surface water regularly pools – 8 (1.3%)	Referent		Referent	
		No, surface water sometimes pools – 31 (4.9%)	0.97 (0.19–5.02)	0.975	0.76 (0.12–4.81)	0.771
		Unsure – 68 (10.8%)	0.48 (0.10–2.31)	0.360	0.54 (0.09–3.10)	0.490
		Yes – 522 (83.0%)	0.90 (0.21–3.85)	0.884	0.61 (0.12–3.09)	0.548
Potential sources of contamination runoff within 50 feet (15 meters)	536/632			**0.193**		**0.112**
		No such sources within 50 feet of well – 458 (85.4%)	Referent		Referent	
		Potential sources within 50 feet of well – 78 (14.6%)	1.40 (0.84–2.34)	0.193	1.63 (0.89–2.97)	0.112
Previous adverse result (from PHOL database)	632/632			< **0.001**		< **0.001**
		No previous adverse result – 529 (83.7%)	Referent		Referent	
		Previous adverse result – 103 (16.3%)	5.24 (3.31–8.28)	<0.001	11.51 (7.05–18.79)	<0.001

[a]Testing frequency (1 = tested at least once per year; 0 = tested less than once per year).
[b]Includes *sub-region* as a random intercept.

Table 2 | Associations between testing frequency[a] (self-reported and laboratory-validated) and well characteristics and adverse test history, based on multivariable multi-level[b] logistic regression using the 2018 survey of well owners in Wellington and Dufferin counties

Source	Self-reported OR/Point Estimate (95% CI)[a]	*p*-Value	Lab-validated OR[A] (95% CI)	*p*-Value	Lab-validated OR[B] (95% CI)	*p*-Value
		< 0.001		**<0.001**	N/A	N/A
Previous adverse result						
No	Referent	–	Referent	–		
Yes	5.12 (3.21–8.16)	<0.001	11.51 (7.05–18.80)	<0.001		
Top of the well						
16 inches above ground level	Referent	–	N/A	N/A	N/A	N/A
At ground level	0.72 (0.38–1.38)	0.326				
Below ground level in an access pit	0.48 (0.27–0.85)	0.012				
Below ground level & non-accessible	0.24 (0.05–1.05)	0.058				
Less than 16 inches above ground level	0.51 (0.30–0.85)	0.009				
Unsure	0.81 (0.43–1.52)	0.505				
Years at this property	N/A	N/A	N/A	N/A		
1–5 Years					Referent	–
6–10 Years					0.50 (0.26–0.98)	0.045
>10 Years					0.47 (0.29–0.76)	0.002
<1 Year					0.26 (0.08–0.91)	0.035
Sub-region: Variance components	0.04 [(4.53 × 10–02) – 0.43]	–	0.02 [(2.31 × 10–05) – 10.7]	–	0.02 [(5.96 × 10–04) – 1.15]	–
Sub-region: Intraclass correlation coefficients	0.01 [(1.37 × 10–03) – 0.11]	–	4.75 × 10–03 [(7.03 × 10–06) – 0.76]	–	7.90 × 10–3 [(1.81 × 10–4) – 0.26]	–

[a]Testing Frequency (1 = tested at least once per year; 0 = tested less than once per year).
[b]Includes *sub-region* as a random intercept.

homoscedasticity; also, no outlying observations were observed in graphical examination of the Pearson residuals. In each model, the ICC and variance component for the variable *sub-region* were small (Table 2).

DISCUSSION

The findings of this study indicate that, for the models fitted with the previous adverse test result variable, a well having had a previous adverse test result and, in the case of self-reported testing frequency, the reported height of the well-head, were significant indicators of well testing frequency among residents with private wells in Wellington and Dufferin counties. For the model fitted with the laboratory-validated outcome, without the inclusion of the adverse testing result variable, the length of occupancy significantly influenced the odds of being classified as a frequent tester. The strong relationship between previous adverse testing results and testing frequency was not unexpected; owners are encouraged by the government to further test their water following an adverse test result. Furthermore, studies have found that lack of urgency is the primary reason for the lack of testing and that the perceived potential for harm motivates owners to test following an adverse result (Roche *et al.* 2013). It should also be acknowledged, however, that because frequent testing might increase the risk of a well receiving an adverse test result, it is difficult from the results of our study to determine with any certainty whether adverse results predict the frequency of testing or whether, conversely, our findings simply reflect the fact that the risk of finding bacteriological contamination is increased by frequent testing.

The small ICCs and variance components indicated that autocorrelation among wells in the sub-regions defined for this study was negligible. In other words, rates of testing of wells within any region were not more alike than those of the wells outside it; in other words there was no apparent clustering by the sub-region. The difference between the results of this study and those of previously mentioned analysis of the 2011–2015 WDG data (Montague *et al.* 2018; Tschritter, unpublished results) is likely explained by the modeling approach used in this study and by the fact that only a subset of the wells in that 2018 study were included in the current analysis.

To date, to the authors' knowledge, there have been no published studies examining how well water characteristics and adverse testing affect owner testing practices. We hypothesized that adverse test results and factors that contributed to well water contamination would increase water testing frequency. The height of the well-head has been identified by researchers as an important factor related to the risk of contamination of well water (Hynds *et al.* 2012). In our study, wells with openings closer to the ground were, in general, significantly less likely to be tested than wells with openings at least 16 inches above the ground. While this may appear counter-intuitive due to the increased risk of contamination closer to the ground, the greater visibility of taller wells may provide visual cues to owners that prompt them to test more frequently.

A number of factors that reportedly influence the risk of contamination of well water were not found to be associated with testing frequency in this study. In particular, the presence of runoff commonly originating from agricultural land adjacent to a well, despite its known strong association with water contamination (Simpson 2004) and its widespread occurrence in Wellington and Dufferin counties, did not significantly affect testing frequency. Variables, such as well type, age, and depth, were also found to not be significantly associated with testing frequency in the multivariable models. However, the length of occupancy, in the laboratory-validated model fitted without the adverse test result variable, was significantly associated with being classified as a frequent tester; it appears that relatively new occupants of a property (i.e., occupancy 1–5 years) are more likely to be vigilant about testing their wells, with longer-term residents becoming more complacent about testing over time. Residents with a tenure of less than one year were also less likely to be categorized as frequent testers, possibly because of the lack of familiarity with testing procedures or simply not yet having had an opportunity to test their well. There was no prior literature found that examined whether respondent characteristics such as homeowner vs. tenant status or time lived at a property were related to testing frequency.

It would be reasonable to expect that those who test frequently even in the absence of adverse results might be more knowledgeable of the factors that contribute to water safety and more proactive in their testing habits. Analysis of data that includes individuals of this group in sufficient numbers might find that the risk factors for water contamination identified in the literature played a significant role in their frequency of testing; in this study, however, few respondents tested at least once a year in the absence of previous adverse testing results. Studies have demonstrated that Canadians using private wells for drinking water rated their water quality highly but desired more information on well stewardship (Jones *et al.* 2006). Lack of such knowledge among our study respondents may possibly explain our non-significant results concerning well characteristics related to adverse testing in predicting testing frequency; well owners may be motivated to test their wells following an adverse result by the perceived risk to health, but may not actually have knowledge about what factors contribute to contamination, or an accurate sense of their own well's risk for contamination.

It is also possible that lack of respondents' accurate knowledge concerning the characteristics of their wells may have adversely affected our results through misclassification bias; survey respondents might not have had sufficiently accurate information about the properties of their wells to provide the correct information when answering questions. When questions gave the option to answer 'unsure', there were substantial numbers (i.e., >10%) of respondents who chose this option, suggesting that knowledge about their wells may have been limited among respondents. The potential consequences of the lack of familiarity on the part of owners with the characteristics of their wells, and with what characteristics make wells vulnerable to contamination, should not be underestimated when crafting public health messaging.

The significant differences between self-reported testing frequency based on the survey and the testing frequency variable that was based on PHOL data suggest that survey tools may be unreliable for estimating true testing frequency in this population. We found that self-reported testing frequencies were substantially higher than the actual laboratory data revealed, for which there are several possible explanations. One is that some well owners identified as non-testers based on the PHOL database may have been misclassified as such. This, for example, could have been the result of individuals testing their water in laboratories outside the PHOL network, despite public health offering free testing services. This is not thought to be a common practice; however, for the purpose of our analyses, any such respondents would have been incorrectly classified as non-testers. There may be some possibility that results for the wells of some survey respondents may have been missed in the laboratory database; over the years, some rural addresses have changed (e.g., from rural route numbers to civic street numbers or from one postal area to another), and this can make the identification and linking of addresses difficult in some cases. Some households may also be testing their own water at home with the use of private water testing products instead of at the government laboratory. In addition, although representative of only a small proportion of testers, any results for water samples submitted by WDG residents that indicate the wrong health unit would be returned not to WDGPH but to the health unit indicated on the form. As a result, these tests would not have been recorded in our WDGPH database, and those residents would have been classified as non-testers for the laboratory-validated testing-based outcome. Finally, another explanation for the difference in the proportions of frequent testers between the two dependent variables may have been recall bias or even the well-recognized phenomenon of some self-reported behaviours often reflecting a higher level of compliance with recommended practice than might actually be the case – the so-called social desirability bias (Nederhof 1985); participants may have inflated the frequency of their testing habits so as to appear more responsible about well management when faced with inquiries from an official health agency.

The investigation of risk factors for adverse results in WDG should be regarded as an additional area for future research, but the ability of well owners to provide accurate self-reported information should be a concern when conducting these studies; some means of validating survey responses should be considered. Furthermore, an investigation of the potential associations between the frequency of well water testing, and between the risk of adverse bacteriological test results, and specific waterborne illnesses might provide important information on the source of gastrointestinal illness in rural areas of WDG and possibly elsewhere.

The results of this study could be used to support public health efforts to promote well safety education and well testing. Efforts to develop low-cost approaches to obtaining more accurate measures of well characteristics and testing frequency would facilitate such program activities and the collection of more reliable data for surveillance and research.

CONCLUSIONS

Based on our analyses using self-reported and laboratory-validated outcomes, a consistent factor associated with the testing frequency of private wells for microbial contaminants in Wellington and Dufferin counties appears to be a history of an adverse result. Based on self-reported testing frequency, it appeared that in general, in addition to a previous adverse test result, the higher the well-head, the more likely residents were to report having tested their wells at least once annually. These results may reflect a knowledge gap among private well users, where they fail to recognize well characteristics that produce a higher risk of bacteriological contamination. Based on the laboratory-validated outcome, it appears that diligence about testing frequency declines with the length of occupancy. Future health promotion work should aim to educate well users on stewardship and the importance of testing, while also validating self-reported statistics to obtain a more accurate picture of wells in WDG. Survey responses appear to be poor indicators of true testing frequency, as respondents may tend to inflate the degree to which they actually have their water tested for bacteria.

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