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Development of a hierarchical model for predicting microbiological contamination of private groundwater supplies in a geologically heterogeneous region☆

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ABSTRACT

Private groundwater sources in the Republic of Ireland provide drinking water to an estimated 750,000 people or 16% of the national population. Consumers of untreated groundwater are at increased risk of infection from pathogenic microorganisms. However, given the volume of private wells in operation, remediation or even quantification of public risk is both costly and time consuming. In this study, a hierarchical logistic regression model was developed to 'predict' contamination with *E. coli* based on the results of groundwater quality analyses of private wells (n = 132) during the period of September 2011 to November 2012. Assessment of potential microbial contamination risk factors were categorised into three groups: Intrinsic (environmental factors), Specific (local features) and Infrastructural (groundwater source characteristics) which included a total of 15 variables. Overall, 51.4% of wells tested positive for *E. coli* during the study period with univariate analysis indicating that 11 of the 15 assessed risk factors, including local bedrock type, local subsoil type, septic tank reliance, 5 day antecedent precipitation and temperature, along with well type and depth, were all significantly associated with *E. coli* presence ($p < 0.05$). Hierarchical logistic regression was used to develop a private well susceptibility model with the final model containing 8 of the 11 associated variables. The model was shown to be highly efficient; correctly classifying the presence of *E. coli* in 94.2% of cases, and the absence of *E. coli* in 84.7% of cases. Model validation was performed using an external data set (n = 32) and it was shown that the model has promising accuracy with 90% of positive *E. coli* cases correctly predicted. The developed model represents a risk assessment and management tool that may be used to develop effective water-quality management strategies to minimize public health risks both in Ireland and abroad.

1. Introduction

It is estimated that private groundwater sources in the Republic of Ireland provide domestic drinking water to approximately 750,000 people or 16% of the population, with many thousands more served on a non-domestic, intermittent basis (CSO, 2012a). Similarly, private wells supply 4.1 million Canadians (11.7%) and 45 million Americans (14.1%), with private wells constituting the largest proportion of water wells in both countries (Hynds et al., 2014b, Murphy et al., 2016). A further 200–500 million Europeans are reliant on groundwater for their domestic supply (Job, 2010). Private groundwater supplies in Ireland typically comprise two source types, namely, small private supplies (SPS) serving individual households, and private group water schemes (PrGWS), which typically supply <50 persons and/or <10 m^3d^{-1}. Both supply types are exempt from the European Commission Drinking Water Directive (DWD) 98/83/EC (EU 1998) and hence water treatment is entirely voluntary, and if employed, the sole responsibility of the owner/caretaker. Hynds et al. (2013), report that 64% of interviewed private well owners (n = 245) in the Republic of Ireland did not

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utilise an appropriate domestic water treatment system.

Rural Ireland is home to approximately 38% (1.76 million) of the national population, and is characterized by a heavily dispersed yet locally dense settlement pattern (Scott and Murray, 2009), with most settlements comprised of individual private or "one-off" dwellings situated outside urban administrative zones (Duffy, 2000, CSO, 2012b). The spatial distribution of private groundwater supplies thus exhibits a marked Urban:Rural divide accredited to the reduction in piped infrastructure, in concurrence with decreased population density (Óhaiseadha et al., 2017). Moreover, SPS reliance in rural Ireland is increasing; during the period 2006–2011, SPS use rose from 74.3% to 76.1%, likely due to accelerated private property development prior to the global recession (CSO, 2012b). Subsequently, due to the combined effects of high private groundwater source reliance, the rural ubiquity of private domestic wastewater treatment systems and pastoral agriculture, a temperature maritime climate, and diverse bedrock and quaternary geology, Ireland may be considered to represent the "perfect storm" with respect to groundwater susceptibility to contamination.

The association between groundwater contamination and waterborne disease has long been acknowledged, with Dr John Snow (1813–1858) establishing the source of a significant cholera outbreak in the London district of Soho during the summer of 1854, as being from a faecally contaminated public well (Donaldson, 2002). More recently, Murphy et al. (2017) have presented clear epidemiological evidence of the transmission of disease through groundwater contamination on a global scale. A review of waterborne outbreaks of enteric infection in the Nordic region over a 15-year period (1998–2012) by Guzman-Herrador et al. (2015) reports that 76% ($n = 124$) of outbreaks with a confirmed source were associated with groundwater. Overall, Guzman-Herrador et al. (2015) found that a majority of outbreaks were associated with single household (i.e. private) water supplies, while 35% of outbreak clusters were confined to a single household. Moreover, where factors contributing to the waterborne outbreak had been confirmed, 96% of outbreaks associated with private groundwater supplies were deemed to have occurred due to source (well) contamination. Similarly, Pitkänen et al. (2015) note that the presence of *Aeromonas* and *Giardia* among a cohort of 20 vulnerable small (<500 consumers) groundwater supplies in Finland, highlights the significant potential adverse health effects of pathogen ingress to groundwater sources. In the United States (Wallender et al., 2014), have found that 30.3% of 818 drinking water outbreaks reported to the US Centre for Disease Control (CDC) between 1971 and 2008 were attributable to untreated groundwater sources.

Of particular significance within the Irish context is the prevalence of verotoxigenic *E. coli* (VTEC) infection which has been linked to private water supplies (Hynds et al., 2014a, O'Dwyer et al., 2014, Óhaiseadha et al., 2017). Ireland has had the highest crude incidence rates (CIR) of VTEC in Europe, increasing from 3.9/100,000 in 2007 to 15.3/100,000 in 2013 (HPSC, 2015). O'haiseadha et al. (2017) report that during the period 2008–2013, private well usage was significantly associated (OR 6·896, $p < 0·001$) with the incidence of confirmed primary VTEC O157 infection, while Hynds et al. (2014a) predict an endemic VTEC CIR of 28.3/100,000 private well users per annum; as much as 5–6 times that of the national population. Furthermore, recent work by O'Dwyer et al. (2017) reports that 21.4% of *E. coli* isolates recovered from a cohort of private wells in the mid-west of Ireland exhibited resistance to $\geq$1 human antibiotic, with 100% of isolates presenting resistance to $\geq$1 veterinary antibiotic. Accordingly, there is little doubt that the human health risks posed to private groundwater consumers in the Republic of Ireland are potentially significant, and likely increasing. However, due to the dispersed, decentralised nature of these sources in Ireland and abroad, in addition to their abundance, appropriate monitoring, maintenance, and remediation is both complex and financially prohibitive.

Groundwater microbial quality may be affected by myriad environmental and source-specific risk factors, including well design, location and maintenance, septic system location and maintenance, local hydrogeological setting, and significant climatic events (e.g. flooding, snowmelt, etc.) (Hynds et al., 2012; Wallender et al., 2014; Atherholt et al., 2017; Andrade et al., 2018). Moreover, groundwater pathogens may derive from multiple human or animal faecal sources such as adjacent septic systems, livestock grazing, manure spreading and/or farmyards (Kozuskanich et al., 2014; Wallender et al., 2014). Recent work has shown that up to 70% of source contamination occurs via "localized" pathways, as opposed to "generalized" aquifer contamination (Hynds et al., 2012, 2014a, b), with groundwater contamination risk (susceptibility) typically increasing in areas characterized by high hazard (i.e. faecal source) densities in concurrence with inappropriate setback distances/gradients, with this relationship mediated by local hydrogeological characteristics e.g. hydraulic conductivity, aquifer productivity, etc. (Bremer and Harter, 2012; Hynds et al., 2014a, b). A relatively recent study of monitoring wells in eastern Ontario detected the presence of both human and animal pharmaceuticals in groundwater, suggesting that feacal indicator bacteria (FIB) were from both human and animal sources (Kozuskanich et al., 2014). While well siting and construction regulations exist in an effort to prevent drinking water contamination, waterborne AGI outbreaks may still occur where infrastructure predates regulation, or when assessments do not properly account for the geological vulnerability of the well area (Bremer and Harter, 2012). Similarly, Atherholt et al. (2017) have shown FIB detection rates are significantly reliant on recent climatic conditions, and particularly local 10-day cumulative antecedent precipitation, in addition to groundwater physical chemistry.

Consequently, there is a need for identifying areas of concern with respect to effective custodianship and development of focused environmental health policy. Accordingly, the current study sought to identify and quantify the associated environmental and social factors affecting the susceptibility of private water wells to contamination. The spatial and temporal distribution of groundwater *E. coli* presence in the mid-western region of Ireland has been examined via a mixed methods approach which comprised a 13-month field sampling programme, a formalised source owner survey, and geostatistical analysis. Collated risk factor variables have been characterised as increasing the Intrinsic (environmental factors), Specific (local (sampling area) features) or Infrastructural (groundwater source and domestic wastewater treatment system characteristics) susceptibility to contaminant ingress, and subsequently employed to develop a predictive hierarchical logistic model of private source contamination. It is considered that the employed approach and subsequent findings are internationally transferable, and may be used by water resource managers, private well owners/users, and local/national governments to support evidence-based risk management and develop quantitative source protection strategies.

2. Materials and methods

2.1. Study area

The study region is situated in the mid-west of Ireland, extends 8248 km^2 (11% of total area of the Republic of Ireland), and comprises three administrative counties (Limerick, Clare and North Tipperary) (Fig. 1). Regional climate is described as temperate