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Groundwater source contamination mechanisms: Physicochemical profile clustering, risk factor analysis and multivariate modelling

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ABSTRACT

An integrated domestic well sampling and "susceptibility assessment" programme was undertaken in the Republic of Ireland from April 2008 to November 2010. Overall, 211 domestic wells were sampled, assessed and collated with local climate data. Based upon groundwater physicochemical profile, three clusters have been identified and characterised by source type (borehole or hand-dug well) and local geological setting. Statistical analysis indicates that cluster membership is significantly associated with the prevalence of bacteria ($p = 0.001$), with mean *Escherichia coli* presence within clusters ranging from 15.4% (Cluster-1) to 47.6% (Cluster-3). Bivariate risk factor analysis shows that on-site septic tank presence was the only risk factor significantly associated ($p < 0.05$) with bacterial presence within all clusters. Point agriculture adjacency was significantly associated with both borehole-related clusters. Well design criteria were associated with hand-dug wells and boreholes in areas characterised by high permeability subsoils, while local geological setting was significant for hand-dug wells and boreholes in areas dominated by low/moderate permeability subsoils. Multivariate susceptibility models were developed for all clusters, with predictive accuracies of 84% (Cluster-1) to 91% (Cluster-2) achieved. Septic tank setback was a common variable within all multivariate models, while agricultural sources were also significant, albeit to a lesser degree. Furthermore, well liner clearance was a significant factor in all models, indicating that direct surface ingress is a significant well contamination mechanism. Identification and elucidation of cluster-specific contamination mechanisms may be used to develop improved overall risk management and wellhead protection strategies, while also informing future remediation and maintenance efforts.

1. Introduction

Private groundwater sources in the Republic of Ireland are often poorly maintained, largely un-monitored and unregulated; they are the primary drinking water supply for an estimated 210,000 households or 14–15% of the Irish population (CSO, 2012). Two principal private supply types exist in Ireland: private, unregulated groundwater supplies typically serving individual households; and private group water schemes serving <50 people (EPA, 2010). Similarly, large consumer numbers rely on private domestic wells in other developed countries; for example, McDonald et al. (2005) estimate that there are 20,000–30,000 private groundwater wells currently in use in Scotland, while an estimated 3–4 million Canadians (13%) are served by private supplies (Charrois, 2010; Corkal et al., 2004). Private domestic wells constitute the largest share of water wells in the United States — more than 13.2 million year-round occupied households have their own well, supplying 45 million people (US

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Bureau of the Census, 2008). The majority of aquifers in the Republic of Ireland are composed of consolidated bedrock formations in which groundwater storage and transmission primarily occur in fractures (i.e. secondary porosity). Accordingly, bedrock type is paramount with regard to the overall groundwater yielding potential of Irish aquifers (IGI, 2007). It is considered that limited attenuation of contaminants typically occurs in the bedrock due to the relatively rapid nature of fissure flow; thus, the overlying subsoils act as the primary protective layer for attenuating contaminants. Consequently, subsoil type and thickness are the most important natural features influencing groundwater vulnerability and groundwater contamination in Ireland (Misstear and Fitzsimons, 2007; Swartz et al., 2003). The two most important and common subsoil types in Ireland are glacial deposits (tills) and glaciofluvial sand and gravel deposits.

A large proportion of private groundwater sources, both in Ireland and abroad, are situated in rural areas; accordingly, a multitude of potential point and non-point pathogen sources are present. These include diffuse agricultural sources such as grazing animals and land-spreading, point agricultural sources including farmyards, silage pits and animal housing and point sources such as on-site wastewater treatment systems, solid waste landfill sites and road runoff (Borchardt et al., 2003; Giannoulis et al., 2005; Rozemeijer and Broers, 2007). There are two main processes by which domestic wells may become contaminated: generalised aquifer contamination and localised “source-specific” contamination (Godfrey et al., 2006). Hynds et al. (2012) further classify localised mechanisms as being related to direct ingress at the wellhead or due to rapid and/or shallow groundwater pathways. Hence, areas dominated by low permeability subsoils may exhibit higher than expected levels of domestic well contamination, particularly in the case of poorly designed or constructed wells, due to direct ingress of contaminants at the wellhead. Localised pathways may be developed through poor design, construction and/or operation of private groundwater supplies, particularly areas with low permeability soils and subsoils that generate high runoff. More generalised groundwater pathways may exist due to the hydrogeological setting in a particular area, including bedrock type, subsoil type and depth (groundwater vulnerability) and aquifer importance (Godfrey et al., 2006; Hynds et al., 2012). Aquifers can be classified in terms of their importance using multiple criteria (Olaniyan et al., 2010; Payne and Woessner, 2010). In Ireland, aquifer classification is based primarily on the overall aquifer productivity (potential) yield and areal extent of the aquifer. These factors are amalgamated to formulate an overall aquifer value as a groundwater resource (Table 1). There are three main aquifer categories (Regionally important, Locally important and Poor aquifers) defined in Groundwater Protection Schemes (DoELG/EPA/GSI, 1999), further subdivided into nine categories (Table 1).

Based upon previous work by the authors (Hynds et al., 2012), the objective of the current study is to further elucidate domestic well contamination mechanisms in diverse geological regions, using the Republic of Ireland as a case-study. To date, little research has focused specifically on this topic. The overall study approach and findings will aid water managers, well users and local government in improving risk management decisions and developing evidence-based quantitative wellhead protection strategies. Moreover, where contamination has occurred, results may be used to inform remediation and maintenance efforts.

2. Materials and methods

2.1. Study areas

In all, 211 private groundwater sources over four study areas were assessed, sampled and included in the current study (Fig. 1). Study areas were selected using developed inclusion/exclusion criteria to maximise (hydro)geological and source type representivity with respect to the Republic of Ireland. Descriptions of the selection procedures and the study areas have been given previously in Hynds et al. (2012). Inclusion/exclusion criteria included: groundwater vulnerability, availability of previous monitoring data, well density, laboratory proximity and hydrogeological mapping status. Three areas of *High* or *Extreme* groundwater vulnerability were selected for study. Additionally, one area categorized as *Low* vulnerability was selected for comparative purposes (Table 2).

2.2. Sample analysis

Groundwater samples were obtained in accordance with Standard Methods (APHA/AWWA/WEF, 2005), while all on-site analyses were undertaken in accordance with USGS National Field Manual for the Collection of Water Quality Data (USGS, 2005). Sterilised 500 ml glass bottles were used for sample collection, whereupon samples for *Escherichia coli* analysis were immediately transferred to a cooler and transported to a laboratory. Time between sample collection and microbial analysis did not exceed 6 h. All physicochemical parameters were measured in the field and recorded. Groundwater

Table 1
Aquifer classification in the Republic of Ireland.

	Regionally important (R)	Locally important (L)	Poor (P) aquifers
Sub-categories	• Karstified where conduit flow is dominant (Rk) • Fractured bedrock aquifers (Rf) • Extensive sand/gravel aquifers (Rg)	• Sand/gravel (Lg) • Generally moderately productive (Lm) • Moderately productively in local zones (Ll) • Karstified (Lk)	• Generally unproductive except for local zones (Pl) • Generally unproductive (Pu)
Criteria for main aquifer categories	- Areal extent >25 km^2 - Well yields >400 m^3 d^{-1} - Specific capacities >40 m^3 d^{-1} m^{-1} - Occurrence of large springs	- Areal extent <25 km^2 - Well yields 100–400 m^3 d^{-1}	- Well yields typically <100 m^3 d^{-1} (<40 m^3 d^{-1} in Pu sub-category)

(Adapted from Misstear and Daly, 2000).