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Geophysical and hydrogeological characterisation of the impacts of on-site wastewater treatment discharge to groundwater in a poorly productive bedrock aquifer

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HIGHLIGHTS

- Multidisciplinary approach defines pollutant plume in a poorly productive aquifer.
- Geophysics helps define domestic wastewater effluent extent and aquifer geometry.
- Ground attenuates wastewater pollutants despite the absence of significant vadose zone.
- Faecal indicator microorganisms impacted groundwater quality at 100 m + from source.

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ABSTRACT

Contaminants discharging from on-site wastewater treatment systems (OSWTSs) can impact groundwater quality, threatening human health and surface water ecosystems. Risk of negative impacts becomes elevated in areas of extreme vulnerability with high water tables, where thin unsaturated intervals limit vadose zone attenuation. A combined geophysical/hydrogeological investigation into the effects of an OSWTS, located over a poorly productive aquifer (PPA) with thin subsoil cover, aimed to characterise effluent impacts on groundwater. Groundwater, sampled from piezometers down-gradient of the OSWTS percolation area displayed spatially erratic, yet temporally consistent, contaminant distributions. Electrical resistivity tomography identified an area of gross groundwater contamination close to the percolation area and, when combined with seismic refraction and water quality data, indicated that infiltrating effluent reaching the water table discharged to a deeper more permeable zone of weathered shale resting on more competent bedrock. Subsurface structure, defined by geophysics, indicated that elevated chemical and microbiological contaminant levels encountered in groundwater samples collected from piezometers, down-gradient of sampling points with lower contaminant levels, corresponded to those locations where piezometers were screened close to the weathered shale/competent rock interface; those immediately up-gradient were too shallow to intercept this interval, and thus the more impacted zone of the contaminant plume. Intermittent occurrence of faecal indicator bacteria more than 100 m down gradient of the percolation area suggested relatively short travel times. Study findings highlight the utility of geophysics as part of multidisciplinary investigations for OSWTS contaminant plume characterisation, while also demonstrating the capacity of effluent discharging to PPAs to impact groundwater quality at distance. Comparable geophysical responses observed in similar settings across Ireland suggest the phenomena observed in this study are more widespread than previously suspected.

1. Introduction

Residential on-site wastewater treatment systems (OSWTS), where wastewater discharges to the subsurface, act an important means of domestic wastewater disposal in many parts of the world where reticulated sewerage proves unavailable. This includes concentrated occurrence in urban areas in developed and developing countries (Hatt et al., 2004; Viraraghavan, 1976), and more diffuse occurrence in rural areas (Hoxley and Dudding, 1994; Withers et al., 2011) In Ireland it is estimated that approximately one third of all private dwellings use these systems (CSO, 2012), particularly in rural areas where they constitute the principle technology employed for sewage treatment and wastewater disposal.

OSWTS can be broadly divided into two categories, septic tank systems and secondary treatment systems (e.g. mechanical aeration

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systems, filter systems, constructed wetlands). In both cases treatment of effluent should ideally render it innocuous with no significant impact on groundwater quality (Jenssen and Siegrist, 1990; van Cuyk et al., 2001). Processes operating in the vadose zone receiving OSWTS play a significant role in attenuating contaminants before they reach groundwater (van Cuyk et al., 2001). These include a variety of natural physical, chemical and biological processes, which remove microbiological and chemical pollutants (van Cuyk et al., 2001). The capacity of subsoil to appropriately receive and treat the wastewater, depends on its physical and geochemical properties of the receiving medium, including porosity, organic matter content, ion exchange capacity, unsaturated subsoil thickness separating effluent percolation areas from the water table, and permeability (Beal et al., 2005). Physical properties and loading rates influence the residence time of wastewater percolating through the vadose zone. Since the permeability (K) of the soil varies with water content, wastewater flows more slowly through unsaturated subsoil, as described by the Richards Equation, thereby providing a greater opportunity for time-dependant chemical and biological processes to influence water quality. This, along with the availability of oxygen, enables decomposition and biodegradation of various contaminants (Canter and Knox, 1985). Conversely, the absence of a sufficiently thick vadose zone can result in reduced effluent attenuation capacity, elevating risk of contaminant delivery to human and surface water receptors.

In the Republic of Ireland, groundwater is classified as having “extreme vulnerability” if bedrock is located within 3 m of the surface (DELG/EPA/GSI, 1999). It is estimated that 37% of land area of the Republic of Ireland falls within this category (Dr. Robert Meehan, Pers. comm), leaving groundwater at risk of contamination where OSWTS have been inappropriately sited in these areas. As Bales et al. (1995) demonstrated, the wider impacts of OSWTS effluent on groundwater will depend on contaminant migration rates, which in turn are a function of the geological and hydrogeological properties of aquifers.

Although they are generally not considered to be important sources of water supply, poorly productive aquifers (PPAs) are believed to be important for baseflow and nutrient delivery to surface water receptors via shallower groundwater pathways, notably through relatively permeable transitional basal subsoil units and adjacent weathered bedrock (Moe et al., 2010). In Ireland, PPAs immediately underlie over 65% of the total land area (Comte et al., 2012). These often occur in extreme vulnerability settings. Despite their widespread occurrence, hydrogeological processes operating in PPAs, including contaminant transport and attenuation, remain poorly understood, largely as a consequence of a lack of studies arising from their perceived low productivity as groundwater supplies. However, promulgation of the EU Water Framework Directive requires member states to develop an integrated view of water resources and pressures threatening groundwater and surface water quality in catchments; this includes assessing the impacts of OSWTS on groundwater quality in PPAs (European Commission, 2000).

Ordovician and Silurian lithified sandstone (greywacke) and shale units are considered as PPAs (Moe et al., 2010). Despite their wide distribution across Europe (UK, Ireland, Scandinavia) (McKerrow, 1981; Andersson, 1985) and Eastern North America (Sloss, 1963) and their local use as domestic water supplies, their role as units facilitating groundwater flow in the near surface remains poorly defined (Robbins, 2002), Comparable shale and greywacke deposits occur widely elsewhere around the globe. The presence of pyrite, organic matter and carbonate, particularly in shales, can make these units susceptible to chemical weathering (Littke et al., 1991), while at the same time these substances, and associated chemical weathering by-products, such as iron oxides, can influence contaminant fate and transport in groundwater systems (Tesoriero et al., 2000; Ryan et al., 1999). The effects of chemical weathering are considerably less pronounced in more recently glaciated terrains, where physical weathering dominates (Summerfield, 1991). The impact of these conditions on contaminant mobility in shale and greywacke groundwater systems in Northern Europe remains poorly characterised despite the presence of widespread pressures that may affect water quality.

Characterising hydrogeological processes operating in PPAs can prove challenging. Geological conditions are often poorly defined compared to more productive aquifers, despite significant progress in this area in recent years (Nitsche, 2014; Moe et al., 2010; Comte et al., 2012). On the other hand an understanding of the configuration and distribution of hydrogeological properties in the subsurface forms the cornerstone of realistic conceptual model development. Studies on PPAs, completed to date, show that although they can have highly heterogeneous subsurface configurations, their geometry can be better constrained by geophysics (Comte et al., 2012; Cassidy et al., 2014). These configurations in turn can influence contaminant transport rates and, depending on conditions encountered along flow paths, also affect attenuation processes.

Geophysical methods have also been used by a number of authors for detecting, characterising and monitoring contaminants derived from domestic and/or industrial waste storage/disposal facilities (landfills). Electrical and electromagnetic methods often prove useful for detection of ionic contaminants that increase pore fluid conductivity (thereby reducing the bulk resistivity). Applications of these techniques for detecting and monitoring contaminant plumes and for predicting future contaminant pathways have been described by many authors (e.g. Aristodemou and Thomas-Betts, 2000; Buselli and Lu, 2001; Martinho and Almeida, 2006; Santos et al., 2006; Lee et al., 2006; Perozzi and Holliger, 2008; Casado et al., 2015). A number of authors have also demonstrated reasonable correlations between apparent electrical resistivity/conductivity (EC_a) and concentrations of various chemicals in groundwater, including those that may contain microbiological contaminants. For example, EC_a has been correlated with concentrations of K^+, Na^+, Cl^-, SO_4^{2-}, NH_4^+, and NO_3^- in soils affected by animal manure wastes (Eigenberg et al., 1998; Martínez-Pagán et al., 2009; Ranjan and Karthigesu, 1995; Stevens et al., 1995). By contrast, more limited research has been published on the use of geophysics for assessing contaminants resulting from wastewater treatment systems (e.g. Lee et al., 2006; Donohue et al., 2010).

By utilising a combined geophysical/hydrogeological approach, this study aimed to investigate the impact of OSWTS effluent on groundwater quality in a poorly productive shale and greywacke aquifer with a shallow water table. Selection of a subset of a suite of water quality parameters focusing on (a) a non-reactive chemical constituent (Chloride) and (b) microbiological parameters, whose concentrations depend on residence time in groundwater systems, provided a basis for refining a conceptual model of the physical hydrogeology of the system by integrating findings with water level, hydraulic conductivity and geophysical data.

2. Methodology

2.1. Site description

The Drumaliss Test Site is located within the Lough Muckno Catchment, Co. Monaghan, Ireland (Fig. 1). An abstraction point draws water from the lake to provide three towns with potable water. Owing to community concern regarding the deterioration of the raw water quality, the Lough Muckno catchment has been the subject of an intensive water quality monitoring programme. A catchment-wide survey identified the principal water quality pressures as poor farmyard practices, cattle access to streams, and runoff from slurry and synthetic fertiliser spreading (McCarthy et al., 2010). However, the impact of other types of contamination on water quality within the poorly drained sub-catchment containing the test site has warranted more detailed investigation of domestic wastewater delivery mechanisms to surface water bodies. Based on these observations, a site-specific environmental monitoring programme aimed to assess the impact of OSWTS effluent