10 – REPEATED MEASURES RISK ASSESSMENT OF THE 2018 EUROPEAN DROUGHT ON MICROBIAL GROUNDWATER QUALITY IN SOUTHERN IRELAND

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Abstract

Global climate change models predict significant increases in the frequency and severity of extreme weather events, including the occurrence of prolonged drought conditions, thus posing a unique set of challenges for regions traditionally unaccustomed to severe climatic phenomena. This is particularly notable regarding the occurrence of drought periods in areas characterised by temperate maritime climates, such as the Republic of Ireland (ROI), and their potential impact on our national groundwater resources. Notwithstanding the importance of groundwater availability during absolute or near drought conditions, research over the past two decades has brought the direct and indirect links between climate change and groundwater quality into sharp focus. However, to date, little research has sought to explore the relationship between drought conditions and microbial groundwater quality in i) private (unregulated) groundwater sources, or ii) temperate maritime climates not typically associated with extreme climatic events. Accordingly, the 2018 (June-August) European drought event represented a unique opportunity to investigate the effects of prolonged low rainfall and elevated temperatures (relative to seasonal means) on the incidence of faecal indicator organisms (FIOs) among unregulated domestic groundwater supplies in the south west (Co. Cork) of the ROI. A repeated-measures fieldwork regime (i.e. during and post-event) of private well sampling ($n = 74$) and subsequent risk factor analysis was used to evaluate the potential role of meteorological and site-specific hydro(geo)logical conditions on the incidence of microbial contamination. *Escherichia coli* (*E. coli*) were present during both drought (7/74; 9.5%) and post-drought (18/74; 24.3%) sampling periods. The relatively high level of *E. coli* contamination during drought conditions was unexpected, due to the likely absence of recharge/infiltration for microbial transport, tentatively suggesting some level of subsurface bacterial adaptation. However, risk factor analyses also suggest a hydrodynamic shift, with the significance of *E. coli* sources and pathways shown to change between sampling periods. More specifically, during drought conditions, septic tank density ($p = 0.001$) and local subsoil type ($p = 0.009$) were both associated with the presence of *E. coli*, while neither variable was significant during post-drought conditions. Given the increased threat of drought conditions in temperate maritime regions under expected climate change scenarios, the current study shines a new light on the potential challenges facing groundwater users, while reiterating the persistent issue of microbial contamination (and perhaps microbial persistence) of domestic drinking water wells in the ROI. Findings promote the need for further research in this area to increase our understanding of groundwater contamination mechanisms in response to a changing climate.

1.0 INTRODUCTION

Categorized as a natural "hazard" by the World Meteorological Organization (WMO), droughts are technically defined as a period of lower than average precipitation which fails to meet human and environmental hydrological demands (WMO, 2008). Within the sphere of emerging climatic hazards, droughts are frequently considered the least understood, being classified as complex, cumulative, slow onset (i.e., creeping), persistent, and regionally extensive (Pulwarty and Sivakumar, 2014). Depending on the duration, severity and impacts, droughts are typically classified into four types, namely, meteorological, hydrological, agricultural, and socio-economic (van Loon, 2015). Regardless of classification, drought events serve to deplete available freshwater resources, thus altering hydrodynamic regimes in both surface water and groundwater catchments, with environmental and socio-economic impacts frequently outlasting the drought period (Kayam et al., 2009; Mishra and Singh, 2010; Daneshmand et al., 2014).

Hydrologically, groundwater drought is defined as "below-normal" groundwater level(s) and/or storage, with depletion of soil water (i.e. holding capacity) during prolonged drought resulting in declining groundwater levels (Hisdal et al., 2004; van Loon, 2015), albeit this depends on antecedent (pre-event) conditions. Fluctuating recharge rates, water-table and groundwater temperatures in the vadose zone and producing aquifers, will affect pore water chemistry and contaminant transport thus affecting both local and regional groundwater quality (Ghazavi et al., 2012). Multiple mechanisms including decreased dilution potential, decreased subsurface attenuation and retention, and decreased aquifer transmissivity may combine to alter the vulnerability of aquifers to both point and diffuse contamination (van Vliet, 2007; Shahid et al., 2017).

Typically, meteorological drought conditions propagate through the hydrological cycle, with surface-water resources affected relatively rapidly, while groundwater resources are typically the last impacted hydrological component. Groundwater environments are often associated with an inherent resilience to external stimuli and the capacity to "buffer" the effects of short-term climate hazards (Vaux, 2011; Sonnenborg et al., 2012). However, those subsurface components which support this buffering capacity (e.g., overlying subsoil type, thickness and permeability), and the associated temporal decoupling from surface processes, may also result in groundwater reserves remaining affected for prolonged periods following pronounced drought events (Faye et al., 2009; Sonnenborg et al., 2012). Several studies have explored the impacts of drought on groundwater yields (Panda et al, 2012; Lee et al, 2019) and chemical contamination (Kampbell et al, 2003; Appleyard and Cook, 2008; Polemio et al, 2009). However, to date, there is a paucity of research investigating the impacts of drought conditions on the microbial quality of domestic groundwater supplies.

The pronounced meteorological drought experienced across Europe during summer 2018 presented a unique opportunity to investigate the effects of an extended period of low rainfall and high (relative) temperatures on the incidence of faecal indicator organisms (FIOs) in unregulated domestic groundwater supplies. A repeated-measures fieldwork sampling regime (during and post-event) was undertaken, followed by statistical risk factor analyses to evaluate the potential role of local risk variables (e.g., infrastructure, hydrogeological setting) on FIO presence. As such, this study aims to provide a critical and novel characterization of the impacts of a meteorological (and hydrological) drought on groundwater microbial quality in a temperate maritime region not normally characterised by drought occurrence. Study findings provide some clarity on the effects of sporadic drought events on groundwater microbiological parameters and associated human risks of enteric infection. Presented results are directly relevant to a range of stakeholders and provide key feedback with applications in safeguarding against human health effects linked to climate change and consequent environmental hazards.

2.0 METHODS

2.1 Study Region

The study region is situated in the south-west of the ROI, extending 6,800 km² (8.1% of total area of ROI), largely comprising the administrative County of Cork (Figure 1). The ROI has a temperate maritime climate (Cfb) (viz. Köppen Classification), however, both annual precipitation (30-year Annual Mean 977.6 mm) and relative humidity (30-year Annual Mean 71.9%) are somewhat higher regionally than national averages due to the coastal Atlantic location, in addition to a slightly lower mean annual temperature (10.7°C) (Met Eireann, 2020). Like much of Ireland, County Cork is characterised by relatively high private groundwater reliance with 23,014 private (i.e., one household supplied) groundwater supply sources in operation; equivalent to ~16% of households across the county (CSO, 2012).

Regional bedrock geology is dominated by Devonian and Lower Carboniferous sandstones, siltstones and mudstones of the Munster Basin in areas of topographic relief with a limited number of low-lying areas underlain by Lower Carboniferous limestone formations (Meere et al., 2013). The sandstones have limited fracture permeability and are classified as locally-productive aquifers whereas solution enlargement of limestone fissures has given rise to a high-permeability karstic flow regime locally (Kelly et al., 2015). Regionally, well-drained soils predominate, resulting in a high prevalence of areas characterised by "extreme" (~33%) and "high" (~32%) groundwater vulnerability in addition to those underlain by thin (<1m) or absent top-soil layers (i.e., rock or karst) (~21%) (GSI, 2019). The prevalence of high permeability soils is further reflected by estimated recharge coefficients; 40% of the county is characterised by intermediate (>40% of effective precipitation available for recharge) to high (70-90%) recharge (GSI, 2019). Overall, local geological characteristics and associated parameters indicate a significant degree of groundwater susceptibility to external (i.e., surface) stimuli.

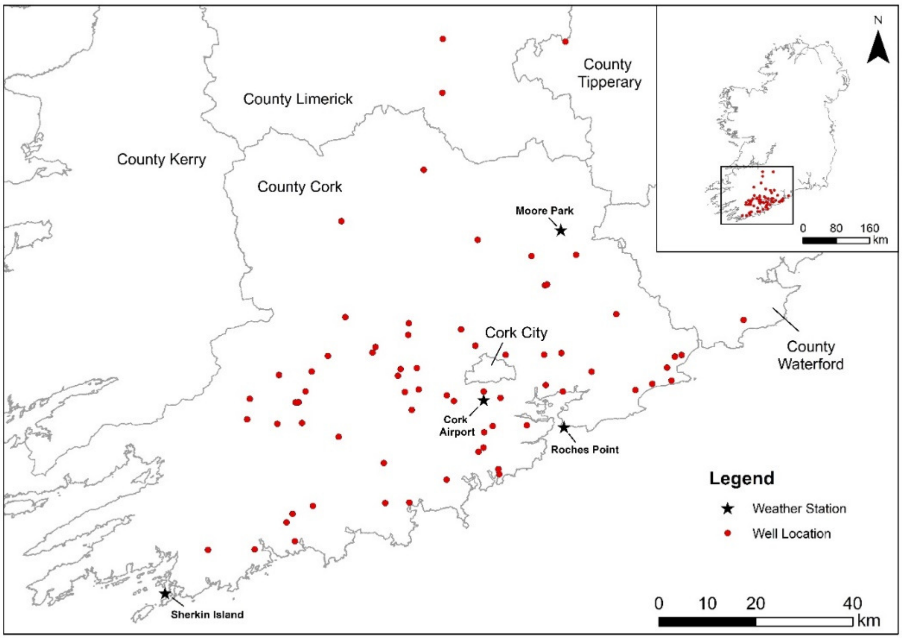

Figure 1: *Map of the extent of the study area (south-west Ireland) including the location of groundwater wells analyzed and the four local synoptic weather stations used for collation of climatic data*

2.3. Supply Source Selection and Study Design

Private well owners were invited to participate in the present study by e-mail via a University College Cork (UCC) list-server. Overall, 74 suitable groundwater supply sources were identified and sampled, with a "temporal" (i.e., repeated-measures) sampling campaign undertaken, comprising two distinct phases representative of drought (June/July 2018) and post-drought (October/November 2018) conditions. In all, 148 groundwater samples were collected, with each source (n = 74) sampled during drought and re-sampled during "non-drought" conditions. Post-drought samples were collected approximately 3-4 months after the drought event (October/November 2018), a period considered adequate to allow restoration of baseline hydro(geo)logical conditions with respect to surface-groundwater connectivity and soil moisture conditions. Groundwater sampling was carried out in accordance with Standard Methods for the Examination of Water and Wastewater methods (APHA, 2005). Untreated samples (100 mL) were taken directly from a pre-sterilised (70% ethanol) kitchen tap after a 2-minute flushing period and collected in sterile, disposable 120 mL sampling bottles. Samples were immediately transferred to a cooler-box and transported to a laboratory, with analysis undertaken within 4-6 hours. All samples were assayed for Total Coliforms (TCs) and *Escherichia coli* using a standard US Environmental Protection Agency (USEPA) approved commercial culture kit (Colilert, IDEXX Laboratories Inc., Westbrook, ME, USA) and in accordance with manufacturer's specifications.

2.4. Contamination Risk Factors and Dataset Development

Variables associated with three risk factor categories (source infrastructure, contaminant source setback/adjacency, and hydrogeological setting) were collated and spatially geo-matched to source-specific geographical location (GPS Coordinates) (Table 1). Site-specific infrastructural data were collated via a participant survey, completed by all well owners during the first (drought) sampling phase. The geographical coordinates of each sampling point were acquired through requisition of participants unique Eircode (Irish national postcode system), converted to GPS coordinates and added to a geo-spatial database created in ArcMap 10.3. Contaminant source data were subsequently also sourced from existing national databases (Table 1). Agricultural (cattle, sheep numbers) and wastewater (septic tank unit number) data were extracted from the Central Statistics Office (CSO) Census of Agriculture (2010) and Census of Ireland (2016) datasets, respectively. CSO data were compiled and spatially indexed to one of 3,440 "Electoral Divisions" (EDs); these represent the smallest administrative unit in the ROI (Table 1). Similarly, local hydrogeological data obtained from the Geological Survey Ireland (GSI) were joined to each sampled groundwater supply (Table 1). Subsoil permeability was discretised (ranked and coded) ranging from Low permeability (1) to 'thin or absent' (4) analogous to O'Dwyer et al., (2018).

Table 1. *Description and source of risk factor variables assessed*

	Risk Factor	***Data Type***	***Data Source***
Well Infrastructure	Well Type	Categorical	Research Survey
	Well Age	Categorical	Research Survey
	Well Depth	Categorical	Research Survey
Contaminant Sources	Septic Tank (Y/N)	Binary	Research Survey
	Manure Spreading (Y/N)	Binary	Research Survey
	Animals Grazing (Y/N)	Binary	Research Survey
	No. of Septic Tanks[1]	Continuous	Central Statistics Office (CSO)[1]
	No. of Cattle[1]	Continuous	CSO[1]
	No. of Sheep[1]	Continuous	CSO[2]
Hydrogeology	Groundwater Vulnerability	Categorical	Geological Survey Ireland (GSI)
	Subsoil Permeability	Categorical	GSI
	Subsoil Group	Categorical	GSI

2.5. Statistical Analysis

Prior to analyses, all independent variables were evaluated for normality via Q-Q plots and Shapiro-Wilkes tests. Numerous variables exhibited a non-normal distribution, thus non-parametric analyses were employed for all subsequent analyses. A McNemars exact test was used to evaluate the statistical association between the paired dependant variables of interest (i.e. Presence/Absence of TCs and EC during drought and post-drought conditions). Bivariate (risk factor) analyses were undertaken using the Mann-Whitney U or Chi-Square tests, as appropriate, to determine the level of association among *E. coli* presence/absence (dependant variable) and identified risk factors (independent variables) (Table 1) under both drought and post-drought conditions. IBM SPSS® 26 was employed for all statistical analyses, with a confidence level of 95% ($\alpha = 0.05$) employed throughout by convention.

3.0 RESULTS

3.1 General Contamination Status

Summary statistics for supply source contamination integrating drought and non-drought sampling periods are presented in Table 2. During drought conditions, 56.8% (n = 42/74) and 9.5% (n = 7/74) of supply sources analysed tested positive for TCs and *E. coli*, respectively. Comparatively, upon alleviation of drought conditions, TCs and *E. coli* were detected in 56% (n = 42/74) and 24.3% (n = 18/74) of private wells. An exact McNemar's test determined that there was a statistically significant difference in *E. coli* presence during- and post-drought ($X^2 = 6.722$; $p = 0.008$). However, the same relationship was not present for TCs with analogous detection rates encountered during both sampling periods. A total of 6 supply sources exhibited dual (i.e., repeated) detection of *E. coli* throughout the two sampling phases (Figures 2 and 3).

Table 2: *Total Coliforms and E. coli presence during and post drought conditions.*

Parameter	Detected (%)		X^2	Sig.
	Drought Conditions	Non-drought Conditions		
Total Coliforms	42/74 (56.8)	42/74 (56.8)	-	1.000
E. coli	7/74 (9.5)	18/74 (24.3)	6.722	0.008

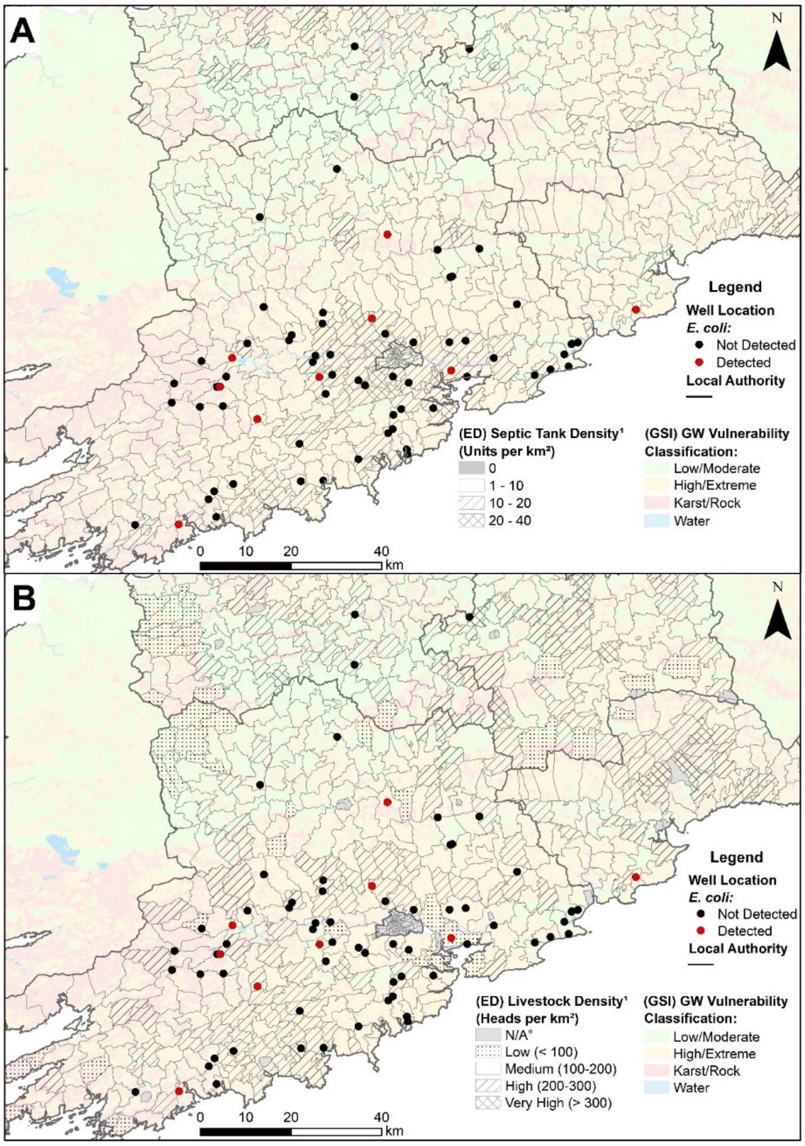

***Figure 2**: Map illustrating E. coli detection rates in supply sources analyzed during the June/July (drought) sampling phase and selected wastewater, agricultural and hydrogeological variables. **(A)** Map incorporating CSO (ED) septic tank density and (GSI) groundwater vulnerability. **(B)** Map integrating CSO (ED) livestock density and (GSI) groundwater vulnerability.*

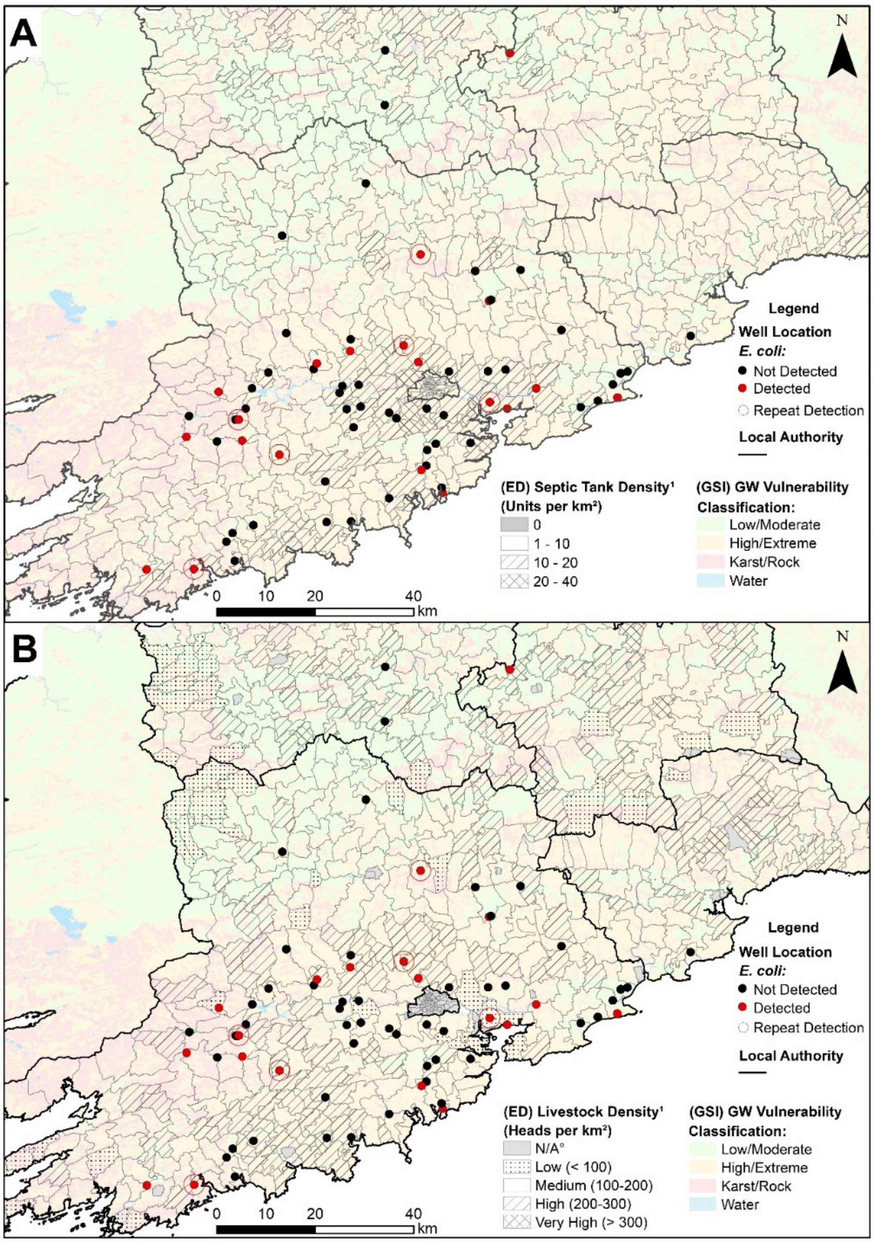

Figure 3: *Map illustrating E. coli detection rates in supply sources analyzed during the October/November (post-drought) sampling phase including locations with dual (drought and non-drought) detection.* ***(A)*** *Map incorporating CSO (ED) septic tank density and (GSI) groundwater vulnerability.* ***(B)*** *Map integrating CSO (ED) livestock density and (GSI) groundwater vulnerability.*

3.2. Risk Factor Analysis

Summary statistics derived from risk factor analysis specific to drought and post-drought conditions are presented in Tables 3 and 4 with key trends described as follows.

3.2.1 Drought Conditions

As shown (Table 3), no collated "infrastructural" variables (i.e., well type/depth/age) were significantly associated with *E. coli* presence. However, within the contaminant source category, two variables were found to be statistically associated with *E. coli* occurrence; namely, presence of an on-site septic tank ($X^2 = 9.761$; $p = 0.008$) and ED-specific septic tank number ($U = 3.407$; $p = 0.001$). In supplies where

E. coli was detected, the mean number of septic tanks per Electoral Division was found to be higher (n = 349; S.D = 116.6) compared to areas where *E. coli* was absent (n = 168.9; S.D = 118.05). Subsoil type was the only additional variable significantly associated (95% confidence level) with *E. coli* presence ($X^2 = 20.345$; $p = 0.009$); *E. coli* detection was significantly higher in areas underlain by Lower Palaeozoic sandstone tills (n = 6). Additionally, subsoil permeability ($X^2 = 6.676$; $p = 0.083$) and groundwater vulnerability ($X^2 = 6.914$; $p = 0.075$) were also significant, albeit at the 90% confidence level, albeit, subsoil permeability and groundwater vulnerability are colinear.

Table 3: *Risk factor analysis of vulnerability variables relative to the presence of E. coli during drought conditions*

	Risk Factor	***Test Statistic***	***p***
Well Infrastructure	Well Type	0.876[a]	0.563
	Well Age	1.259[a]	0.342
	Well Depth	0.567[a]	0.874
Contaminant Sources	Septic Tank (Y/N)	9.761[b]	0.008
	Manure Spreading (Y/N)	0.465[a]	0.596
	Animals Grazing (Y/N)	1.126[a]	0.187
	No. of Septic Tanks[1]	3.407[b]	0.001
	No. of Cattle[1]	3.563[b]	0.163
	No. of Sheep[1]	0.459	0.689
Hydrogeology	Groundwater Vulnerability	6.914[a]	0.075
	Subsoil Permeability	6.676[a]	0.083
	Subsoil Type	20.345[a]	0.009

[a] Chi Square, [b] Mann Whitney U, [1]Per Electoral Division

3.2.1. Post-Drought Conditions

No infrastructural variables were significantly associated with *E. coli* presence during the post-drought period (Table 4). Variables relating to agricultural practices including local presence of manure spreading ($X^2 = 3.335$; $p = 0.067$) and number of cattle per ED ($X^2 = 1.778$; $p = 0.074$) were identified as approaching statistical significance. For post-drought conditions, *in-situ* septic tank presence and septic number per ED were not significantly associated with *E. coli* presence. Similarly, no hydrogeological parameters demonstrated any statistical significance with *E. coli* presence.

Table 4: *Risk factor analysis of vulnerability variables relative to the presence of E. coli during post-drought conditions*

	Risk Factor	***Test Statistic***	***p***
Well Infrastructure	Well Type	0.528[a]	0.934
	Well Age	1.763 [a]	0.231
	Well Depth	1.023 [a]	0.125
Contaminant Sources	Septic Tank (Y/N)	1.443 [b]	0.149
	Manure Spreading (Y/N)	3.335 [a]	0.067
	Animals Grazing (Y/N)	0.726 [a]	0.532
	No. of Septic Tanks[1]	1.287 [b]	0.172
	No. of Cattle[1]	1.778 [b]	0.074
	No. of Sheep[1]	0.425 [a]	0.735
Hydrogeology	Groundwater Vulnerability	2.442 [a]	0.175
	Subsoil Permeability	1.636 [a]	0.295
	Subsoil Type	0.232 [a]	0.669

[a] Chi Square, [b] Mann Whitney U, [1]Per Electoral Division

4.0 DISCUSSION

The present study represents one of the first to provide field-validated evidence of the effects of drought on the microbial quality of private groundwater supplies in a temperate maritime climate. Overall, *E. coli* detection rates during drought (9.5%) and post-drought (24.3%) conditions indicate domestic groundwater supply sources are at risk of "frequent" faecal contamination, irrespective of precipitation patterns and temperatures.

A markedly higher *E. coli* detection rate was recorded during the post-drought sampling regime, providing direct evidence of enhanced microbial mobilization to groundwater supplies following resumption of seasonally "normal" meteorological conditions. As such, evidence of low rainfall increasing groundwater contaminant concentrations (through reduced dilution potential) (Moors et al, 2013) is not substantiated by findings from the current study. Overall, presented findings seem to concur with previously reported seasonal trends with respect to the occurrence of *E. coli* in groundwater supplies situated in hydrodynamically predictable catchments (e.g., Leber et al, 2011; Shrestha et al, 2014; Chuah and Ziegler, 2018; O'Dwyer et al, 2018).

Post-drought *E. coli* detection rates were, however, below the national average reported during the year 2016 (31.8%) (EPA, 2018), and from those calculated in additional investigations based in the ROI (e.g., 32%; Hynds et al, 2012; 51.4%; O'Dwyer et al, 2018). It is possible the results obtained indicate that catchment hydrology, comprising soil moisture, land-groundwater "coupling" mechanisms, and recharge rates, had not "fully" recovered by October/November, thus emphasizing the prolonged environmental effects of drought (Mishra and Singh, 2010).

In addition to decreased catchment hydrological connectivity, periods of drought will also affect temperature and soil moisture, factors potentially influencing *E. coli* survival and inactivation rates in potential sources (e.g., manure), (sub-)soil and groundwater environments (John and Rose, 2005; van Elsas et al, 2010; Blaustein et al, 2013; Levy et al, 2016). For example, the potential interplay among soil desiccation and compaction, concentration of faecal material in dry surfaces, and eventual amplification of *E. coli* contamination through (post-drought) rainfall "pulsing" should be considered

(Yusa et al, 2015; Levy et al, 2016). Conversely, soil desiccation can lead to higher inactivation of *E. coli* which generally benefit from the environments provided by (semi-)aquatic habitats at higher latitudes (Ishii et al, 2008). As with other bacteria, evaluating the potential influence of higher temperatures on *E. coli* inactivation is challenging considering the nexus between (sub-)surface temperatures, competition/predation with other microorganisms and nutrient availability (John and Rose, 2005; Levy et al, 2016). Generally, the effects of fluctuating temperatures on (non-host) *E. coli* survival is not fully understood (van Elsas et al, 2012). However, both soil microcosm and groundwater-based investigations suggest variations in temperature, including exposure to higher temperatures (often > 20°C), increase deactivation rate of *E. coli* through physiological responses (Sjogren, 1994; John and Rose, 2005; Semenov et al, 2007; Blaustein et al, 2013). As such, the exceptionally high (relative) temperatures (up to 32°C) recorded during the summer of 2018 may also help explain the substantially lower detection rates observed.

Risk factor analysis and subsequent comparison between drought and post-drought periods highlight the relevance of two specific hazard "sources" for source supply contamination, local septic tank prevalence and agricultural practices, respectively. During drought conditions, both the presence of a septic tank ($p = 0.008$) and the number of septic tanks in the locality ($p = 0.001$) were associated with *E. coli* presence, which is in accordance with previous Irish research (Hynds et al., 2012; O'Dwyer et al., 2018), but unexpected given the lack of precipitation. In the ROI and similar climatic regions (e.g. New Zealand), microbial contamination of groundwater is primarily associated with i.) recharge/infiltration and ii.) bypass/preferential flow as the two primary modes of microbial transport to and within the subsurface (Hynds et al., 2012; Weaver et al., 2016; O'Dwyer et al., 2018), both of which are largely absent during prolonged dry periods. Thus, the presence of *E. coli* during drought conditions may be indicative of *E. coli* naturalisation (i.e. environmental adaptation) within select Irish groundwater supplies. This potentially important finding requires further investigation as the apparent survival and adaptation of *E. coli* within groundwater would invalidate the use of *E. coli* as a faecal indicator bacterial species (Hagedorn et al., 2011).

Across both sampling periods (drought and post-drought), hydrogeological factors were shown to exert negligible influence on *E. coli* contamination, with subsoil type ($p = 0.009$) during drought conditions representing the only significant factor at a 95% confidence level. Subsoil type is considered a major factor influencing the transfer of pathogens from soil into groundwater via "traditional" recharge (Abu-Ashour et al., 1994) with soil moisture (and to a lesser extent, temperature, pH, and resident existing microbes) ultimately governing pathogen survival, fate and transport.

5. CONCLUSION

The presented opportunistic field study offers a rare, if not first, insight into the relationship between drought conditions and groundwater quality in private (unregulated) groundwater sources located in temperate maritime climates, not typically associated with drought events. *E. coli* presence was noted across both sampling regimes (drought and post-drought) underscoring the persistence of microbial contamination in groundwater within the ROI, and thus the potentially ever-present public health threat to private supply users. In light of the significantly reduced (or altogether absent) level of subsurface transport during the sampled drought event (i.e. recharge/infiltration), it is tentatively hypothesised that *E. coli* contamination identified during summer 2018 may represent 'legacy' contamination i.e. naturalisation/adaptation of *E. coli* within (vulnerable) groundwater systems overlain by high permeability tills. Given the increased threat of drought conditions in temperate maritime regions under expected climate change scenarios, the current study shines a light on the potential challenges facing groundwater users, while reiterating the persistent issue of microbial contamination of domestic drinking water wells in the ROI. Findings promote the need for further research in this area to increase our understanding of groundwater contamination mechanisms in response to extreme meteorological events.

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