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Impact of the 2018 European Drought on Microbial Groundwater Quality in Private Domestic Wells: A case study from a temperate maritime climate

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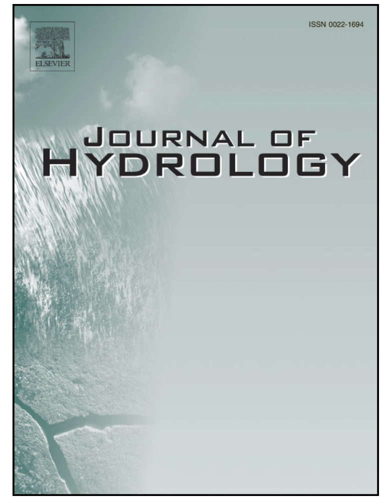

Research papers

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Impact of the 2018 European drought on microbial groundwater quality in private domestic wells: a case study from a temperate maritime climate

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Abstract

A significant volume of research over the past two decades has highlighted both direct and indirect links between climate change and groundwater quality. However, to date, few studies have sought to explore the relationship(s) between drought conditions and groundwater quality in i) private (unregulated) groundwater sources, or ii) temperate maritime climates not commonly prone to drought events. The Republic of Ireland (ROI) represents an appropriate case-study due to its' high reliance on private groundwater supplies, and while the region is largely unaffected by climatological extremes, modelling studies indicate that drier summers and drought conditions will increase in frequency. Accordingly, the current study sought to quantify the effects of the Summer 2018 drought experienced throughout Europe on private groundwater quality in the southwest of Ireland via an opportunistic field study. A repeated measures sampling campaign comprised of "drought" (June/July) and "post-drought" (October/November) analyses of 74 wells was undertaken, with complementary mapping and statistical analyses. Both Total Coliforms (TCs) and *Escherichia coli* (*E. coli*) were present during both drought (TCs: 42/74; 56.8%, *E. coli:* 7/74; 9.5%) and post-drought (TCs: 42/74; 56.8%, *E. coli*: 18/74; 24.3%) sampling periods. *E. coli* contamination during drought conditions was unexpected due to an absence of recharge or infiltration for microbial transport. Bivariate analyses suggest a hydrodynamic change, with the significance of *E. coli* sources and pathways shown to switch between sampling periods i.e. a shift from a combination of regional and local (site specific) contamination mechanisms, to solely site-specific mechanisms. 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. The current study is the first to provide a quantitative comparison of private groundwater quality during and after a large-scale drought event in a temperate maritime climate and may be used to improve our understanding of the effects of extreme events, and thus necessary preventative and monitoring strategies, going forward.

Keywords: Groundwater; Drought; Climate Change; Microbial Contamination; Domestic Water Supplies

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) estimates that the global mean surface temperature increased by 0.85°C (0.6 - 1.06 °C) between 1880 and 2012, predicting a further 2 - 4 °C increase over the next century (IPCC, 2013). Climate change modelling projects a higher incidence and duration of severe weather events including significant flooding and drought conditions, posing significant global environmental and human health risks and a particularly unique challenge for regions unaccustomed to severe climatic phenomena (Stanke et al., 2013; Cioffi et al., 2017; Forzieri et al., 2017). Categorized as a natural "hazard" by the World Meteorological Organization (WMO), droughts are technically defined as a period of lower than average precipitation failing 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 their duration, severity and impact, droughts may be classified into four types, namely, meteorological, hydrological, agricultural, and socio-economic (van Loon, 2015). Irrespective of classification, drought events serve to deplete available freshwater resources, thus altering hydrodynamic regimes in both surface water and groundwater dominated catchments, with environmental and socio-economic impacts frequently outlasting the drought period (Kayam et al., 2009; Mishra and Singh, 2010; Daneshmand et al., 2014). Notably, droughts represent a relative, as opposed to absolute, condition (as opposed to flooding) and are thus contingent on "normal" (i.e., baseline) and antecedent hydrological conditions (Wilhite, 2016).

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 dependant on antecedent (pre-event) conditions. Fluctuating recharge rates, piezometric surface and groundwater temperatures in the vadose zone and producing aquifers, all affect 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 susceptibility of aquifers to both point and diffuse contamination (van Vliet, 2007; Shahid et al., 2017). Moreover, periods of drought, and particularly those experienced in non-arid regions, are invariably associated with increased anthropogenic water demand in concurrence with decreased resource availability, potentially leading to over-exploitation and exacerbation of groundwater quality deterioration (Stanke et al., 2013).

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" effects of short-term climate hazards (Vaux, 2011; Sonnenborg et al., 2012). However, those subsurface attributes 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, there is a paucity of research which has explored the impacts of drought conditions on the microbial quality of domestic groundwater supplies. Overall, investigations focusing on the nexus between drought events, groundwater quality and potential waterborne human infections remain extremely limited within the scientific literature. For example, work by Levy et al. (2016), which investigated the impact of climate change on waterborne diseases noted that literature relating to drought and disease was "particularly sparse" even when including all water exposures (i.e., surface water, groundwater etc.).

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 campaign (during and post-event) was undertaken, followed by statistical risk factor analyses to evaluate the regional and local hydrodynamics of 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 may provide some clarity around the effects of a sporadic drought event on groundwater microbiological parameters and associated contaminant sources and pathways. While limited in scope due to the 'one-off' nature of the event, 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 exposure to potentially pathogenic microorganisms. Moreover, this research provides valuable insight for future research, highlighting potential sources and pathways for microbial contamination in groundwater under drought conditions.

2. Methods

2.1 Study Region

The study region is situated in the south-west of the Republic of Ireland (ROI), extending 6,800 km^2 (8.1% of total area of ROI), largely comprising the administrative County of Cork (Figure 1). The ROI has a temperate maritime climate (Cfb) under the Köppen Climate Classification system, 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^{o}C) (Met Eireann, 2020). Like much of Ireland, County Cork is characterised by relatively high private groundwater reliance with 23,014 domestic (i.e., one household supplied) groundwater supply sources in operation; equivalent to ~16% of households across the county (CSO, 2012). A significant majority of groundwater wells are located in categorically rural areas (98.4%; n = 22,651), where access to public infrastructure (i.e. municipal mains) is limited.

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., outcrop, subcrop 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 capacity (GSI, 2019). Depth to bedrock is reflected in the groundwater vulnerability classification with ‘extreme’ vulnerability areas representative of bedrock located between 0-3m from the surface. Similarly, ‘high’ vulnerability areas are typically characterised as having 3-5m depth to bedrock, overlain with a moderately permeable till. Overall, local geological characteristics and associated parameters indicate a significant degree of groundwater susceptibility to external (i.e., surface) stimuli.

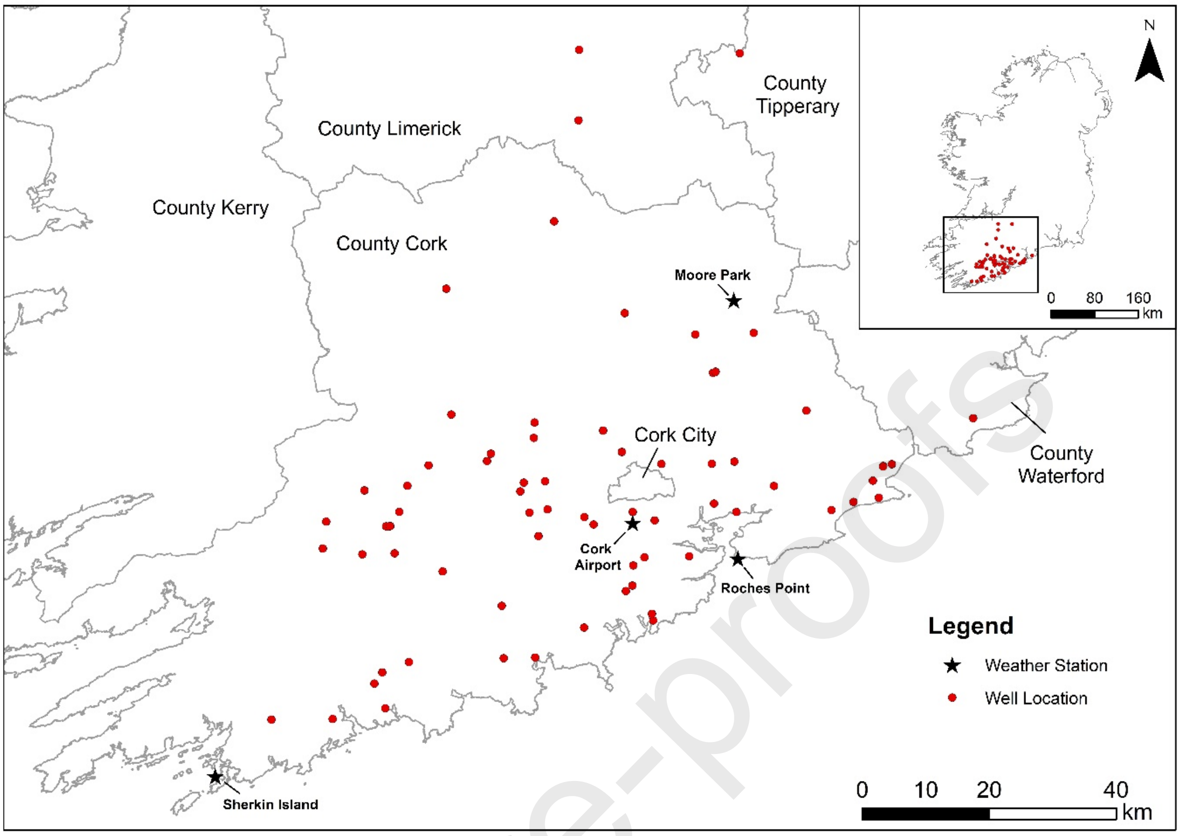

Figure 1. *Map of the extent of the study area (south-west Ireland) including the location of sampled groundwater wells and four local synoptic weather stations used for collation of climatic data*

2.2 The 2018 European Drought – An Irish Perspective

While largely unaffected by temperature extremes, recent analyses of historical data (1850-2015) indicate that the ROI has exhibited an increasing tendency towards wetter winters and drier summers (Murphy et al., 2019). Measured surface temperatures have increased by 0.8°C since 1900; an average of 0.06°C per decade (until 1979), increasing to 0.14°C per decade between 1980 and 2008 (Coll and Sweeney, 2013). Climate projections indicate regional conditions will deteriorate with even wetter winters and drier (and warmer) summers expected, thus increasing the likelihood and intensity (i.e. duration) of future drought events (Murphy et al., 2019). The potential impacts of climate change in the ROI were brought into sharp focus during the summer of 2018 when a meteorological drought was recorded from June 25th to July 14th. Absolute drought conditions (defined as no precipitation recorded for ≥15 days (Met Eireann, 2020a)) were recorded at 21 (out of 25) meteorological stations, with partial drought conditions enduring until July 24th in parts of the country. Records of total summer (May to July) rainfall (109.5 mm) at Cork Airport (Figure 1) represented the driest summer on local record (56 years in duration). Concomitantly, heat-wave conditions were recorded at 15 stations throughout the country at various times between June 24th and July 4th with temperatures of 32.0°C recorded in the mid-west (Shannon Airport, County Clare) on June 28th; the highest temperature ever recorded at a mainland Irish synoptic station (Met Eireann, 2018). National estimates of drought indicators (2018), including Standardised Precipitation Index (SPI) (McKee et al, 1993) and Percent of Normal Index (PNI) (Werick et al, 1994), indicate pronounced drought conditions occurred during June and July, peaking in June, subject to some degree of regional variability (Falzoi et al, 2019). The effects of the drought were particularly marked in south-west Ireland, which contains the study area (Figure 1), characterized by "extremely dry" and "extreme drought" (<40% of normal precipitation) SPI and PNI classifications, respectively. Reported trends are mirrored in regional thermo-pluviometric data collated from all available local synoptic weather stations (Figure 1). Key features include significantly lower rates of rainfall (~10 mm in July 2018) and higher maximum air temperatures (~7 ℃) during drought months, compared with 10-year mean trends (Figure 2). Data also demonstrate atypical pre-event climatic conditions (Falzoi et al, 2019), with unusually low levels of precipitation prevailing throughout May and a summer-long (1st June to 31st August) rainfall deficit. Values derived from the national Soil Moisture Deficit (SMD) model (Schulte et al, 2005), i.e., the volume of infiltrating precipitation (mm) necessary to attain soil field saturation, have been employed to estimate hydrological dynamics within soil environments, and thus provide a soil-specific drought metric. Figure 3 provides SMD data extracted from Cork Airport synoptic station with extremely high values (75-80 mm) calculated during the drought period (note 110 mm values reflect soils entirely devoid of available moisture) indicative of a high soil water deficit and altered surface-groundwater hydrological connectivity (Met Eireann, 2020b).

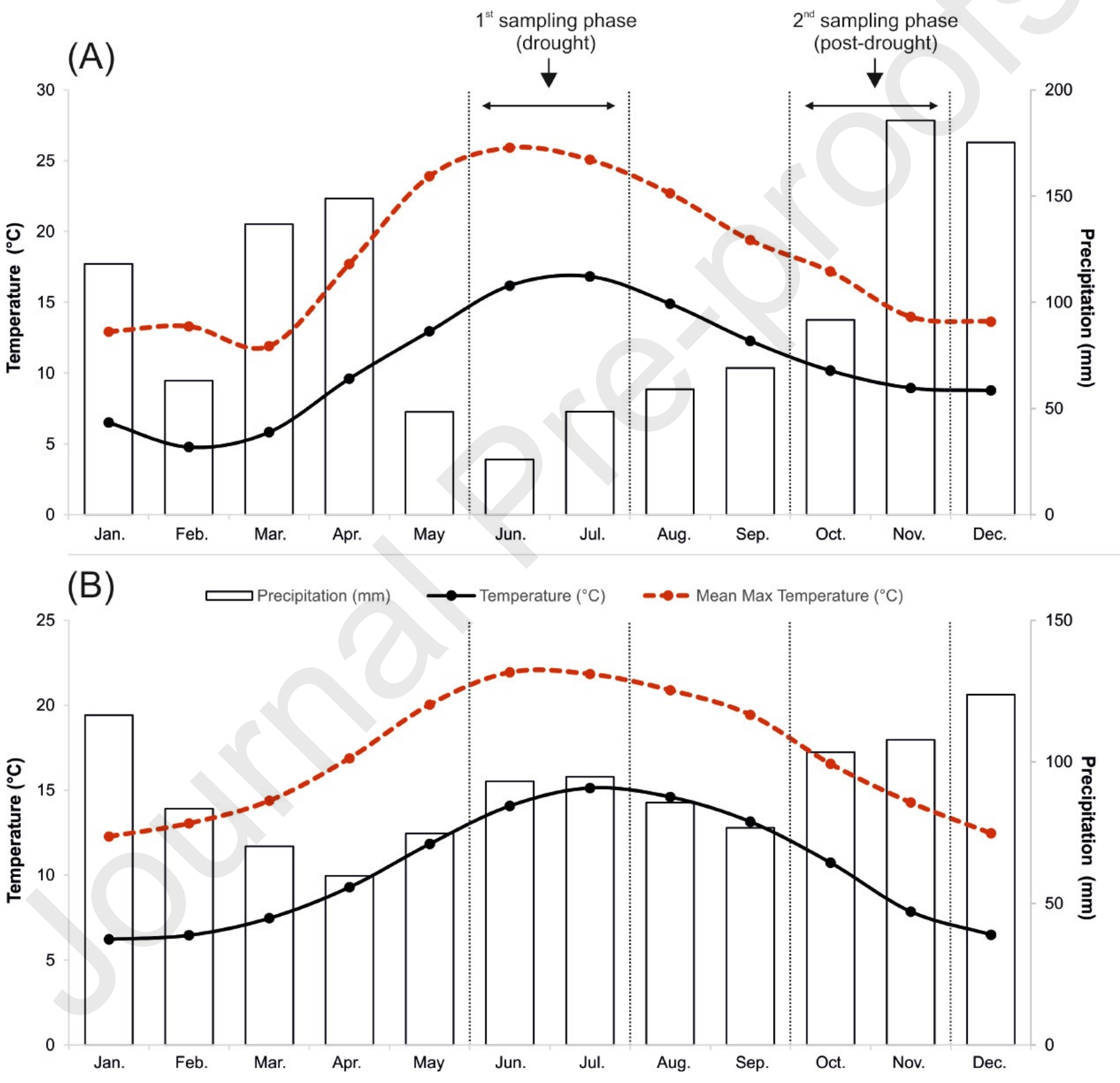

Figure 2. *Monthly thermo-pluviometric data collated from synoptic stations in County Cork (Figure 1).* ***(A)*** *Monthly total precipitation (mm) and maximum/mean air temperature (℃) for the year 2018.* ***(B)*** *Averaged monthly total precipitation (mm) and maximum/mean air temperature (℃) for the period 2007-2017. Bars represent precipitation data with lines illustrating mean (solid) and maximum (dashed) air temperature.*

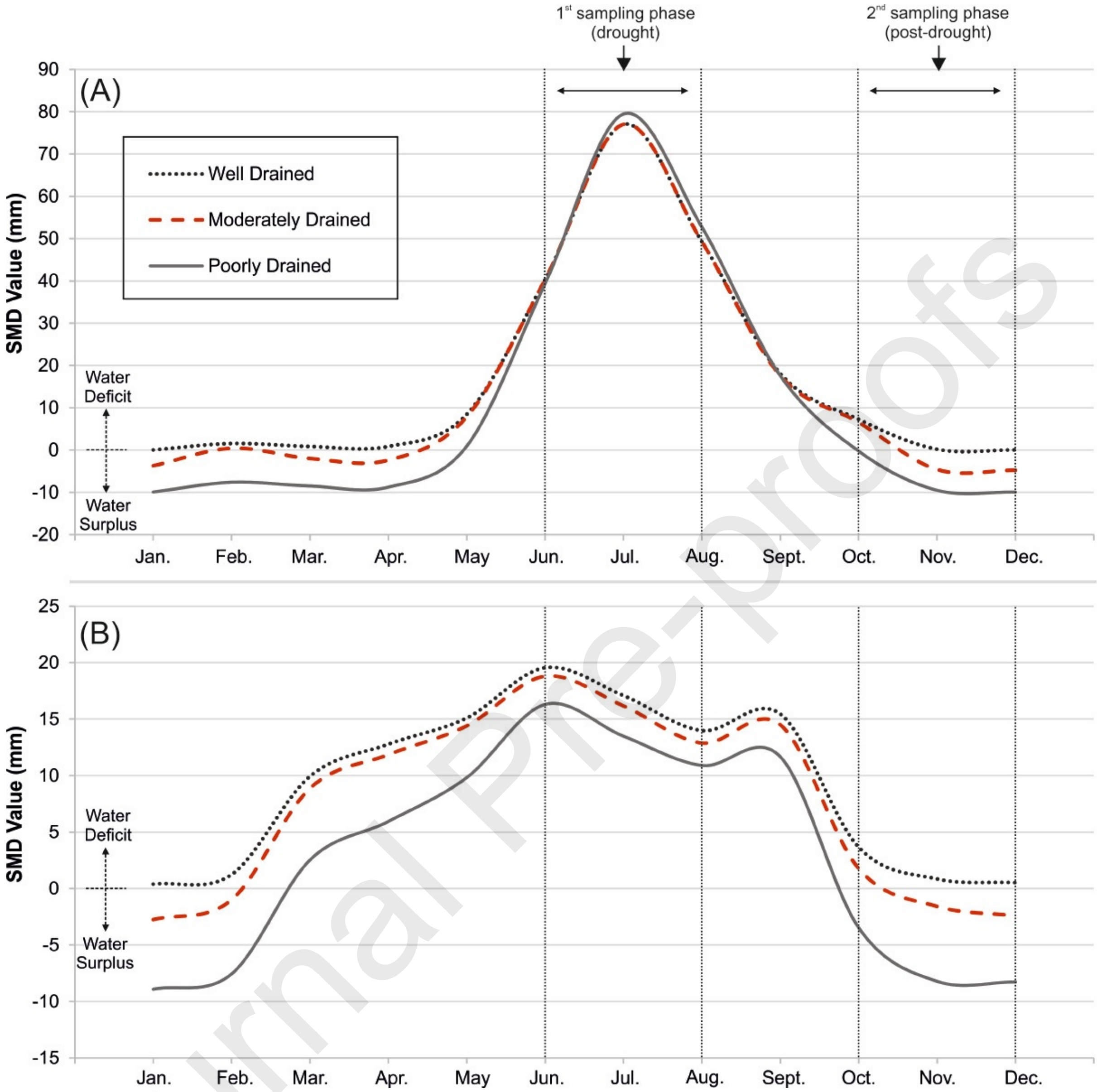

Figure 3. *Soil Moisture Deficit (SMD) model values (mm) extracted from Cork Airport synoptic station.* ***(A)*** *Mean monthly SMD values (mm) during the year 2018.* ***(B)*** *10-year averaged (2007-2017) monthly SMD values (mm). Positive SMD values indicate a deficit and negative values indicate a surplus.*

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. Participants were selected based on the following criteria (a)willingness to commit to two sampling rounds, (b) no treatment system installed, (c) proximity to research laboratory (to ensure prompt analysis) and, (d) to ensure a level of diversity in terms of groundwater vulnerability. Overall, 74 suitable groundwater supply sources were identified and sampled (61/74 (82.4%) of which had never been sampled before thus reducing bias relating to historically defective supplies), 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, resulting

in 148 private groundwater samples collected and analysed. 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 (seasonal) hydro(geo)logical conditions with respect to surface-groundwater connectivity and soil moisture conditions (Figure 3). Pluvial data (Figure 4) highlight the marked difference between the two sampling periods with a cumulative variance of 30.4 mm rainfall during the two 8-week sampling periods. As expected, mean and maximum temperatures were also markedly higher (~ 9℃) during June/July. Following 10-year averages (Figure 2), monthly trends suggest rainfall had significantly recovered by the second sampling phase, although October 2018 still exhibited lower rainfall than average. In turn, SMD values indicate soil hydrology had recovered from the deficits experienced during the drought with values comparable with long-term averages (Figure 3).

Groundwater sampling was carried out in accordance with Standard Methods for the Examination of Water and Wastewater (APHA, 2017). Untreated samples (100 mL) were taken directly from a pre-sterilised (70% ethanol) kitchen or outdoor tap after a flushing period relative to temperature stabilization (generally between 2 and 6 minutes) 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. Negative controls (sterile deionised water) were used during all phases of laboratory analyses.

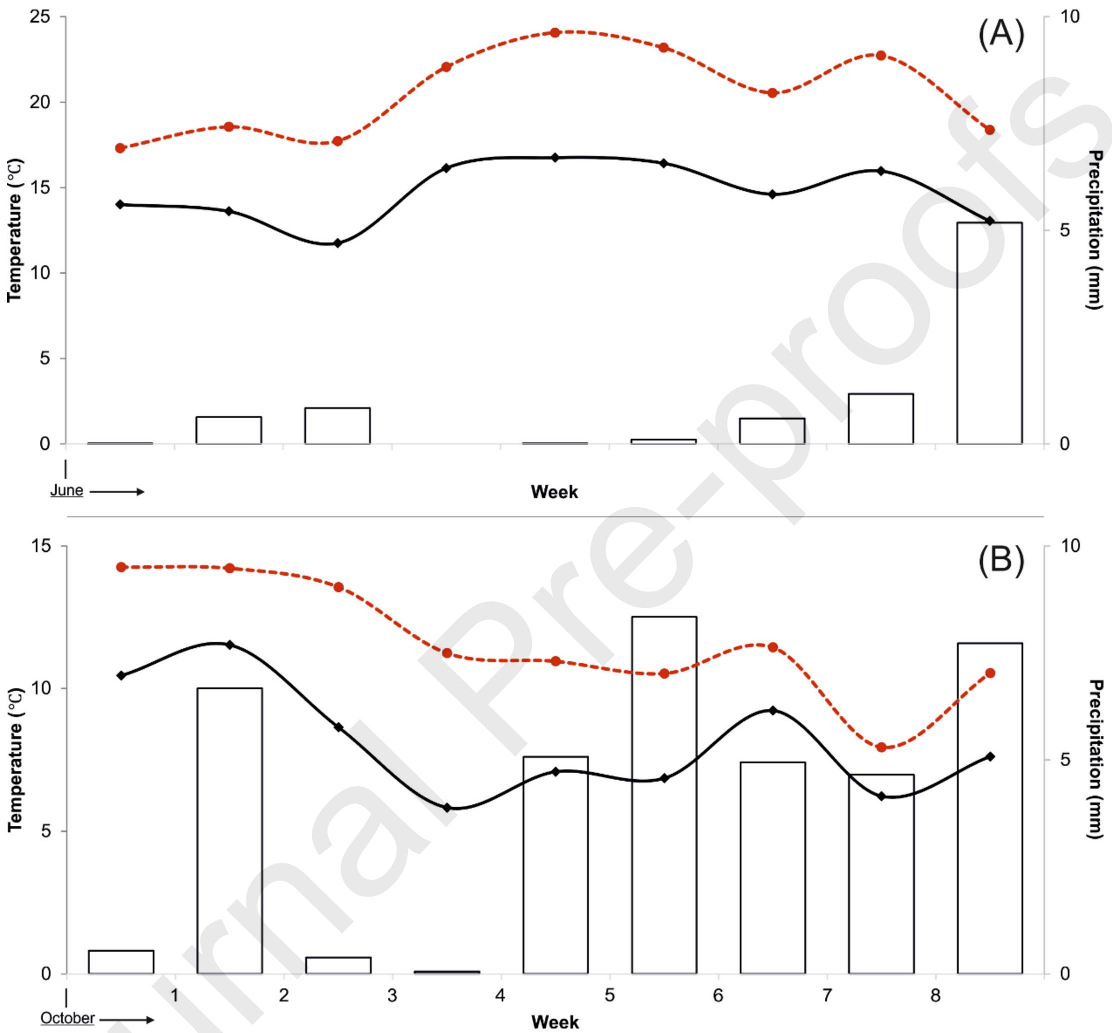

Figure 4. *Weekly thermo-pluviometric data (Cork Airport synoptic station) for the two sampling periods.* ***(A)*** *Weekly total precipitation (mm) and maximum/mean air temperature (℃) for the period of June-July.* ***(B)*** *Weekly total precipitation (mm) and maximum/mean air temperature (℃) for the period of October-November. Bars represent precipitation data with lines illustrating mean (solid) and maximum (dashed) temperature.*

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. Source depth and age were coded as discretized ranked variables (e.g., 1 = <5m, 2 = 5-20m, 3 = 21-50m, 4 = 51-100m), while well type (bored or dug-well) and presence/absence of contaminant sources within 100m (e.g., septic tank presence/absence) were coded as dichotomous categorical variables (see supplementary material).

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). Groundwater recharge estimates were collated from the national Groundwater Recharge Map (Williams et al*.,* 2013), which is derived from existing hydrogeological and meteorological data layers. Meteorological data were sourced from the Irish Meteorological Office (Met Eireann) and the 5-Day antecedent rainfall (mm) relative to each date of sampling was compiled using the Cork Airport synoptic station as the most representative of the study area.

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
	Septic Tank Density	Continuous	Central Statistics Office (CSO)
	Cattle Density	Continuous	CSO[1]
	Sheep Density	Continuous	CSO[2]
Hydrogeology	Groundwater Vulnerability	Categorical	Geological Survey Ireland (GSI)
	Subsoil Permeability	Categorical	GSI
	Subsoil Group	Categorical	GSI
Meteorology	5-Day Antecedent Rainfall (mm)*	Continuous	Met Eireann

*Post-drought only

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. Following bivariate analyses, variables exhibiting significance at the 90% confidence interval were selected for inclusion in two Logistic Regression models (drought and post drought). A 'forced entry' method was employed whereby all variables were analysed simultaneously followed by backward eliminated of variables which contributed least to the model ($p > 0.1$). The Hosmer Lemeshow test was used to validate model goodness-of-fit, with Nagelkerke's pseudo R^2 used to estimate effect size and explained system variance. IBM SPSS® 26 was employed for all statistical analyses, with a confidence level of 95% ($\alpha = 0.05$) employed throughout by convention.

3. Results

3.1 General Contamination Status

Summary statistics for supply source contamination during 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 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 and 22 supply sources exhibited dual (i.e., repeated) detection of *E. coli* (Figures 5 and 6) and TCs during the two sampling phases, respectively.

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

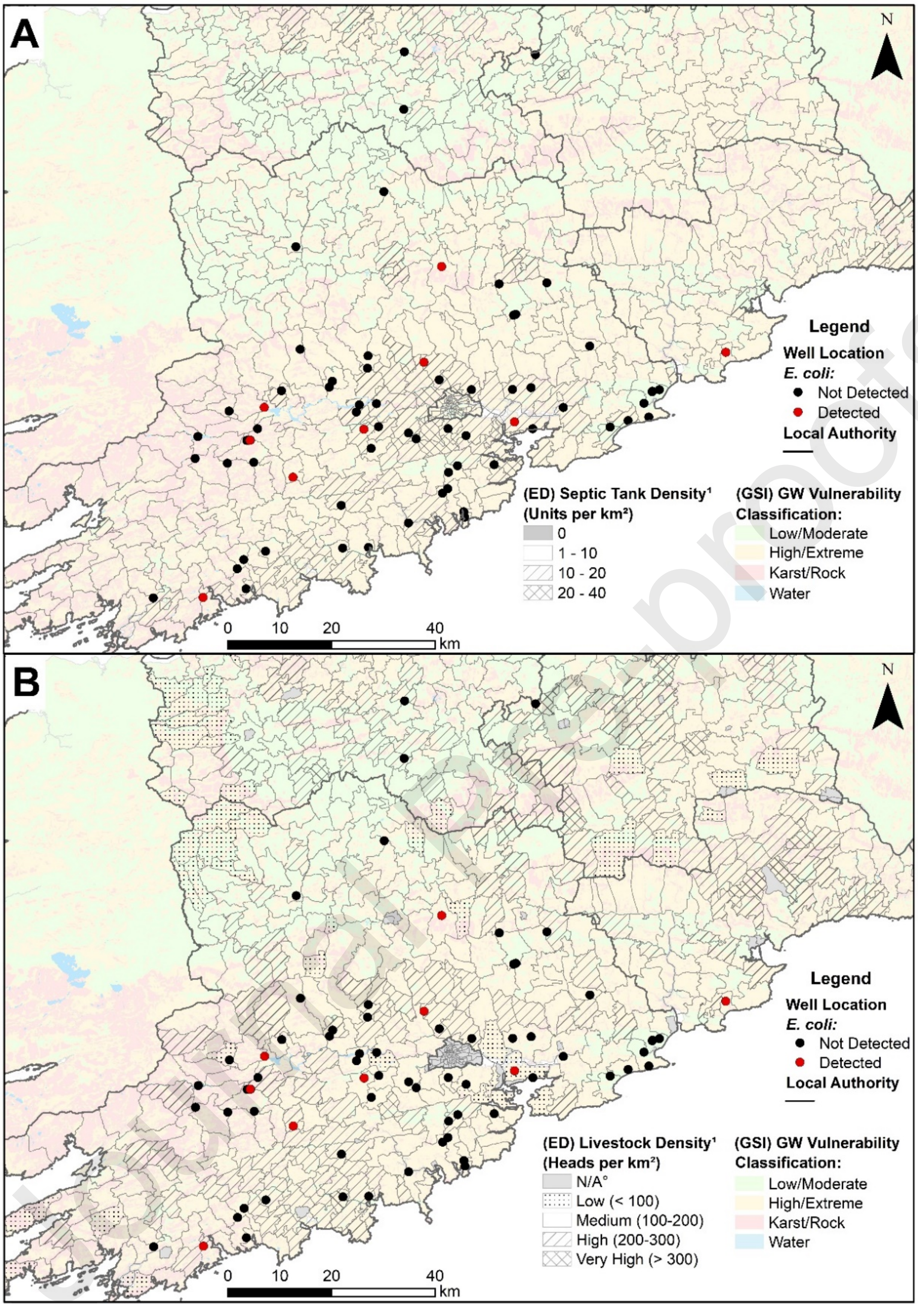

Figure 5. Map illustrating *E*. *coli* detection rates in supply sources analyzed during the June/July (drought) sampling phase and selected wastewater, agricultural and hydrogeological variables. **(A)** Map incorporating CSO (ED) septic tank density and (GSI) groundwater vulnerability. **(B)** Map integrating CSO (ED) livestock density and (GSI) groundwater vulnerability.

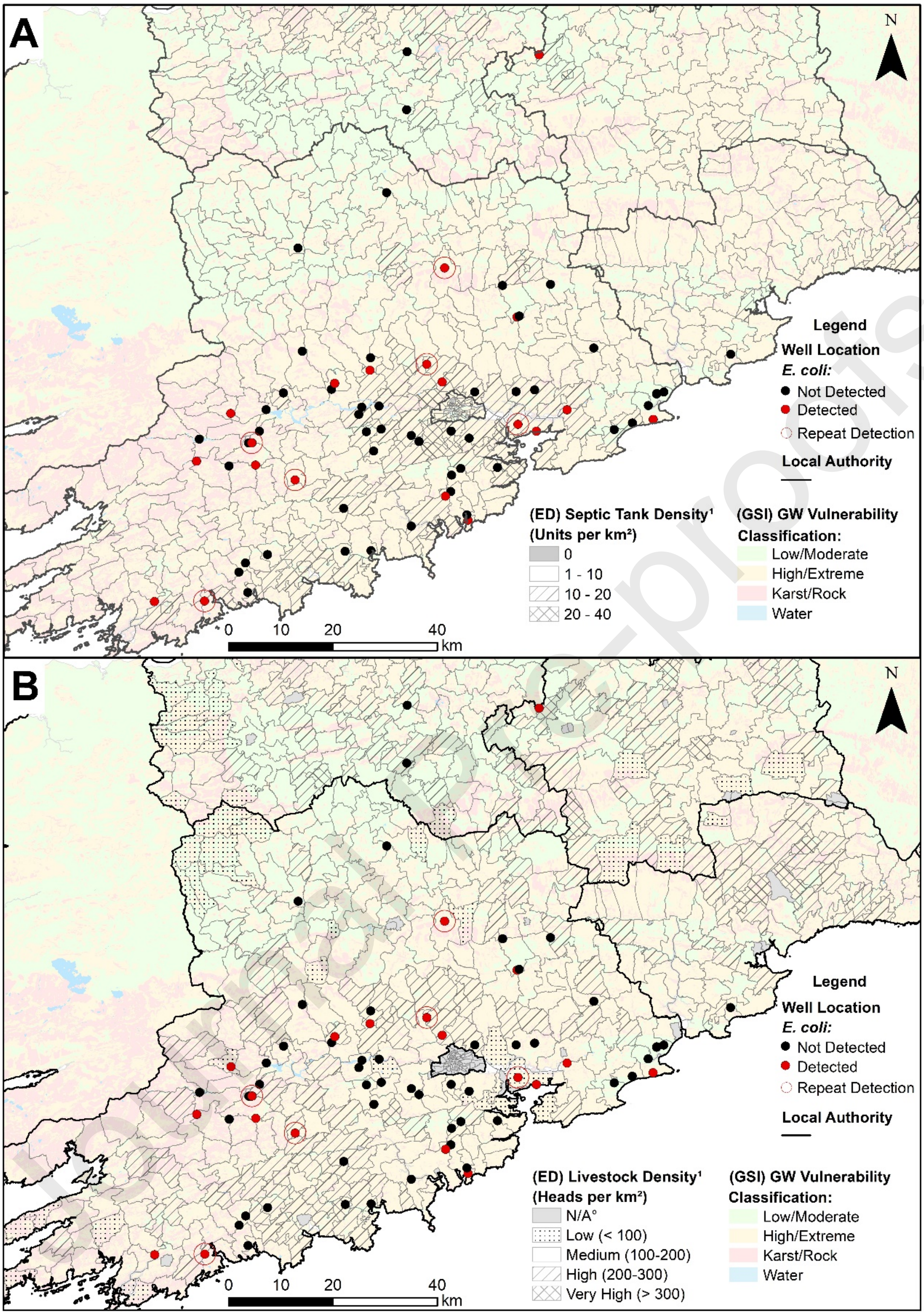

Figure 6. Map illustrating *E. coli* detection rates in supply sources analyzed during the October/November (post-drought) sampling phase including locations with dual (drought and non-drought) detection. **(A)** Map incorporating CSO (ED) septic tank density and (GSI) groundwater vulnerability. **(B)** 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 statistically associated with *E. coli* occurrence; namely, presence of an on-site septic tank ($X^2 = 9.761$; $p = 0.008$) and Electoral Division (ED)-specific septic tank density ($U = 3.407$; $p = 0.001$). In supplies where *E. coli* was detected, the mean density of septic tanks per ED was significantly higher (n = 349; S.D = 116.6) compared to areas where *E. coli* was absent (n = 168.9; S.D = 118.05). Local 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 sources situated in 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, with subsoil permeability and groundwater vulnerability deemed to be 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
	Septic Tanks Density[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

Following bivariate analysis, variables (n = 5) associated with *E. coli* presence at the 90% confidence level or above ($p<0.1$) were included in a logistic regression model prior to the application of backwards elimination, whereby variables which contributed least to the model ($P > 0.1$) were removed (n = 4). The number of septic tanks per area was the sole variable deemed statistically satisfactory for inclusion in the final model. Model outputs indicate that during drought conditions, the likelihood of *E. coli* contamination increases by a factor of 1.009 (95% CI 1.003- 1.015, $p = 0.002$) for every additional septic tank system in an area. Overall, model predictive sensitivity was skewed, with *E. coli* absence correctly classified in 97.1% of samples, while *E. coli* presence was correctly classified in 14.3% of samples. The Hosmer and Lemeshow test for goodness of fit produced an insignificant p-value ($p = 0.927$); thus, the null hypothesis that the observed and expected event rates (*E. coli* present/absent) are matched within subgroups of the sample population is accepted. The Nagelkerke coefficient of determination (cumulative R^2) was 0.284, thus the model input variable explains ~28% of system variability.

3.2.2. 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. Meteorological conditions, i.e., 5-Day antecedent rainfall

(U = 31.70, p = 0.002), was the only variable to be statistically associated with *E. coli* presence during the post-drought sampling regime.

Table 3: 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
Meteorology	5 day antecedent rainfall (mm)	3.170[b]	0.002

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

Analogous to the drought sampling regime, subsequent to bivariate analysis, variables (n = 3) associated with *E. coli* presence at the 90% confidence level or above (p<0.1) were included in a logistic regression model prior to the application of backwards elimination, whereby variables which contributed least to the model (P > 0.1) were removed (n = 2). In this instance, 5-Day antecedent rainfall was the primary predictor with an increase in rainfall increasing the likelihood of *E. coli* presence within the sampled supplies (OR: 1.106; 95% CI 1.022- 1.197, p = 0.012). Model predictive sensitivity was similarly skewed, with *E. coli* absence correctly classified in 93% of samples, while *E. coli* presence was correctly classified in 11.1% of samples. The Hosmer and Lemeshow test for goodness of fit produced an insignificant p-value (p = 0.628) and the Nagelkerke coefficient of determination (cumulative R^2) was 0.124, thus the model input variable explains ~12% of system variability.

4. Discussion

The presented study represents the first to provide field 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 susceptible to “frequent” faecal contamination, irrespective of precipitation patterns and temperatures. Reported *E. coli* detection rates fail to meet the legislative microbiological standards (0/100 mL) set out by the Drinking Water Directive 98/83/EC (European Commission, 2014). Lower prevalence of FIBs have been reported during drought periods (Mosley, 2015; Latchmore *et al.*, 2020), for example Latchmore *et al*. (2020) have recently reported *E. coli* detection rates of 1.6% to 5.2% during summer sampling seasons over an 8-year study period, with detection rates of 1.7% to 1.9% during 2016, which was considered a “drought year”. Notably, the drought-associated detection rate found during the current study was significantly higher. Findings are thus highly relevant for groundwater consumers and public-health authorities, particularly considering the predominant lack of treatment among supplies analysed (59/74; 79.7%) and potential health-risks associated with consumption of contaminated groundwater (O’Dwyer et al., 2018).

A significantly higher *E. coli* detection rate was recorded during the post-drought sampling regime, indicating enhanced microbial mobilization to groundwater supplies following resumption of “normal” hydrogeological conditions (determined by groundwater physiochemistry of nearby monitoring wells). Interestingly, even within the relatively short sampling timeframe (~2 months) a statistical association was found between 5-Day antecedent rainfall and the presence of *E. coli* within sampled supplies, further substantiating the role of precipitation in contaminant transport within Irish groundwater supplies (Hynds et al., 2014, O'Dwyer et al., 2014, O'Dwyer et al., 2018). However, it must be noted that during the post-drought sampling event, the precipitation values were marginally above the 10-year mean trend (~6mm) in November (Figure 2), which may have increased the likelihood of microbial contamination. For example, Carlton et al. (2014) have previously shown that rainfall events occurring after an 8-week dry period enhanced microbial transfer capacity via runoff and surface water, consequently leading to increased detection rates and prevalence of pathogenic and non-pathogenic E. coli in drinking water sources. Notwithstanding, presented findings (i.e. higher prevalence of E. coli during 'wet' conditions) concur with previously reported seasonal trends with respect to the occurrence of E. coli in groundwater supplies during "normal" conditions in hydrodynamically predictable regions (e.g., Leber et al, 2011; Shrestha et al, 2014; Chuah and Ziegler, 2018). For example, Bacci and Chapman (2011) report a thermotolerant coliform incidence rate of 24%, based on microbial analyses of private wells (n = 75) from a similar geographical region, however, this is lower than E. coli estimates reported from elsewhere in the ROI (e.g. 51.4%) (O'Dwyer et al., 2018).

Risk factor analysis and subsequent comparison between drought and post-drought periods highlight the relevance of two specific hazard "sources" for source supply contamination; 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, with the latter providing predictive capacity ($p = 0.012$). Groundwater source susceptibility (i.e. environmental fate of FIOs) modelling by Hynds et al. (2014) and O'Dwyer et al. (2018) have previously found that two or more mechanisms typically co-occur, both spatially and temporally, to result in private source contamination. For example, O'Dwyer et al (2018) report that intrinsic (e.g. aquifer classification, presence of karst bedrocks), specific (e.g. local livestock density, local septic tank density) and infrastructural (e.g. individual source depth and type) were concurrently predictive of source contamination (*E. coli*) in the southwest of Ireland over a 2-year sampling period. Likewise, Hynds et al. (2014) report that intrinsic (e.g. bedrock type) and infrastructural (e.g. source wellhead finish, liner clearance) attributes were highly predictive (≈90%) of *E. coli* presence in private wells across five Irish study areas from 2008-2011. Accordingly, findings from the current study provide strong evidence of a significant hydrodynamic shift, whereby specific mechanisms (localised preferential flow) predominate. Across both sampling periods (drought and post-drought), hydrogeological factors were shown to exert negligible influence on *E. coli* contamination, with local subsoil type ($p = 0.009$) during drought conditions representing the only significant factor at a 95% confidence level, representing further evidence to the abovementioned hypothesis i.e. cessation of intrinsic and infrastructural contamination mechanisms, with localised specific mechanisms predominant in the absence of significant aquifer-specific attributes (i.e. decreased (vertical) catchment hydrological connectivity).

Periods of hydrological drought inherently affect subsurface temperature and soil moisture, both of which influence *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). Evaluating the potential influence of higher temperatures on *E. coli* inactivation is challenging considering the nexus between (sub-)surface temperatures, subsurface microbial competition/predation and nutrient availability (John and Rose, 2005; Levy et al, 2016). While the effects of fluctuating temperatures on (non-host) *E. coli* survival is not fully understood (van Elsas et al, 2012), previous soil microcosm and groundwater-based investigations suggest variations in temperature, including exposure to higher temperatures (> 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. This is particularly relevant considering the potential for autochthonous *E. coli* populations developing potential phenotypic adaption to the local climate and subsurface buffering (Brennan et al., 2010). Considering the concurrent soil moisture deficit during the 2018 drought in concurrence with the reported environmental survival of *E. coli* (6-10 weeks), the presence of *E. coli* in groundwater supplies overlain by Lower Palaeozoic sandstone tills, which have a relatively high permeability, may be indicative of 'legacy' contamination events, thus supporting the hypothesis that *E. coli* naturalisation within groundwater may have occurred, as reported elsewhere (Filip & Demnerova, 2009). 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 or during specific climactic periods. 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).

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 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 represents a significant hydrodynamic shirt whereby localised "specific" contamination mechanisms predominate, with a partial or total cessation of intrinsic and infrastructural mechanisms. Moreover, findings that 'legacy' contamination events i.e., faecal materials deposited in sub-surface prior to drought onset, are likely the primary source of *E. coli* in sampled groundwater sources, thus pointing to potential 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. With available groundwater contamination data generally restricted to expected seasonal cycles (i.e., current information on groundwater microbial contamination during drought events is extremely limited), the evidence presented provides key insights into the influence of drought on microbial contamination of private groundwater supplies. Findings promote the need for further research in this area to increase our understanding of groundwater contamination mechanisms in response to extreme meteorological events.

Author Contributions

Jean O'Dwyer: Conceptualization, Methodology, Writing- Original draft preparation, Writing-Reviewing and editing. Carlos Chique.: Data curation, Writing- Original draft preparation. John Weatherill: Data curation, Reviewing and Editing. Paul Hynds: Conceptualization, Writing-Reviewing and Editing.

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Highlights

- Novel assessment of groundwater microbial quality during and post drought event
- *E. coli* were present during drought and post-drought sampling periods
- *E. coli* contamination during drought unexpected due to lack of microbial transport
- Results tentatively suggest some level of bacterial adaptation in the subsurface