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Spatiotemporal analysis of associations between flood hydrometeorology and gastroenteric infection: The Winter 2015-2016 flood event in the Republic of Ireland

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Abstract

While the infrastructural damage and subsequent costs associated with flood events have, and will continue to receive widespread attention, less attention is given to the adverse human health effects of these events. This is particularly significant in the ROI, which is characterised by the highest crude incidence rates of verotoxigenic *E. coli* (VTEC) enteritis and cryptosporidiosis in Europe. Accordingly, weekly infection incidence from July 2015 to June 2016 were employed in concurrence with weekly time-series of antecedent hydrometeorological parameters (rainfall, surface water discharge and groundwater level), and high-resolution flood risk mapping. An ensemble of statistical and time-series approaches were employed to quantify the influence and timing of flood hydrometeorology on infections. Seasonal decomposition identified a high residual infection peak (excluding seasonal pattern) during April 2016, with space-timing scanning used to identify the location, size and temporal extent of excess infection clusters. Excess cases of VTEC enteritis were geographically associated with the Shannon basin, while cryptosporidiosis excess was nationwide. Generalised linear modelling indicates that areas with a surface water body exhibited significantly higher incidence rates for both infections (OR 1.225 - 1.363 $p < 0.001$). Non-parametric ranking identified a clear association between hydrometeorology and infection incidence, with lagged associations from 16-20 weeks proving particularly strong, thus indicating a link between infection peaks (April 2016) and the flood event which began approximately 18 weeks earlier. Findings demonstrate all three hydrometeorological variables could be used to predict the increase in cryptosporidiosis during April 2016, while only surface water discharge was associated with VTEC enteritis.

Spatiotemporal analysis of associations between flood hydrometeorology and gastroenteric infection: The Winter 2015-2016 flood event in the Republic of Ireland

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Abstract

During a 6-week period in November and December 2015, a series of Atlantic Storms swept across the Republic of Ireland (ROI) and Great Britain, beginning with Storm Abigail, followed in quick succession by Storm Desmond (December 4th), Storm Eva (December 23rd) and Storm Frank (December 29th). Severe, widespread pluvial and fluvial flooding occurred, particularly in the Irish west and midlands, with rainfall up to 200% above normal in many regions, making it the wettest winter ever recorded. While the infrastructural damage and subsequent costs associated with flood events have, and will continue to receive widespread attention, far less attention is given to the potential adverse human health effects of these events. This is particularly significant in the ROI, which is characterised by the highest crude incidence rates of verotoxigenic *E. coli* (VTEC) enteritis and cryptosporidiosis in Europe, however to date, the role of extreme weather events on incidence rates have not been studied. Accordingly, weekly spatially-referenced infection incidence from July 2015 to June 2016 were employed in concurrence with weekly time-series of cumulative antecedent rainfall, surface water discharge and groundwater level from largest river basin in Ireland (Shannon River), and high-resolution flood risk mapping. An ensemble of statistical and time-series analyses were employed to quantify the influence and timing of flood hydrometeorology on the incidence of confirmed infections. Seasonal decomposition a high residual infection peak (excluding seasonal patterns and long-term trends) during April 2016, with space-timing scanning used to identify the location, size and temporal extent of excess infection clusters. Excess cases of VTEC enteritis were geographically associated with the Shannon basin, while cryptosporidiosis excess was widespread. Generalised linear modelling of infection locations show that areas with a surface water body exhibited significantly higher incidence rates for both VTEC (OR: 1.225; $p < 0.001$) and cryptosporidiosis (OR: 1.363; $p < 0.001$). Non-parametric ranking identified a clear association between rainfall, surface water discharge, groundwater levels and infection incidence, with lagged associations from 16-20 weeks proving particularly strong, thus indicating a link between infection peaks (April 2016) and the flood event which began approximately 18 weeks earlier. Findings demonstrate that all three hydrometeorological variables could be used to predict the increase in

cryptosporidiosis during April 2016, while only surface water discharge was associated with VTEC enteritis.

1. Introduction

Recent climate change projections predict an increase in the frequency and severity of major flooding events across Europe (Arnell & Gosling, 2016); over the past six decades, north-western Europe, and particularly the UK and Ireland have experienced significant increases in rainfall and soil moisture, resulting in significantly elevated flood discharges (Blöschl et al., 2019). For example, what was considered a 100-year flood event in north-western Europe during the 1960s, is now described as a 50 to 80 year-event (Blöschl et al., 2019). While the economic burden associated with current and projected flooding has been extensively explored within the scientific literature, the adverse effects of increasingly frequent and severe flooding on human health is still characterised by significant knowledge gaps, particularly in high-income regions (Cann et al., 2016; Andrade et al., 2018). This is partially due to the frequently unclear temporality related to the human health impacts of flood events with effects frequently indirect, complex, spatially variable, and subject to post-event delays of days, weeks or months (Penning-Rowsell et al., 2005). Notwithstanding, previous studies have highlighted the link between increasing flood occurrence due to climate change and both direct and indirect human health impacts (Hajat et al.,2003; Smith et al., 2014; Andrade et al., 2018). Apart from directly attributable human fatalities associated with these events (Jonkman et al., 2008; Boudou et al., 2016), indirect health impacts and more specifically, the incidence of sporadic waterborne enteric infections, are likely to increase in concurrence with flood frequency and severity (Brown et al., 2013; Andrade et al., 2018). Inundation of anthropogenic infrastructure (e.g. wastewater treatment, roads, farmyards, etc) will lead to mobilization of enteric pathogens and subsequent contamination of rivers, lakes, groundwater wells and aquifers, subsequently triggering waterborne infections (Semenza, 2020).

Recent work indicates that Ireland will be the second most affected European country in terms of proportion of the national population likely to reside in flood-prone areas by 2100 (Arnell & Gosling, 2016; Forzieri et al., 2017), and is thus particularly susceptible to flood-associated health impacts. Compounding this, recent notification rates of verocytotoxigenic *Escherichia coli* (VTEC) enteritis and cryptosporidiosis in Ireland, two enteric infections with historically high rates of waterborne transmission (Hunter et al., 2005; Karmali et al., 2010), are the highest in the European Union, (ECDC, 2019). VTEC is a zoonotic bacterial pathogen causing gastrointestinal illness in humans, with the spectrum of severity ranging from mild diarrhoea to haemorrhagic colitis and haemolytic uremic syndrome (HUS), a severe complication that can cause renal failure or death (Karch et al., 2005; Karmali et al., 2010). Cryptosporidiosis is caused by *Cryptosporidium* spp., an oocyst-forming protozoan parasite (Fayer & Ungar, 1986), also characterised by a wide range of symptoms (diarrhoea, weight loss, vomiting, abdominal pain, nausea and fever), and potentially resulting in acute dehydration and death in very severe cases. In Ireland, a high proportion of both infections have been linked with the consumption of, or exposure to, contaminated water (Cummins et al., 2010; Hynds et al., 2014).

Winter 2015/16 was characterized by extremely wet conditions resulting from a series Atlantic storms, resulting in unprecedented, widespread flooding across Ireland and the UK. In addition to the primary, readily observable impacts of the event (e.g. flooding of households and businesses, interruption of transport networks, etc.), a significant number (>200) of incidents were reported pertaining to Irish drinking water and wastewater services. From December 2015, several boil-water notices were issued, affecting approximately 23,000 people, due to specific concerns around drinking water quality and its potential impact on public health (National Directorate for Fire and Emergency Management, 2016). Despite these warnings and the potentially high-risk scenario, no significant confirmed outbreaks of waterborne infection were officially reported to the Irish Health Service Executive (HSE) during or immediately after the event. To date, no studies have investigated the link between this particular event and the incidence of infectious disease within the population.

The current study sought to investigate the potential relationship between the winter flood event of 2015/16 and the incidence of confirmed VTEC enteritis and cryptosporidiosis in Ireland via a retrospective ecological study comprising an ensemble of (geo)statistical techniques. Seasonal decomposition and space-time scanning were used to detect potential irregularities in the seasonal and spatial distribution of infections during and after the flood period. Subsequently, generalised linear modelling was employed to explore spatial relationships between flood risk exposures, observed flood extent, and the incidence of infection at a fine geographical resolution. Finally, exemplar hydrometeorological data (surface water discharge, groundwater level, and precipitation) from the Shannon River Basin (largest river basin in Ireland) were used as flood indicators, and modelled in concurrence with infection data via time-series analyses to provide new insights on the timing and "behaviour" of infections within the context of a significant flood event.

2. Methods

2.1 Analytical Protocol

A three-phase ensemble of existing analytical approaches was employed to investigate the presence, magnitude and timing of associations between infection and flooding, in line with overarching research objective, as follows:

- **Phase 1:** Seasonal decomposition was carried out in concurrence with space-time scanning to examine the space-time distribution of atypical (i.e. minus seasonal trend) infections during and after the flood period.
- **Phase 2:** Generalised Linear Modelling (GLM) was employed to explore spatial links between categorical flood risk based on calculated return periods, measured flood extent and presence/absence of confirmed infections.
- **Phase 3:** Time-series analyses (antecedent Spearman's Rho, ARIMA) was performed to investigate the relationship between infection incidence and three temporally lagged hydrometeorological variables (rainfall, surface water discharge and groundwater level) delineated as indicators of the flood event.

2.2 The 2015-2016 flood event in the Republic of Ireland

Meteorological characterisation

Winter 2015/16 has become synonymous with some of the most widespread and severe flooding ever recorded across the Republic of Ireland (ROI). From November 2015 to January 2016, both regions experienced a series of winter storms, resulting in exceptionally wet conditions. Following a relatively dry October, Storm Abigail impacted the ROI over the 2-day period 13th/14th November 2015, triggering heavy rainfall exceeding 80mm over 24 hours in some areas (Walsh, 2016). Two lower intensity storms subsequently occurred on November 17th (Storm Barney) and November 29th (Storm Clodagh); November 2015 has since been ranked the seventh wettest November since records began in 1850 (Walsh, 2016). During December 2015, a succession of Atlantic storms were recorded – Storm Desmond (4th/5th), Storm Eva (23rd), and Storm Frank (29th/30th). Maximum rainfall intensities were recorded during Storms Desmond (259.7 mm over 48 hours; Leenane, Co. Galway) and Frank (159.9 mm over 48 hours; Cloone Lake, Co Kerry). December 2015 is ranked as the wettest December ever recorded in Ireland. Approximately 500 mm of monthly rainfall were registered locally at several synoptic stations (e.g. Co. Kerry, Cork and Galway), with mean rainfall equating to 250% above normal in most parts of the country and exceeding 300% in southern regions. Likewise, both January and February 2016 were particularly wet, being ranked as the 9th wettest January and February recorded in the ROI.

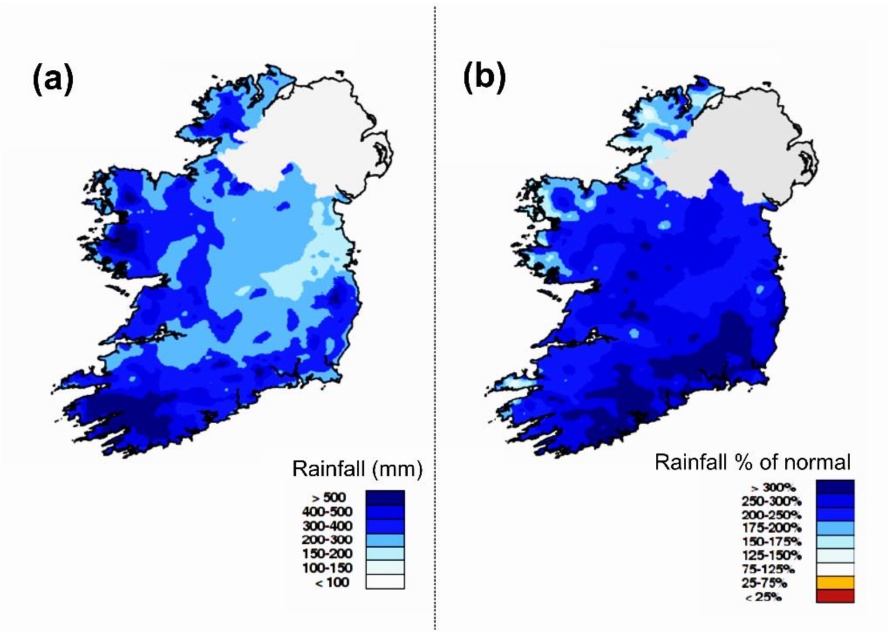


Figure 1. (a) Measured precipitation (mm) during December 2015 (a) - and (b) percentage of long term (1981-2010) average measured during December 2015. Adapted from Walsh (2016).

Hydrological characterisation

Three primary flood periods have been identified during the period 12th November 2015 to 5th January 2016, corresponding with the occurrence of the three main storm events (Figure 2). Flood records indicate that the spatial extent of hydrological impacts were widespread across the country, with 37 of 75 river gauging stations (49.3%) recording their highest ever discharge levels during the event (Nicholson & Gebre, 2016). Due to large uncertainties and the atypical nature of the flood (succession of events), no return periods have been calculated to assess the intensity of the 2015-2016 flood event.

Flood longevity represents one of the primary characteristics underpinning the severity of the Winter 2015/16 event in Ireland, with flood duration far outlasting the period of maximum recorded river discharges (29th of November to 5th of January) (National Directorate for Fire and Emergency Management, 2016). Several secondary flood episodes associated with persistent rainfall or short-term heavy rainfall events occurring on saturated land were reported from January to April 2016. For example, during the 10th-11th April 2016 a 24-hour rainfall event triggered a significant increase in flood extent, increasing from 2,500 hectares on the 30th of March to 7,600 hectares on the 11th of April (O'Hara *et al.*, 2019).

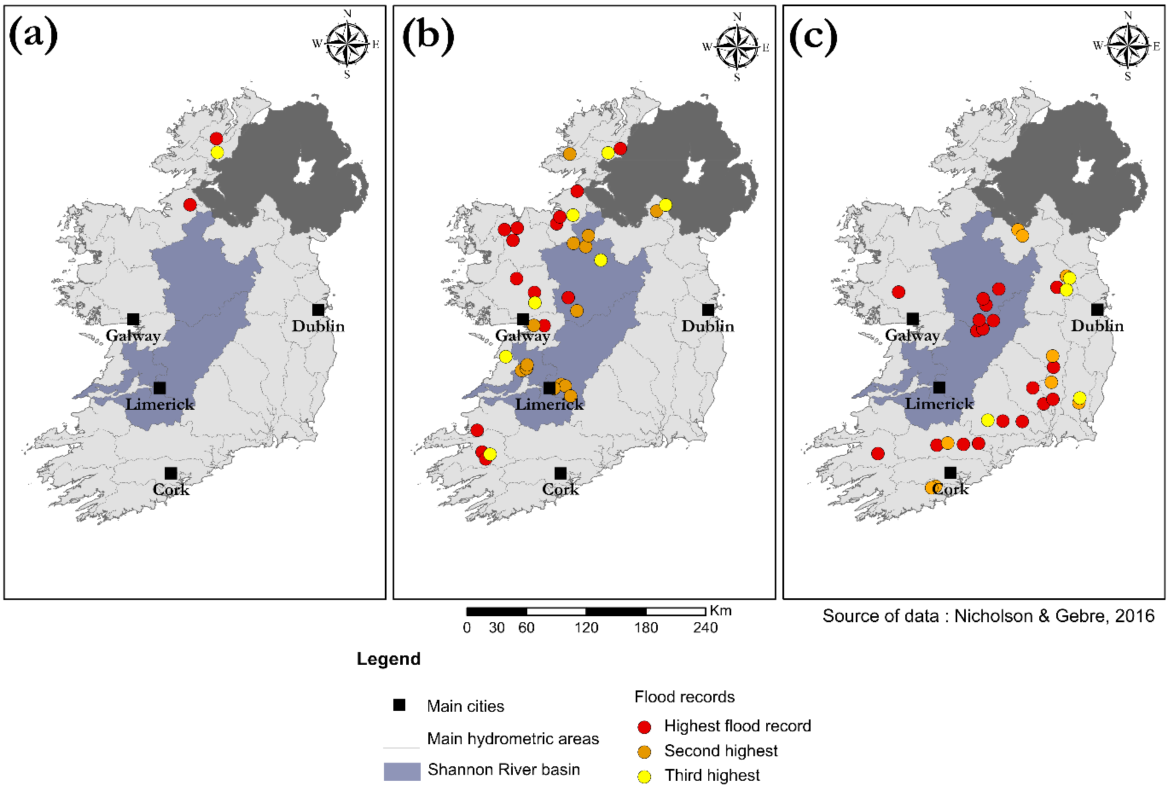


Figure 2. Water level rankings measured in Ireland during storms Abigail (a), Desmond (b) and Frank (c). Adapted from Nicholson & Gebre (2016).

2.3 Data Sources

Following receipt of ethical approval for this study from the Royal College of Physicians of Ireland Research Ethics Committee (RECSAF_84), access to address-level infectious disease notification data from Ireland's Computerised Infectious Disease Reporting (CIDR) system was granted by the National CIDR Peer Review Committee. CIDR is an information system developed to manage the surveillance and control of infectious diseases in Ireland, using standard case definitions for all notifiable diseases, as per the Infectious Diseases (Amendment) Regulations 2020 (S.I. No. 53 of 2020).

Datasets comprised all confirmed cases of sporadic (i.e. non-outbreak) verotoxigenic *E. coli* (VTEC) enteritis reported by regional departments of public health between 1st January 2013 and 31st December 2017. VTEC cases prior to January 2013 were not obtained due to geographically divergent testing and reporting protocols. The cryptosporidiosis dataset included all confirmed cases notified from 1st January 2008 to 31st December 2017; cases occurring prior to January 2008 were not integrated due to a significant outbreak which took place in April 2007, thus representing a likely source of bias. All individual case notifications for both infections were geographically linked to the centroid of a Central Statistics Office (CSO) Small Area (SA), the smallest administrative delineation currently employed in the Republic of Ireland for national census reporting (18,488 SA in 2011). Two main periods were identified for the current study:

- **The "non-flood" period,** corresponding to the total duration of both infection datasets: 2013-2018 for VTEC (2,755 cases) and 2008-2017 for cryptosporidiosis (4,509 cases).
- **The "flood period**", corresponding to the period between 1st July 2015 and 1st July 2016. This timeframe was selected to comprise a complete hydrological year and delineated by the maximum life expectancy of the longest lived pathogen, estimated to be a maximum of 5 to 6 months for Cryptosporidium spp. Case numbers of VTEC enteritis and cryptosporidiosis occurring during the flood period were 577 and 607, respectively (Figures 3 & 4).

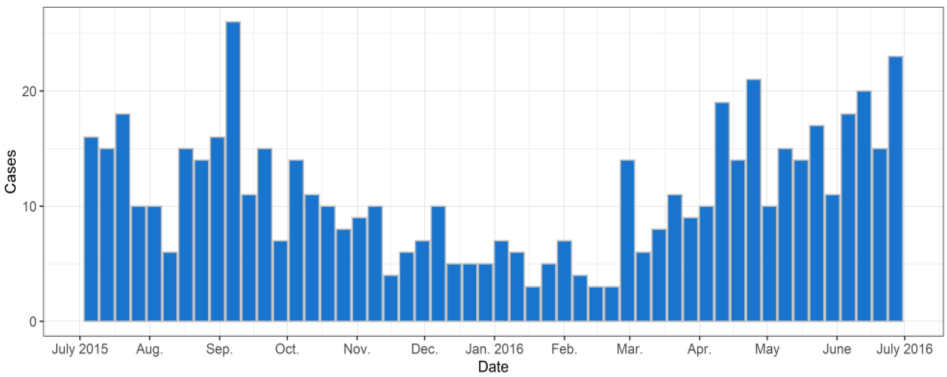


Fig. 3 Weekly VTEC cases from July 2015 to July 2016

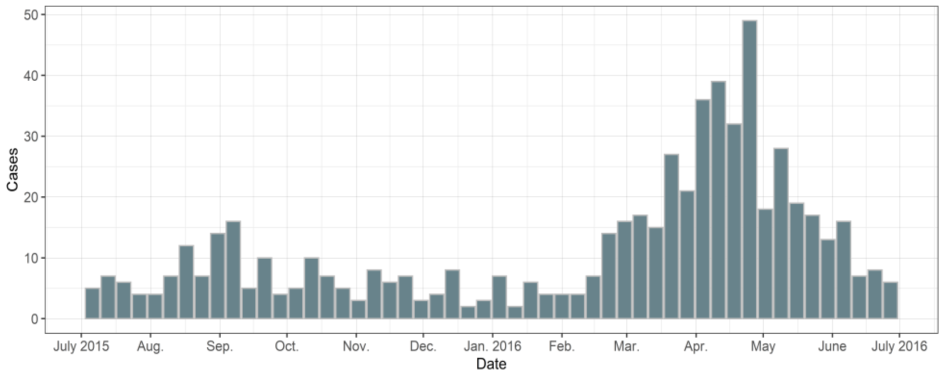


Fig. 4 Weekly cryptosporidiosis cases from July 2015 to July 2016

2.4 Spatiotemporal analysis of VTEC enteritis and cryptosporidiosis

Seasonal decomposition

Seasonal decomposition of confirmed cases of infection were undertaken at both weekly and monthly resolutions using Seasonal Trend decomposition (STL) with the Loess (Locally Estimated Scatterplot Smoothing) method, to decompose the incidence rate of infection (*Yv*) into seasonal variation (*Sv*), overall trend over time (*Tv*) and residuals (*Rv*). An additive STL model was employed due to the relatively constant trend associated with peak (annual/seasonal) values over time. For the purposes of the current study (i.e. examining a specific event and time-period), particular focus was given to the trend and residual series of both infections (i.e. seasonal signal extraction). Weekly decompositions were undertaken using R Studio (V 4.0) and the "forecast" package (V3.6), on total datasets for both infections (2013-2018 for VTEC, 2008-2018 for cryptosporidiosis), and extracted for the flood period from July 2015 to July 2016.

Space-time scanning

Space-time scanning analyses were carried out on the entire study period (non-flood period) and extracted for the flood period to detect temporally specific clusters of infection defined by significantly higher numbers of observed cases than expected within specified temporal and spatial windows. Analyses are based on the null hypothesis that cases are randomly distributed over space and time, with scanning conducted at SA scale using SaTScan v9.6 (Kulldorf and Information

Management Services, Inc., MA, USA) (Kulldorf, 1999). SaTScan requires a series of user defined parameters. Based on previous optimisation for the ROI (Boudou et al., 2020), a discrete Poisson model was selected considering the high spatial resolution (i.e. 18,488 SAs) and likely low case numbers per SA. Similarly, a maximum of 10% of the population at risk (PAR) was employed, with a maximum cluster radius of 50km. A minimum threshold of 10 cases was employed to ensure that only significant infection clusters were identified (i.e. avoid small household clusters). Data were aggregated at the monthly scale with a maximum cluster duration of 3 months, thus accounting for seasonal trends of infection.

2.5 Generalised Linear Modelling

Generalised Linear Modelling was used to assess the link between dichotomised (presence/absence) spatially-specific (SA-level) occurrence of infection and mapped categorical flood risk/extent parameters. Analyses were undertaken using mapped results from:

- Historical surface water flood mapping (GWFlood Project), based on Winter 2015/16 observations and indicating the fluvial and pluvial extent of the flood event (McCormack *et al*., 2020),
- High-resolution flood mapping of coastal and fluvial risks, with three "risk scenarios" based on calculated return periods (low: 1000 years, medium: 100 years (fluvial) - 500 years (coastal), and high: 10 years) (OPW, 2020),
- Presence of permanent surface water bodies (lakes, rivers) (Environmental Protection Agency, 2020).

All mapped datasets were imported to ArcGIS 10.7, with SA identifiers (national census area centroids) used to geographically attribute anonymised spatially-referenced case data, resulting in an anonymised dataset of confirmed infections linked to geographically explicit flood risk, flood extent and surface water attributes. Generalised linear modelling with a binary link function was applied to calculate probabilistic odds ratios (OR) between flood extent, fluvial/coastal flood scenarios (flood presence/absence), surface water presence, and confirmed human infection (infection presence/absence). Analyses were performed using R studio (v 4.0) for flood and "non-flood" periods.

2.6 Hydrometeorological indicators

To examine the presence of associations between flood-related hydrometeorology and the occurrence of infection, a national-level case study was performed using three hydrometeorological variables extracted from the Shannon River Basin: cumulative rainfall, river discharge (surface water) and groundwater level. The Shannon River Basin was selected as a representative area due to its central location and geographical significance (15,695 km^2), covering approximately 22% of the country. The river basin was significantly affected by flooding during the 2015-2016 event (National Directorate for Fire and Emergency Management, 2016) and is considered a "hotspot" for both VTEC enteritis and cryptosporidiosis (Boudou *et al.,* 2020).

A distinction was made between the Lower and Upper Shannon sub-basins to assess for spatial hydrodynamic variation (**Figure 5**). For each sub-basin, hydrometeorological data were extracted as follows:

- Daily cumulative rainfall from Met Éireann synoptic stations,
- Daily mean discharge (cubic meter per second). from OPW gauging stations,
- Daily groundwater level (meters) from the Environment Protection Agency (EPA) of Ireland.

The groundwater levels extracted from the EPA stations were rescaled (0 - 10) to ensure homogeneity.

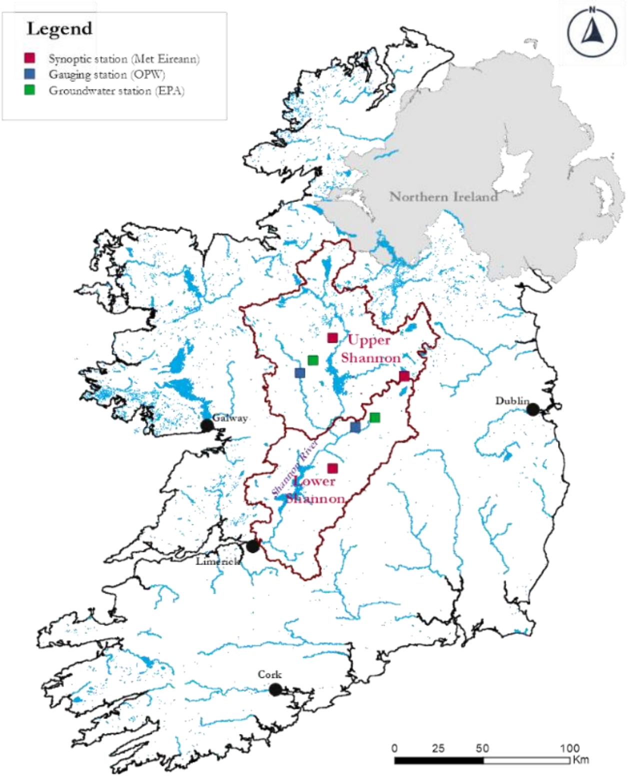


Figure 5. The Shannon River Basin and measurement stations selected for hydrodynamic data extraction and analyses

Measurement station/gauge selection was undertaken based on:

- dataset length and completeness,
- proximity of discharge and groundwater gauging stations to appropriately capture hydrodynamic patterns (i.e. interactions),
- synoptic stations were selected via calculation of the k-nearest neighbour to gauging stations (surface water and groundwater).

Two synoptic stations were used for the lower catchment (the discharge station being closer to the Gurteen station (Co Tipperary) while the groundwater station is closer to the Mullingar station (Co. Westmeath). The mean between these two stations was used to characterize rainfall in the Lower catchment.

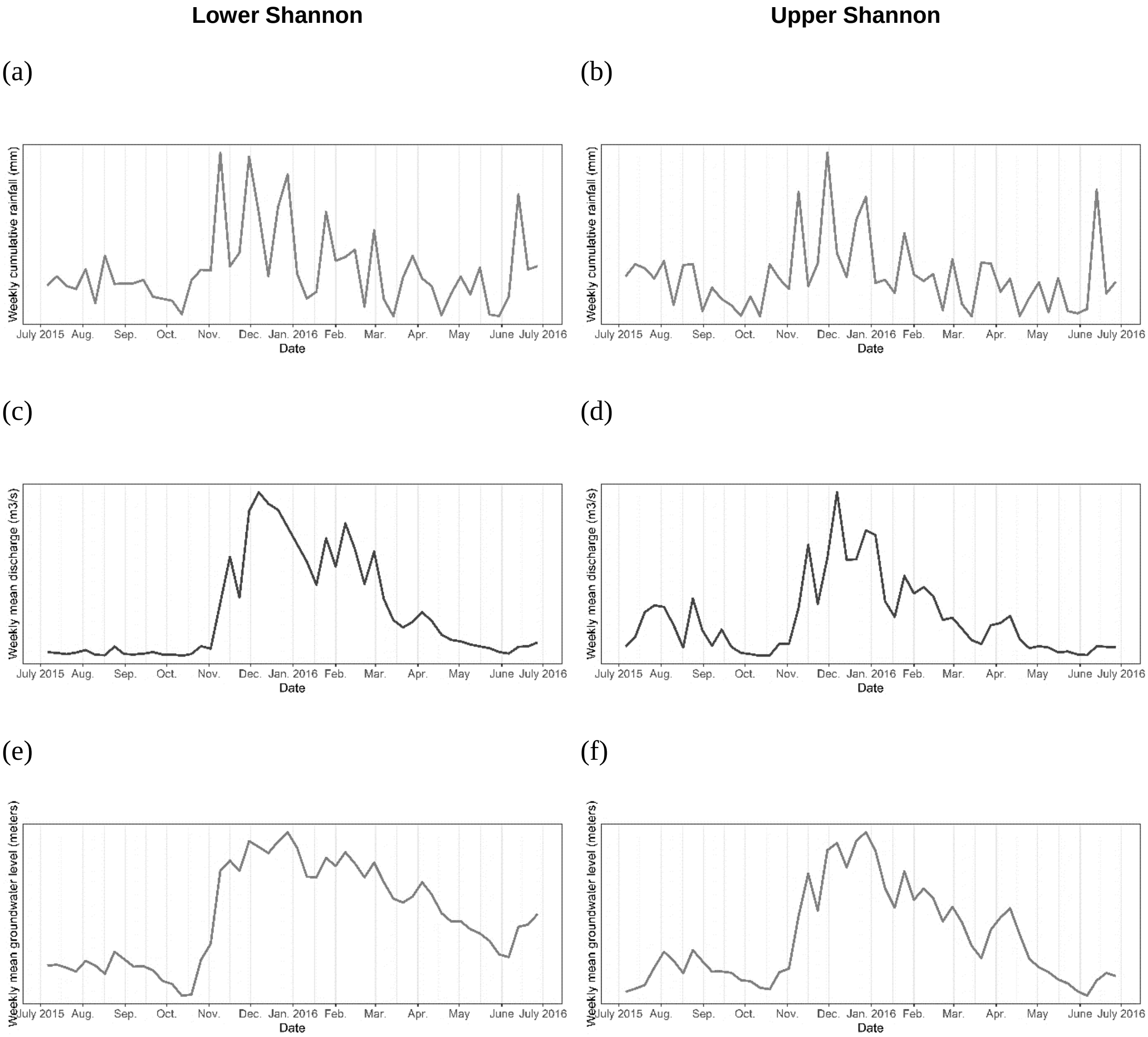


Fig. 6 Hydrometeorological variables recorded in lower and upper Shannon for the flood period: Weekly cumulative rainfall – (a) Lower Shannon: mean rainfall between Gurteen, Co. Tipperary and Mullingar, Co. Westmeath – (b) Upper Shannon, Mount Dillon station – Weekly mean discharge – (c) Lower Shannon: Brosna River at Ferbane, Co. Offaly – (d) Upper Shannon: Suck River at Rookwood, Co. Galway – Weekly mean groundwater levels – (e) Lower Shannon, Co. Offaly – (f) Upper Shannon, Co. Galway

2.7 Time-Series Analyses

Based on weekly time-series (Fig. 6), time-series analyses were conducted to identify lagged association between antecedent hydrometeorology and infection incidence. Analyses were carried out on the summed trend and residuals of both VTEC and cryptosporidiosis obtained from seasonal decomposition (Section 2.4), as the primary objective was to identify and elucidate atypical infection excess. Spearman's non-parametric Rho was calculated for weekly hydrometeorological time-series and the weekly lagged sum of infection trends and residuals in both upper and lower sub-basins. National infection data were used, based on the hypothesis the hydrometeorological means recorded within Shannon catchment can be used as indicators for country wide infection incidence. A range of 1 to 24 weeks was calculated and employed to assess minimum and maximum lags periods, with analysis carried out using R studio (v 4.0) and the GGally (v. 2.0) package. The lag range of 24 weeks was selected according to the maximum environmental survival of both pathogens, estimated to be up to 24 weeks in a 15°C environment for *Cryptosporidium* spp. (Alum *et al.*, 2014).

ARIMA modelling was used to assess the weight of weekly lagged hydrometeorological time-series on infection incidence during the flood period via back-casting. Differencing (Order – 1) was performed on all time-series to ensure stationarity. Similarly, as ARIMA does not appropriately account for overarching trends and data seasonality (as opposed to SARIMA), environmental time-series were seasonally adjusted. The final order parameters used for analysis (*p*,*d*,*q*) were ARIMA (0,1,1), obtained via optimisation diagnostics. Repeated iterations were performed on infection time-series (trend and residuals from July 2015 to July 2016), using stepped lags (from 1 to 24 weeks) of the three environmental time-series (rainfall, surface water, groundwater) as regressors, for both lower and upper Shannon sub-basins. The Ljung-Box test, a statistical test used for examining the autocorrelation of time-series, was used to indicate significance between hydrometeorological variables and infection incidence, with $p > 0.05$ used to confirm the magnitude of autocorrelation.

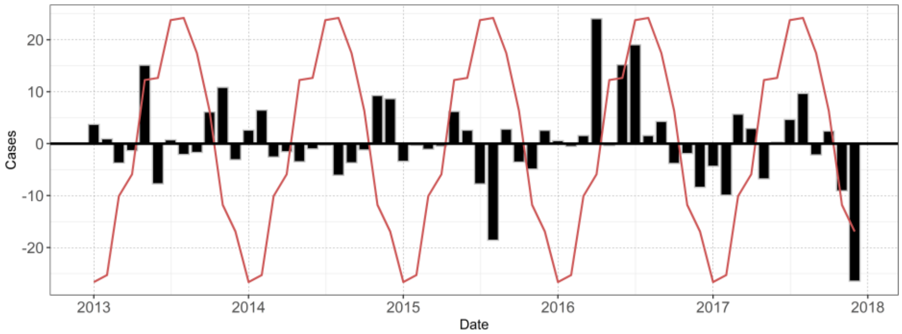
3. Results

3.1 Spatiotemporal patterns of infection during 2015-2016

Seasonal decomposition

Seasonal decomposition identified specific seasonal patterns for both infections (Figure 8). With respect to seasonal variations, VTEC infection exhibits high incidence during mid/late summer (peaking in July) with a second peak in September, while cryptosporidiosis is highest during spring (March to May, peaking in April). Both infections displayed a general (cumulative) trend increase over their respective study periods. Notably, both infections exhibited a marked residual (i.e. seasonal trend excluded) peak during April 2016, accounting for +23 observed residual cases for VTEC and +57 observed residual cases for cryptosporidiosis. Other secondary residual peaks were identified, particularly during June-July 2016 for VTEC enteritis.

(a)



(b)

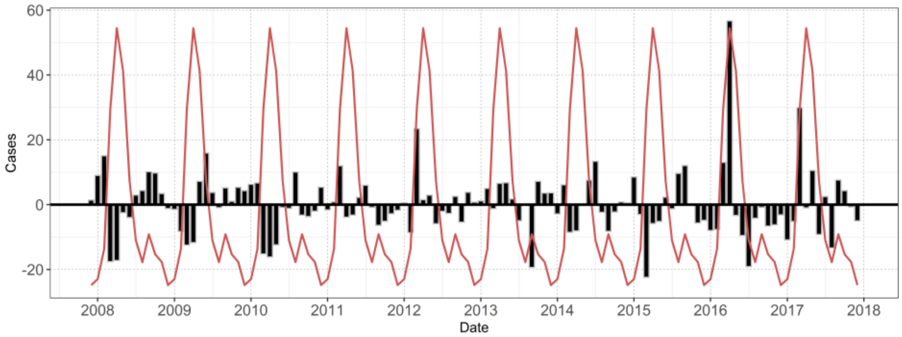


Fig. 7 Residuals (in black) and seasonal variations (in red) obtained from Loess seasonal decomposition (a) VTEC (2013-2018) – (b) Cryptosporidiosis (2008-2018)

Space-time scanning

Space-time scanning of VTEC cases indicates three significant (RR >1, p <0.05) clusters (83 cases in total) during the flood period, all of which intersected (25-35%) with the Shannon catchment area. The two largest clusters (40 and 29 cases) were identified east and south west of Limerick City, respectively, and occurred between April and June 2016 (Figure 9). A third cluster was observed further north (Co. Cavan) during September 2015 (14 cases).

Eight significant space-time clusters of cryptosporidiosis were identified during the flood period, accounting for 238 cases (Figure 9). The spatial distribution of these clusters was relatively widespread across the country, with 4 clusters intersecting the Shannon basin. The temporal distribution of clusters were from March to May 2016 for clusters 1, 2, 3 and 7 (south midlands and south) and from April to June 2016 for clusters 4, 5, 6 and 8 (north midlands and north).

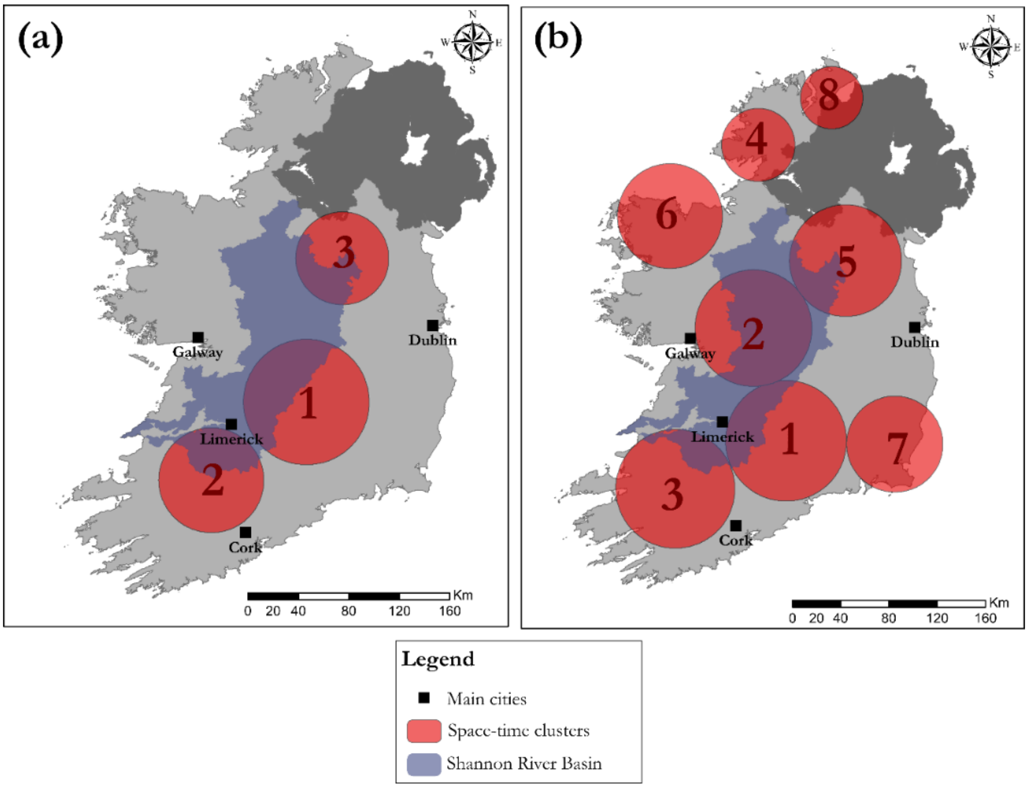


Fig. 8 Space-time clusters from July 2015 to July 2016, (a) VTEC, (b) Cryptosporidiosis with Shannon Basin indicated in blue

3.2 Flood exposure and infection

Results suggest an association between the spatial extent of the 2015-2016 flood event and the occurrence of infection during both study periods. During the non-flood period, approximately 39% of VTEC cases (OR: 1.487; $p < 0.001$) and 44% of cryptosporidiosis cases (OR: 1.792; p <

0.001) occurred within the spatial boundary of the 2015-2016 flood extent (Tables 1,2&4). Similarly, within the flood period, the SA units situated within the flood extent were more likely to report ≥1 VTEC (40% of total cases; OR: 1.355; p: < 0.001) or cryptosporidiosis case (40% of total cases; OR: 1.574; p < 0.001) (Tables 3&5).

Generalised Linear Models indicate that both infections occur significantly more frequently within areas prone to the risk of fluvial flooding. For example, from 2008 to 2018, a case of cryptosporidiosis was approximately 13% (p < 0.001) more likely to occur in an SA characterized by a high probability of fluvial flood risk (10-year flood return period, Table 4). Similarly, during the flood period, VTEC enteritis occurred more frequently within areas classified under the medium fluvial risk scenario (100-year flood return period: OR: 1.094; p = 0.025, Table 3). Results show no association between coastal (surge) flood risk areas and the incidence of either infection (p > 0.05, Tables 2&4) for the non-flood period, while a significant negative association was found with cryptosporidiosis for the flood period (Table 5).

A strong statistical relationship was found between infection incidence and the presence of a surface water body (lake or river); 25.4% of VTEC cases (OR: 1.225; p <0.001) and 30.9% of cryptosporidiosis cases (OR: 1.739; p <0.001) occurred within SAs comprising a surface water body over the non-flood period (Tables 1,2&4). A similarly significant association, albeit weaker, was observed for the flood period (VTEC cases: 24.8%; OR: 1.225; p <0.001 – cryptosporidiosis cases: 29.3%; OR: 1.363; p <0.001,Tables 3&5).

Table 1 Cryptosporidiosis and VTEC incidence compared to flood risk and flood extent exposure: Number of cases (percentage of total cases).

Predictors	VTEC cases (2013-2018)	VTEC cases (2015-2016)	Crypto. cases (2008-2018)	Crypto. cases (2015-2016)	Small area Number

Flood extent 2015-2016	1093 (39,7%)	233 (40,4%)	1993 (44,2%)	247 (40,7%)	4585 (24,8%)
Fluvial – High Probability	845 (30,7%)	178 (30,8%)	1379 (30,6%)	180 (29,7%)	5012 (27,1%)
Fluvial - Medium Probability	879 (31,9%)	194 (33,6%)	1450 (32,2%)	190 (31,3%)	5382 (29,1%)
Fluvial - Low Probability	921 (33,4%)	201 (34,8%)	1489 (33%)	194 (32%)	5726 (31%)
Coastal - High Probability	234 (8,5%)	46 (8%)	342 (7,6%)	54 (8,9%)	1713 (9,3%)
Coastal - Medium Probability	254 (9,2%)	52 (9%)	373 (8,3%)	55 (9,1%)	1874 (10,1%)
Coastal - Low Probability	271 (9,8%)	55 (9,5%)	390 (8,6%)	56 (9,2%)	2026 (11%)
Surface Water Present	701 (25,4%)	143 (24,8%)	1393 (30,9%)	178 (29,3%)	3110 (16,8%)

Table 2 Generalised linear modelling results for VTEC (Non-flood period:2013-2018): flood extent of 2015-2016, fluvial and coastal risk scenarios (CFRAM mapping) and presence of surface water bodies (Lakes/Rivers)

Predictors	Estimated Standard Deviation	P Value	OR	Cl 2,5	Cl 97	Significance[1]
Flood extent 2015-2016	0,397	> 0,001	1,487	1,414	1,564	***
Fluvial – High Probability	0,000	> 0,001	1,098	1,043	1,155	***
Fluvial - Medium Probability	0,060	0,017	1,062	1,011	1,116	*
Fluvial - Low Probability	0,071	0,006	1,073	1,020	1,128	**
Coastal - High Probability	-0,047	0,256	0,954	0,879	1,034	
Coastal - Medium Probability	-0,062	0,110	0,940	0,871	1,014	
Coastal - Low Probability	-0,053	0,180	0,948	0,876	1,024	
Lakes/Rivers	0,323	> 0,001	1,381	1,304	1,462	***

[1] Level of p-value significance : 0 '***' 0.001 '**' 0.01 '*' 0.05'.' 0.1 ' ' 1

Table 3 Generalised linear modelling results for VTEC (Flood period: July 2015 – July 2016) : flood extent of 2015-2016, fluvial and coastal risk scenarios (CFRAM mapping) and presence of surface water bodies (Lakes/Rivers)

Predictors	Estimated Standard Deviation	P Value	OR	Cl 2,5	Cl 97,5	Significance[1]

Flood extent 2015-2016	0,304	> 0,001	1,355	1,254	1,464	***
Fluvial – High Probability	0,073	0,071	1,076	0,993	1,165	
Fluvial - Medium Probability	0,090	0,025	1,094	1,011	1,182	*
Fluvial - Low Probability	0,076	0,055	0,998	1,164	1,164	
Coastal - High Probability	-0,075	0,262	0,927	0,810	1,055	
Coastal - Medium Probability	-0,057	0,373	0,945	0,831	1,068	
Coastal - Low Probability	0,066	0,285	0,936	0,827	1,054	
Lakes/Rivers	0,203	> 0,001	1,225	1,120	1,337	***

[1] Level of p-value significance : 0 '***' 0.001 '**' 0.01 '*' 0.05'.' 0.1 ' ' 1

Table 4 Generalised linear modelling results for cryptosporidiosis (Non-flood period: 2007-2018): flood extent of 2015-2016, fluvial and coastal risk scenarios (CFRAM mapping) and presence of surface water bodies (Lakes/Rivers)

Predictors	Estimated Standard Deviation	P Value	OR	Cl 2,5	Cl 97,5	Significance[1]
Flood extent 2015-2016	0,583	> 0,001	1,792	1,711	1,876	***
Fluvial – High Probability	0,120	> 0,001	1,128	1,077	1,182	***
Fluvial - Medium Probability	0,103	> 0,001	1,109	1,059	1,160	***
Fluvial - Low Probability	0,002	0,002	1,075	1,028	1,125	**
Coastal - High Probability	-0,075	0,047	0,928	0,861	0,999	*
Coastal - Medium Probability	-0,080	0,028	0,923	0,859	0,991	*

Coastal - Low Probability	-0,106	0,003	0,900	0,839	0,964	**
Lakes/Rivers	0,553	> 0,001	1,739	1,652	1,831	***

[1] Level of p-value significance : 0 '***' 0.001 '**' 0.01 '*' 0.05'.' 0.1 ' ' 1

Table 5 Results of generalised linear modelling for cryptosporidiosis (Flood period: July 2015 – July 2016): flood extent of 2015-2016, fluvial and coastal risk scenarios (CFRAM mapping) and presence of surface water bodies (Lakes/Rivers)

Predictors	Estimated Standard Deviation	P Value	OR	Cl 2,5	Cl 97,5	Significance[1]
Flood extent 2015-2016	0,317	0,000	1,574	1,272	1,482	***
Fluvial – High Probability	0,050	0,220	1,051	0,970	1,138	
Fluvial - Medium Probability	0,040	0,319	1,041	0,962	1,125	
Fluvial - Low Probability	0,015	0,698	1,015	0,939	1,097	
Coastal - High Probability	-0,036	0,582	0,965	0,847	1,093	
Coastal - Medium Probability	-0,069	0,278	0,933	0,821	1,055	
Coastal - Low Probability	-0,097	0,121	0,907	0,800	1,023	
Lakes/Rivers	0,310	0,000	1,363	1,252	1,483	***

[1] Level of p-value significance : 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05‘.’ 0.1 ‘ ’ 1

3.3 Flood hydrometeorology – Time-series analyses

Spearman’s non-parametric rank correlation

Results indicate significant positive associations with all three hydrometeorological variables, for both Lower and Upper Shannon sub-basins (Figure 10). Two primary lag periods of correlation are highlighted (R_{SP} > 0.4), namely from weeks 1 to 5 and from weeks 18 to 19. Highest R_{SP} values calculated for each variable, thus indicating the strongest associations, were:

- **Rainfall**: week 5 (Lower and Upper Shannon)
- **Surface water**: week 4 (Lower and Upper Shannon)
- **Groundwater level**: week 1 (Lower Shannon) and week 4 (Upper Shannon)

The highest R_{SP} was associated with rainfall on the lower Shannon (0.62), while associations were stronger with surface water and groundwater in the upper Shannon (0.59). Again, significant positive associations were found between the incidence of confirmed cryptosporidiosis and all three hydrometeorological variables (Figure 11), with the main positive associations (R_{SP} >0.4) occurring between weeks 15 and 19 (surface water and groundwater) and from weeks 16 to 22 (rainfall). The highest R_{SP} calculated for each hydrometeorological variable was:

- **Rainfall**: week 16 (Lower Shannon) and week 19 (Upper Shannon)
- **Surface water**: week 19 (Lower Shannon) and week 16 (Upper Shannon)
- **Groundwater**: week 16 (Lower and Upper Shannon)

The range of highest R_{SP} values was relatively similar within both sub-basins, ranging from 0.5 (rainfall) to 0.55 (groundwater) in the lower Shannon, and from 0.57 (rainfall, groundwater) to 0.58 (surface water) in the upper Shannon.

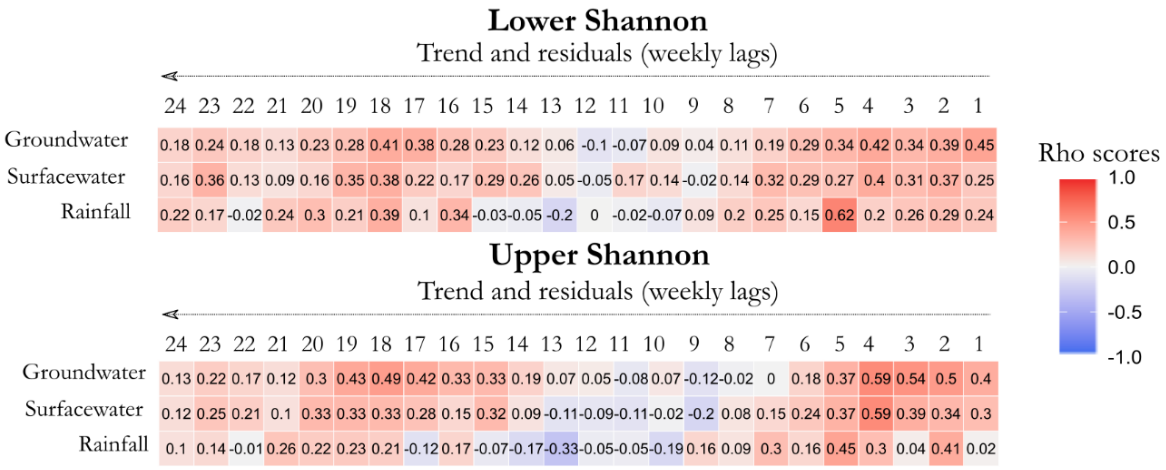


Fig. 9 Spearman's rank correlation tests for VTEC trend and residuals and hydrometeorological variables (lower and upper Shannon)

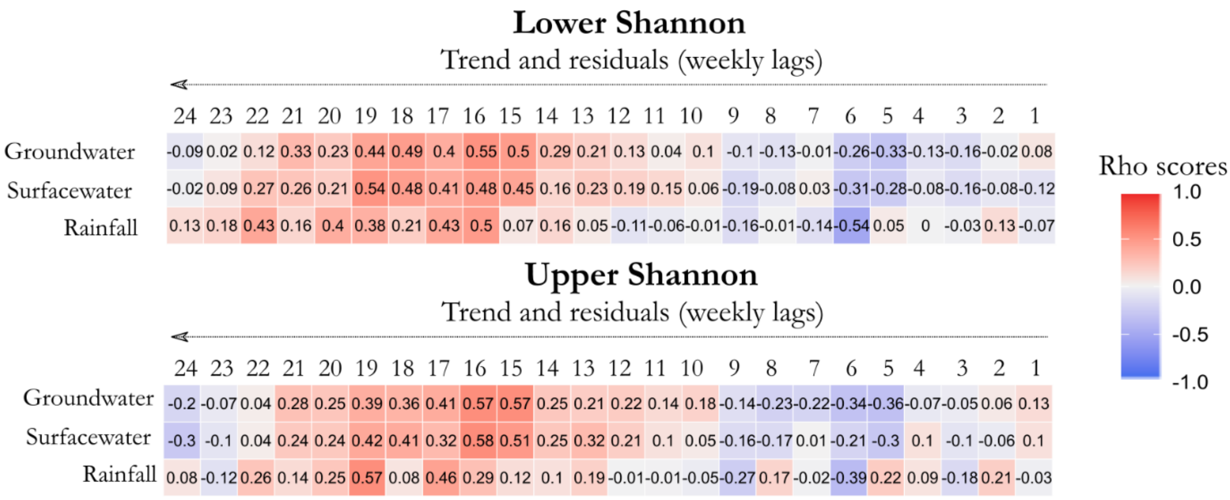


Fig. 10 Spearman's rank correlation tests for cryptosporidiosis trend and residuals and hydrometeorological variables (Shannon Upper and Lower)

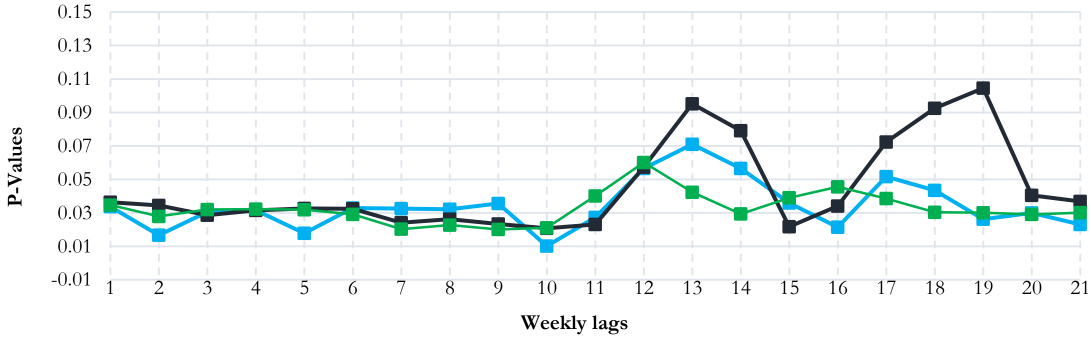
ARIMA modelling

Results of optimised ARIMA modelling for VTEC enteritis indicate relatively similar responses between the two sub-basins, highlighting two significant primary associational periods (i.e. lags) (Ljung-Box p-value > 0.05), from weeks 12 to 14 and from weeks 17 to 19, respectively (Figure 12).

Higher levels of association were observed in the Lower Shannon, with maximum p-values calculated for surface water discharge significantly higher than those obtained for the other two hydrometeorological variables (rainfall and groundwater level) in both sub-basins. Maximum associations found for each variable were:

- **Rainfall**: week 12 (p = 0.062, Upper Shannon) and week 13 (p-value = 0.071, Lower Shannon)
- **Surface water:** week 18 (p = 0.072, Upper Shannon) and week 19 (p = 0.105, Lower Shannon)
- **Groundwater level**: week 12 (p = 0.061, Upper Shannon; p = 0.06, Lower Shannon)

(a)



(b)

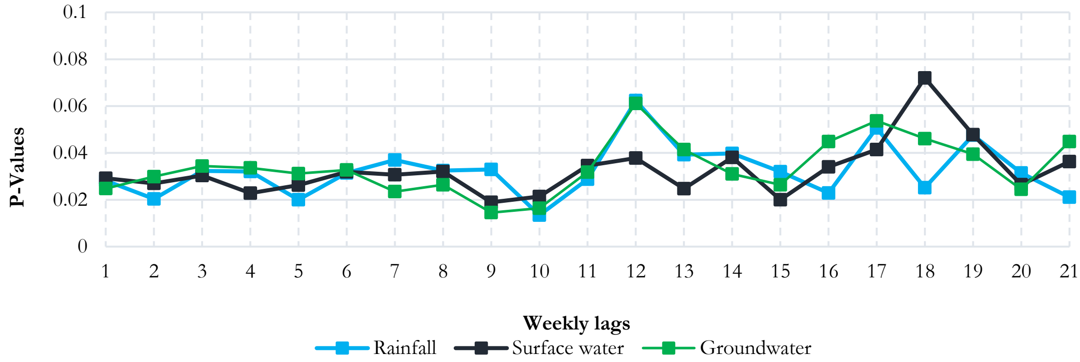
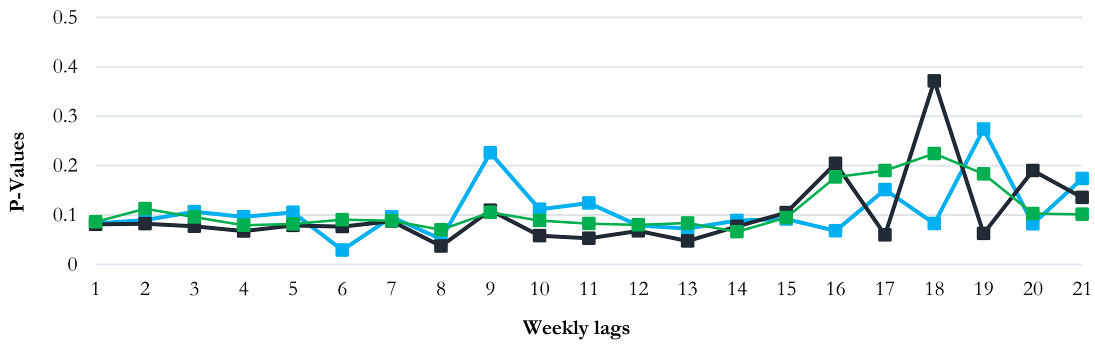


Figure 11. ARIMA Ljung-Box test results for VTEC (a) Lower Shannon – (b) Upper Shannon

Likewise, two specific periods of association were found between antecedent hydrometeorological variables and occurrence of atypical cryptosporidiosis cases, namely from weeks 8 to 10 and from weeks 16 to 21 (Figure 13). Levels of association were higher in the Upper Shannon (Max p-value 0.577) than the Lower Shannon (Max p-value 0.371), and significantly higher than those found for VTEC enteritis. The best fit weekly lags found by calculating the p-values of Ljung-box tests appear identical between both sub-basins, as follows:

- **Rainfall**: week 19 (p = 0.274, Lower Shannon – p = 0.522, Upper Shannon)
- **Surface water**: week 18 (p = 0.371, Lower Shannon – p = 0.577, Upper Shannon)
- **Groundwater level:** week 18 (p = 0.395, Lower Shannon – p = 0.424, Upper Shannon)

(a)



(b)

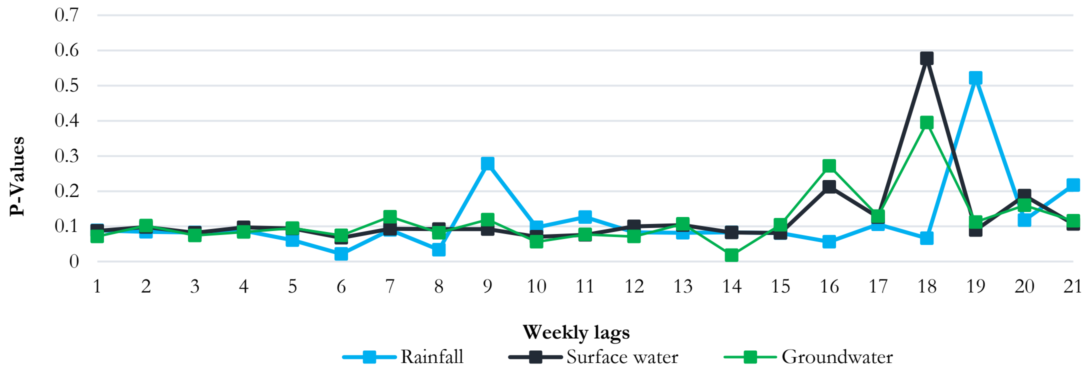


Figure 12. ARIMA Ljung-Box test results for cryptosporidiosis (a) Lower Shannon – (b) Upper Shannon

4. Discussion

Spatiotemporal distribution of VTEC enteritis and cryptosporidiosis

Seasonal decomposition of both infections provided strong evidence of atypical temporal peaks (i.e. residual infections) during April 2016 (both infections), followed by June/July 2016 (VTEC enteritis only). VTEC enteritis and cryptosporidiosis are characterized by differing seasonal patterns in Ireland; human cases of cryptosporidiosis usually peak during late spring (March to May), temporally concurring with agricultural cycles (e.g. calving and lambing seasons, manure spreading) (Callaghan *et al*., 2009; Cacci & Chalmers, 2016). Conversely, the highest incidence rate of VTEC typically occurs during late summer and early autumn due to increased consumption of meat products, livestock grazing and international travel (Lal *et al*., 2012; ÓhAiseadha *et al*., 2017). Accordingly, the atypical timing of the decomposed VTEC peak, in concurrence with the residual synchronicity between both infections represents a strong indicator of an impacting external factor, such as a relatively large, spatially diffuse outbreak (overlooked by standard surveillance measures), or a temporally specific societal or environmental event (Reingold, 1998). An investigation of social and traditional media leads the authors to conclude that the Winter 2015/16 flooding event was the likely source of these synchronous residuals.

Space-time scanning identified 10 spatiotemporally distinct clusters that temporally corresponded with April 2016, with the occurrence of an overlooked infection cluster or outbreak adjudged extremely unlikely. The spatial distribution of identified clusters indicates that cryptosporidiosis cases were nationally widespread, while VTEC clusters intersected with the Shannon River Basin. Rural areas in the Irish Midlands, including the Shannon River basin, have previously been identified as a potential hotspot for both infections (HPSC(a), 2019; HPSC(b), 2019) due to high livestock densities and reliance on private (unregulated) groundwater supplies (CSO, 2016), in addition to the predominance of karstified limestone bedrocks, previously identified as a risk factor for both infections (Money et al., 2010; HPSC, 2019). The presence of unseasonal VTEC clusters in this area adds weight to the likely relationship between flooding and infection incidence; during the 2015-2016 flood event, a large part of the Shannon River basin, including a majority of agricultural land, was identified as one of the worst affected areas of the country (O'Hara *et al.*, 2019).

Generalised linear modelling

During both "event" and "non-event" study periods, a systematic association was found between the spatial extent of the Winter 2015-2016 floods and the incidence of both infections. This finding, in concurrence with a significant (positive) relationship between measured surface water discharge and the incidence of both infections (Fig. 6 & 8), suggests that fluvial flooding played a role in infection transmission. Fluvial flooding has previously been identified as a transmission route for acute gastrointestinal illness; for example, a recent study from Germany (Gertler et al., 2015) revealed that an unexplained outbreak in the city of Halle was related to unusually high concentrations of *C. hominis* oocysts in the Saale River approximately two months after a major flood event. Likewise, Qadri et al. (2004), have shown that enterotoxigenic *Escherichia coli* (ETEC) was a major source of acute gastroenteritis during a flood period in Bangladesh, while Nguyen Huynh et al. (2019) have reported the presence of pathogenic E. coli and rotavirus-A in fluvial floodwaters in the Vietnamese Mekong Delta. Significantly stronger associations were found between cryptosporidiosis and the 2015-2016 flood extent (both periods), the presence of surface water bodies (both periods), and fluvial flood risk scenarios (non-event period only). This is somewhat unexpected as previous studies have shown that VTEC enteritis is more strongly related to waterborne transmission in Ireland (O'Dwyer et al., 2016, ÓhAiseadha et al., 2018), in addition to being typically associated with higher crude incidence rates, particularly in rural areas (Boudou et al., 2020). However, findings suggest that cryptosporidiosis was more likely to occur in flood prone areas and areas with surface water bodies than VTEC enteritis during non-event periods (Table 1). A previous Irish study by Graczyk et al. (2004) reported that *C. parvum* oocysts were present among zebra mussels sampled across the entire Shannon River drainage area, with the high prevalence of *Cryptosporidium* spp. in water sources likely associated with enhanced oocyst resilience in the aquatic environment (Medema & Schijven, 2016). Cryptosporidium oocysts have been shown to survive for up to 24 weeks outside a mammalian host (Alum et al., 2014), with VTEC surviving for approximately 6 to 12 weeks (Lothigius et al., 2010).

Conversely, the stronger link between the occurrence of VTEC enteritis and fluvial risk scenarios during the event period (2015-2016) indicates that VTEC enteritis (and by association, environmental transport of VTEC) is more significantly influenced by surface water during flood periods, which was partially confirmed via ARIMA. Levels of association found for the fluvial flood risk probability scenarios during the non-event period were lower than those for the 2015-2016 flood extent, suggesting that the low-probability fluvial flood risk scenario (based on a 1000-year return period) might have been under-estimated, highlighting the unusual intensity of the 2015-2016 flood event (i.e. > 1000-year flood return period).

Both infections exhibited significantly lower incidence rates in areas characterised by coastal flood risk, with significant negative associations found for cryptosporidiosis during the non-event period (Table 5). Elson *et al*. (2018) report that residing in a coastal region is not a risk factor for VTEC in England, while ÓhAiseadha *et al*. (2018) have noted that lower cattle, septic tank and private well densities in coastal areas likely explain the absence of correlations in these regions (i.e. lower pathogen concentrations on the ground surface and in the subsurface). A recent review by Andrade et al. (2018) reports that, to date, no published studies have provided proof of groundwater contamination with enteric pathogens in concurrence with coastal surges.

Notably, associations between the incidence of both infections and measured flood extent was marginally weaker during the flood period; the authors consider that this likely represents a change in social (healthy) behaviours. A recent Irish study by McDowell *et al.*,2020 reports that private well owners from primarily rural areas experiencing (or observing) flooding in the vicinity of their domestic water source frequently change their drinking source and switch to bottled water during or immediately after these events, with Lavallee et al (2020) reporting similar findings among rural residents of Ontario i.e. source switching driven by the perception of environmental risk including flooding in the vicinity of their domestic water source.

Time-series analysis

Time-series analyses revealed systematic significant positive associations (Spearman's $R_{SP} > 0.4$; ARIMA Ljung-Box p-values > 0.05) between the summed trend and residuals for both VTEC and cryptosporidiosis, and all three hydrometeorological variables, with findings thus indicating differing temporal responses, highlighting the mechanistic complexity of flood events as they pertain to acute gastrointestinal infections. Extreme rainfall has been identified as one of the primary environmental factors associated with occurrences of gastroenteritis via increased environmental transport of pathogens by overland flows or resuspension from sediments (Levy et al., 2016; Latchmore et al., 2020). For example, Ueijo et al. (2017) identified precipitation as a key factor underscoring the high incidence of acute gastrointestinal infections among young residents of areas relying on untreated water systems. A recent case study from Canada showed that higher *E.coli* concentrations were found in surface water during recharging groundwater months in winter, due to a higher pathogen transport capacity during wet conditions (Dwivedi et al., 2016). However, to date, few studies have assessed the link between groundwater level and gastroenteric infections, with none having looked at this association during or after a significant flood event.

ARIMA suggest significantly longer lagged effects for both cryptosporidiosis and VTEC enteritis than presented in previous studies. For example, Bimal et al. (2017) report that the risk of cryptosporidiosis and giardiasis within an urban population supplied by the same drinking water system was significantly higher 4 to 6 weeks after the occurrence of a heavy rainfall event (and particularly after dry periods). Similarly, Galway et al. (2015), demonstrated a link between total precipitation, mean stream flow and AGI incidence within a 4-5 week period in Canada In the current study, two distinct associational periods were identified between the incidence of VTEC enteritis and antecedent hydrometeorology, namely from weeks 12-13 (rainfall and groundwater level) and weeks 18-19 (surface water) (Figures 10 & 12). This would seem to confirm findings obtained from GLMs (i.e. significant association with medium-probability fluvial flood risk scenario), indicating that VTEC enteritis is more significantly influenced by surface water discharges during flood periods. Considering the incubation period for VTEC enteritis (1-2 weeks, Karmali et al., 2010), and the timing of the flood event (approximately 12-16 weeks from April 2016), a link was therefore established between river flows measured in early 2016 (i.e. maximum intensity of the flood event) and the unusual and unseasonal number of VTEC cases during April 2016. This indirect (i.e. outside the maximum environmental survival capacity of VTEC; 6-12 weeks) response between stream flows and the incidence of VTEC enteritis likely arose via mobilisation of faecal material deposited after the flood event on already saturated land (i.e. high runoff coefficient) by overland flow. The association between secondary VTEC peaks during June/July 2016 and groundwater levels suggests that increased overland flows due to subsoil saturation likely resulted in contamination of groundwater sources via direct source ingress and/or preferential flow i.e. concurrent high rainfall and subsoil saturation combined to result in two distinct periods of increased pathogen mobilisation, pathogen concentration, and subsequently human health risk (Williams et al., 2016)

Nagels et al. (2002) have previously shown that pathogenic *E. Coli* concentrations in a pastoral agricultural stream followed stream flow peaks recorded during a recent flood event. Similarly, Gartner et al. (2015) established a link between a flood event and cryptosporidiosis incidence peaks, approximately 10 weeks after the flood event, therefore suggesting longer lags between hydrometeorology and infection after flooding. Moreover, the authors consider that due to the timing and atypical duration of the Winter 2015/16 event, and consequent delays in the release of over-wintered animals onto saturated grazing land (Callaghan et al., 2009), this resulted in increasing the complexity of pathogen mobilisation and transmission (Wilcox & Colwell, 2005; Carlton et al., 2014), and the atypical, multiple lag periods identified.

Findings indicate an association between all three hydrometeorological variables and the residual cryptosporidiosis peak during April 2016, with all three occurring during one distinct associational period, between weeks 15 to 19 (Figures 11 & 13). Strongest associations were obtained during weeks 18 (groundwater, rainfall) and 19 (surface water), and thus notably longer than those identified for VTEC enteritis for both groundwater level and precipitation volume. This longer response may be explained by the longer survival capacity of *Cryptosporidium* spp. in the environment (up to 24 weeks, Alum et al., 2014), with *Cryptosporidium* spp. also significantly more persistent in subsurface environments than *E. coli.* (Bouchier, 1998). Based upon the identification of one associational period, with approximately 2-3 weeks of incubation associated with cryptosporidiosis, the effective association likely occurred from 12 to 16 weeks prior to the April peak, and was thus associated with hydrometeorological features during December 2015-January 2016 (i.e. potentially more direct, less complex influence of the flood event on transmission).

5. Conclusions

Several associations between the Winter 2015-2016 flood event in the Republic of Ireland and an atypical synchronous peak of sporadic cryptosporidiosis and VTEC enteritis approximately 2-4 months (accounting for infection incubation period) post-event were identified. Time-series analysis revealed that a link might be established between hydrometeorology and infections (and more specifically cryptosporidiosis) with longer than expected lags pointing to indirect mechanisms, while shorter-term responses indicate more direct waterborne transmission of pathogens. Thus, both direct and indirect causes-effect (transport/transmission mechanisms) were likely associated with the flood event, whereby more rapid, direct mechanisms occurred due to mobilisation of faecal materials deposited before or during the event, while indirect mechanisms comprised deposition of faecal materials on saturated land months after flood recession. Both employed time-series approaches indicate that the incidence of post-event VTEC enteritis was associated with more than one transport/transmission mechanism. Accordingly, the incidence of potentially waterborne infections within a flood context should be closely monitored several months post-event, and particularly in flood-prone areas, in view of the high susceptibility of these regions as found in the current study. Likewise, environmental monitoring (i.e. surface water and groundwater sampling) campaigns are required to fully understand the spatiotemporal dynamics of both pathogens (and their associated infections) during and after flood events. A multidisciplinary approach, combining hydrology, meteorology, hydrogeology, and epidemiology, is required to address the complex nexus between extreme weather events, waterborne pathogens, and human health.

CREDIT AUTHOR STATEMENT

Martin Boudou Methodology, Software, Validation, Formal Analysis, Writing – Original Draft; **Patricia Garvey:** Resources, Data Curation, Writing – Review/Editing; **Coilin ÓhAiseadha:** Resources, Data Curation, Writing – Review/Editing; **Jean O'Dwyer:** Conceptualisation, Supervision, Funding Acquisition, Writing – Review/Editing; **Paul Hynds:** Conceptualisation, Supervision, Funding Acquisition, Writing – Review/Editing

Bibliography

Allard, R. (1998), Use of time-series analysis in infectious disease surveillance, Bulletin of the World Health Organization, 76(4), 327.

Alum, A., Absar, I. M., Asaad, H., Rubino, J. R., & Ijaz, M. K. (2014) Impact of environmental conditions on the survival of Cryptosporidium and Giardia on environmental surfaces. *Interdisciplinary perspectives on infectious diseases*, Vol. 2014, 7p.

Andrade, L., O'Dwyer, J., O'Neill, E., & Hynds, P., (2018), Surface water flooding, groundwater contamination, and enteric disease in developed countries: A scoping review of connections and consequences. Environmental pollution, 236, 540-549.

Arnell, N. W., & Gosling, S. N. (2016), The impacts of climate change on river flood risk at the global scale, Climatic Change, 134(3), 387-401.

Blöschl, G., Hall, J., Viglione, A., Perdigão, R. A., Parajka, J., Merz, B., ... & Boháč, M. (2019). Changing climate both increases and decreases European river floods. Nature, 573(7772), 108-111.

Bouchier (1998) Cryptosporidium in water supplies. Third report of the group of experts to The Department of the Environment, Transport and the Regions and the Department of Health. London: DETR.

Boudou, M., Lang, M., Vinet, F., & Coeur, D. (2016, October), Lessons from analysing mortality from six major flood events in France (1930-2010).

Boudou M., Cleary E., ÓhAiseadha C., Garvey P., McKeown P., O'Dwyer J., Hynds P. (2020) Spatial and Spatio-temporal Epidemiology of cryptosporidiosis in the Republic of Ireland, 2008-2017 – *Under review*

Brown, L., & Murray, V. (2013). Examining the relationship between infectious diseases and flooding in Europe: A systematic literature review and summary of possible public health interventions. Disaster Health, 1(2), 117-127.

Cacci, S. M., & Chalmers, R. M. (2016). Human cryptosporidiosis in Europe. Clinical Microbiology and Infection, 22(6), 471-480.

Callaghan, M., Cormican, M., Prendergast, M., Pelly, H., Cloughley, R., Hanahoe, B., & O'Donovan, D. (2009), Temporal and spatial distribution of human cryptosporidiosis in the west of Ireland 2004-2007. International Journal of Health Geographics, 8(1), 1-9.

Carlton, E. J., Eisenberg, J. N., Goldstick, J., Cevallos, W., Trostle, J., & Levy, K. (2014). Heavy rainfall events and diarrhea incidence: the role of social and environmental factors. American journal of epidemiology, 179(3), 344-352.

Chhetri, B. K., Takaro, T. K., Balshaw, R., Otterstatter, M., Mak, S., Lem, M., ... & Fleury, M. D. (2017). Associations between extreme precipitation and acute gastro-intestinal illness due to cryptosporidiosis and giardiasis in an urban Canadian drinking water system (1997–2009). Journal of Water and Health, 15(6), 898-907.

Cann, K. F., Thomas, D. R., Salmon, R. L., Wyn-Jones, A. P., & Kay, D. (2013). Extreme water-related weather events and waterborne disease. *Epidemiology & Infection*, *141*(4), 671-686.

Cummins, E., Kennedy, R., & Cormican, M. (2010). Quantitative risk assessment of Cryptosporidium in tap water in Ireland. Science of the Total Environment, 408(4), 740-753.

ECDC(a), European Centre for Disease Prevention and Control, (2019) Cryptosporidiosis - Annual epidemiological report for 2017, 6p.

Dwivedi, D., Mohanty, B. P., & Lesikar, B. J. (2016). Impact of the linked surface water-soil water-groundwater system on transport of E. coli in the subsurface. *Water, Air, & Soil Pollution*, 227(9),

Elson, R., Grace, K., Vivancos, R., Jenkins, C., Adak, G. K., O'Brien, S. J., & Lake, I. R. (2018). A spatial and temporal analysis of risk factors associated with sporadic Shiga toxin-producing Escherichia coli O157 infection in England between 2009 and 2015. *Epidemiology & Infection*, *146*(15), 1928-1939.

Fayer, R., & Ungar, B. L. (1986) Cryptosporidium spp. and cryptosporidiosis. *Microbiological reviews*, *50*(4), 458.

Forzieri, G., Cescatti, A., e Silva, F. B., & Feyen, L. (2017) Increasing risk over time of weather-related hazards to the European population: a data-driven prognostic study. *The Lancet Planetary Health*, *1*(5), e200-e208.

Galway, L. P., Allen, D. M., Parkes, M. W., Li, L., & Takaro, T. K. (2015). Hydroclimatic variables and acute gastro-intestinal illness in British Columbia, Canada: A time series analysis. *Water Resources Research*, *51*(2), 885-895.

Gertler, M., Dürr, M., Renner, P., Poppert, S., Askar, M., Breidenbach, J., ... & Chalmers, R. (2015). Outbreak of Cryptosporidium hominis following river flooding in the city of Halle (Saale), Germany, August 2013. *BMC infectious diseases*, *15*(1), 88.

Graczyk, T. K., Conn, D. B., Lucy, F., Minchin, D., Tamang, L., Moura, L. N., & DaSilva, A. J. (2004). Human waterborne parasites in zebra mussels (Dreissena polymorpha) from the Shannon River drainage area, Ireland. Parasitology research, 93(5), 385-391.

Hajat, S., Ebi, K. L., Kovats, S., Menne, B., Edwards, S., & Haines, A. (2003). The human health consequences of flooding in Europe and the implications for public health: a review of the evidence. Applied Environmental Science and Public Health, 1(1), 13-21.

HSPSC(a) (2019), HSE, Health Protection Surveillance Centre, Cryptosporidiosis in Ireland, 2018. Dublin.

HSPSC(b) (2019), HSE, Health Protection Surveillance Centre, VTEC infection in Ireland, 2017. Dublin.

Hunter, P. R., & Thompson, R. A. (2005). The zoonotic transmission of Giardia and Cryptosporidium. International journal for parasitology, 35(11-12), 1181-1190.

Huynh, T. T. N., Nguyen, H. Q., Vinh, P. V., Baker, S., & Pathirana, A. (2019). Enteric pathogens in flood-related waters in urban areas of the Vietnamese Mekong Delta: a case study of Ninh Kieu district, Can Tho city. Urban Water Journal, 16(9), 634-641.

Hynds, P. D., Gill, L. W., & Misstear, B. D. (2014). A quantitative risk assessment of verotoxigenic E. coli (VTEC) in private groundwater sources in the Republic of Ireland. Human and Ecological Risk Assessment: An International Journal, 20(6), 1446-1468.

Jonkman, S. N., & Vrijling, J. K. (2008). Loss of life due to floods. Journal of Flood Risk Management, 1(1), 43-56.

Karch, H., Tarr, P. I., & Bielaszewska, M. (2005). Enterohaemorrhagic Escherichia coli in human medicine. *International Journal of Medical Microbiology*, *295*(6-7),pp. 405-418.

Karmali, M. A., Gannon, V., & Sargeant, J. M. (2010). Verocytotoxin-producing Escherichia coli (VTEC). Veterinary microbiology, 140(3-4), 360-370.

Kulldorff, M. (1999). Spatial scan statistics: models, calculations, and applications. In Scan statistics and applications (pp. 303-322). Birkhäuser, Boston, MA.

Lal, A., Hales, S., French, N., & Baker, M. G. (2012). Seasonality in human zoonotic enteric diseases: a systematic review. PLoS one, 7(4), e31883.

Latchmore, T., Hynds, P., Brown, R. S., Schuster-Wallace, C., Dickson-Anderson, S., McDermott, K., & Majury, A. (2020). Analysis of a large spatiotemporal groundwater quality dataset, Ontario 2010–2017: Informing human health risk assessment and testing guidance for private drinking water wells. Science of The Total Environment, 738, 140382.

Levy, K., Woster, A. P., Goldstein, R. S., & Carlton, E. J. (2016). Untangling the impacts of climate change on waterborne diseases: a systematic review of relationships between diarrheal diseases and temperature, rainfall, flooding, and drought. Environmental science & technology, 50(10), 4905-4922.

Lothigius, Å., Sjöling, Å., Svennerholm, A. M., & Bölin, I. (2010). Survival and gene expression of enterotoxigenic Escherichia coli during long-term incubation in sea water and freshwater. Journal of applied microbiology, 108(4), 1441-1449.

McCormack, T., Naughton, O., Bradford, R., Campanyà, J., Morrissey, P., Gill, L., Lee, M., (2020) GWFlood Project: Monitoring, Modelling and Mapping Karst Groundwater Flooding in Ireland, Geological Survey Ireland Report, 120p.

McDowell, C. P., Andrade, L., O'Neill, E., O'Malley, K., O'Dwyer, J., & Hynds, P. D. (2020). Gender-Related Differences in Flood Risk Perception and Behaviours among Private Groundwater Users in the Republic of Ireland. International Journal of Environmental Research and Public Health, 17(6), 2072.

Medema, G. J., & Schijven, J. F. (2001). Modelling the sewage discharge and dispersion of Cryptosporidium and Giardia in surface water. *Water Research*, *35*(18), 4307-4316.

Money, P., Kelly, A. F., Gould, S. W. J., Denholm-Price, J., Threlfall, E. J., & Fielder, M. D. (2010). Cattle, weather and water: mapping Escherichia coli O157: H7 infections in humans in England and Scotland. Environmental microbiology, 12(10), 2633-2644.

Nagels, J. W., Davies-Colley, R. J., Donnison, A. M., & Muirhead, R. W. (2002). Faecal contamination over flood events in a pastoral agricultural stream in New Zealand. *Water Science and Technology*, 45(12), 45-52.

National Directorate for Fire and Emergency Management, Department of Housing, Planning, Community and Local Government, 2016, Report on Flooding December 4 2015 – January 13 2016, Report, 95p.

Nicholson O. & Gebre F. (2016) OPW Response to the Winter 2015/2016 flooding in Ireland, Conference Proceedings of the National Hydrology Conference 2016, Athlone, Co. Roscommon, Ireland, pp. 63-80.

ÓhAiseadha, C., Hynds, P. D., Fallon, U. B., & O'Dwyer, J. (2017). A geostatistical investigation of agricultural and infrastructural risk factors associated with primary verotoxigenic E. coli (VTEC) infection in the Republic of Ireland, 2008–2013. Epidemiology & Infection, 145(1), 95-105.

O'Dwyer, J., Morris Downes, M., & Adley, C. C. (2016). The impact of meteorology on the occurrence of waterborne outbreaks of vero cytotoxin-producing Escherichia coli (VTEC): a logistic regression approach. Journal of Water and Health, 14(1), 39-46.

O’Hara R., Green S., McCarthy T., 2019, The agricultural impact of the 2015–2016 floods in Ireland as mapped through Sentinel 1 satellite imagery, Irish Journal of Agricultural and Food Research, 22p.

Penning-Rowsell, E., Tapsell, S., & Wilson, T. (2005). Key policy implications of the health effects of floods. In Extreme weather events and public health responses (pp. 207-223). Springer, Berlin, Heidelberg.

Qadri, F., Khan, A. I., Faruque, A. S. G., Begum, Y. A., Chowdhury, F., Nair, G. B., ... & Svennerholm, A. M. (2005). Enterotoxigenic Escherichia coli and Vibrio cholerae diarrhea, Bangladesh, 2004. *Emerging infectious diseases*, *11*(7), 1104.

Reingold, A. L. (1998). Outbreak investigations--a perspective. Emerging infectious diseases, 4(1), 21.

Semenza, J. C. (2020). Cascading risks of waterborne diseases from climate change. Nature Immunology, 21(5), 484-487.

Smith, K., Woodward, A., Campbell-Lendrum, D., Chadee, D., Honda, Y., Liu, Q., ... & Berry, H. (2014). Human health: impacts, adaptation, and co-benefits. In Climate Change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the fifth assessment report of the Intergovernmental Panel on Climate Change (pp. 709-754). Cambridge University Press.

Uejio, C. K., Christenson, M., Moran, C., & Gorelick, M. (2017). Drinking-water treatment, climate change, and childhood gastrointestinal illness projections for northern Wisconsin (USA) communities drinking untreated groundwater. Hydrogeology Journal, 25(4), 969-979.

Walsh S., 2016, The Rainfall of Winter 2015/16 in Ireland, National Hydrology Conference 2016, Athlone, Co. Roscommon, Ireland.

Wilcox, B. A., & Colwell, R. R. (2005). Emerging and reemerging infectious diseases: biocomplexity as an interdisciplinary paradigm. EcoHealth, 2(4), 244.