04 – IMPACT OF THE 2015-2016 FLOOD EVENT ON THE INCIDENCE OF ACUTE GASTROINTESTINAL INFECTION (AGI) IN THE REPUBLIC OF IRELAND – AN EPIDEMIOLOGICAL PERSPECTIVE ON A HYDROLOGICAL PROBLEM

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Abstract

Beginning on 13th November 2015, a series of Atlantic Storms swept across the Republic of Ireland (ROI), 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 across the country, and particularly in the west and midlands, with numerous large rivers breaking their banks. Rainfall over the period was 200% above normal in many regions, making it the wettest winter ever recorded, with Met Éireann measuring 602mm total mean rainfall during this period. Flooding represents one of the most devastating naturally occurring environmental hazards, with the potential to inflict major societal, infrastructural, and environmental damage. Moreover, it is now widely accepted that climate change will exacerbate the frequency and intensity of significant flood events into the future. While the infrastructural damage and subsequent costs associated with flood events have, and will likely 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, as the country is characterised by the highest crude incidence rates of verotoxigenic *E. coli* (VTEC) enteritis and cryptosporidiosis in Europe. Both infections are suspected as being largely driven by waterborne transmission, however to date, the role of extreme weather events on incidence rates have rarely been studied.

Accordingly, weekly confirmed infection numbers (from the Computerised Infectious Disease Reporting (CIDR) database) from July 2015 to June 2016 were studied in concurrence with weekly time-series of cumulative antecedent rainfall, surface water discharge and groundwater levels from the Shannon River basin (upper and lower sub-basins), and the Office of Public Works (OPW) high-resolution flood risk mapping. An ensemble of statistical and time-series analyses including seasonal decomposition, space-time scanning, generalised linear modelling (GLM), non-parametric rank matrices, and Autoregressive Integrated Moving Average (ARIMA) were employed to quantify the influence and timing of these factors on the incidence of confirmed infections as they potentially related to the winter 2015-2016 flood event.

Seasonal decomposition of confirmed infections revealed a high residual peak (i.e. accounting for and 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 infections. Results indicate that excess VTEC cases were geographically associated with the Shannon basin, while cryptosporidiosis excess was significantly more widespread. Generalised linear modelling of the geocoded location of infections (based on Central Statistics Office Small Areas) as they relate to OPW flood risk categories showed that census areas with a surface water body exhibited significantly higher incidence rates for both VTEC (OR: 1.225; p-value: <0.001) and cryptosporidiosis (OR: 1.363; p-value: <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 April 2016 infection peaks and the flood event which begun approximately 18 weeks earlier. Findings demonstrate that all three hydrometeorological variables could be used to elucidate the increase in cryptosporidiosis during April 2016, while no direct link could be established for VTEC.

1. INTRODUCTION

From November 2015 to January 2016, the Republic of Ireland (ROI) experienced a series of Atlantic winter storms, leading to widespread, unprecedented flooding (Walsh, 2016). The intensity of flooding over this period set multiple records at water gauging stations over the entire country (Nicholson & Gebre, 2016). Total economic losses associated with these events is estimated to be approximatively €106M (Clarke & Murphy, 2019). Outside the most visible impacts of the floods (flooding of buildings, network disruption, etc), a significant number of incidents related to the Irish drink water and wastewater services were also reported, affecting a total of 23,000 people (National Directorate for Fire and Emergency Management, 2016). Despite these incidents, no confirmed outbreaks of waterborne infections were officially notified by the Irish Health Service Executive (HSE). The current study sought to investigate the links (if any) between this extreme weather event and the incidence of two waterborne infections in Ireland (cryptosporidiosis and Verotoxigenic *Escherichia coli* enteritis).

Cryptosporidiosis is a gastroenteric infection caused by an oocyst-forming protozoan parasite *Cryptosporidium* spp. (Fayer & Ungar, 1986). Symptoms include diarrhoea, vomiting, weight loss, abdominal pain, nausea and fever. In the most extreme cases, the infection can lead to acute dehydration and death. VTEC is a zoonotic bacterial pathogen causing gastrointestinal illness; clinical infection is associated with a diverse range of symptoms from mild diarrhoea to haemorrhagic colitis. The most severe cases can contract haemolytic uremic syndrome (HUS), potentially causing renal failure and death (Karch et al., 2005).

Cryptosporidiosis and VTEC have been notably associated with waterborne transmission in the Republic of Ireland (HPSC, 2015). In the light of recent climate change projections, the severity and intensity of flooding is expected to increase across Europe (Amell & Gosling, 2016), along with the incidence of waterborne enteric infections (Brown et al., 2013; Andrade et al., 2018). Accordingly, the ROI is expected to be the second most affected European country in terms of the population living in flood prone areas by 2100 (Arnell & Gosling, 2016; Forzieri et al., 2017). Similarly, the country consistently reports the highest incidence rate of both infections within the European Union (ECDCa&b, 2019). However, to date, no studies explored the link between the occurrence of an historical flood event and the incidence of VTEC and cryptosporidiosis.

2. MATERIAL AND METHODS

2.1. Infections dataset

Data pertaining to confirmed cases of enteric infections reported by regional departments of public health were obtained through the Computerised Infectious Diseases Reporting (CIDR) system. The dataset comprised all confirmed cases of cryptosporidiosis notified from 1st January 2008 and 31st December 2017 and all confirmed cases of primary sporadic infections of Verotoxigenic *E. Coli* enteritis (VTEC) from 1st January 2013 to 31st December 2017. Each individual case of infection was geographically linked to a CSO Small Area, the smallest administrative delineation currently exiting in the Republic of Ireland (18,488 in the 2011 census).

Weekly cases from 1st July 2015 to 1st July 2016 were extracted from the main datasets and used for the current analysis to investigate the link between infection incidence and the 2015-2016 flood event. This period was delineated to provide and asses one complete hydrological year (6 months before and after the flood event). The total number of VTEC and cryptosporidiosis cases for the study period was 577 and 607, respectively (Figures 1 & 2).

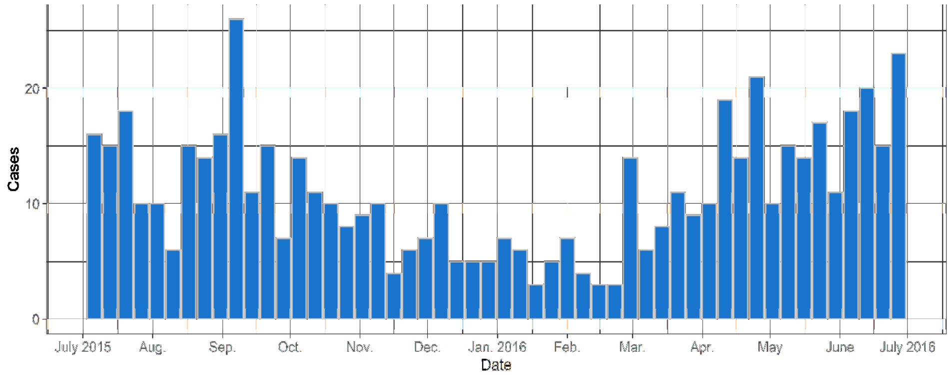


Figure 1: *Weekly VTEC cases from July 2015 to July 2016*

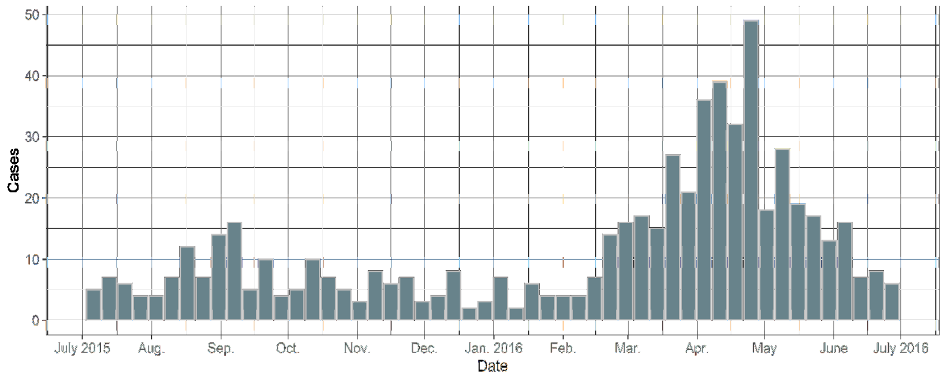


Figure 2: *Weekly cryptosporidiosis cases from July 2015 to July 2016*

2.2. Seasonal decomposition

The first step of the analysis consisted in performing seasonal decomposition of both infections to assess potentially unusual (i.e. unseasonal) patterns during and after the flood period. The analysis was conducted on the full duration of both infection datasets (respectively 2013-2017 for VTEC and 2008-2017 for cryptosporidiosis), by using the Seasonal Trend Decomposition (STL) with the Loess (Locally Estimated Scatterplot Smoothing) method. This method allows decomposition of the incidence rate of infection into seasonal variation, overall trend over time and residuals. All analysis were conducted using R Studio (V 4.0) and the "forecast" package (V3.6).

2.3. Space-Time scanning

Space-time scanning was employed on the study period (2015-2016) to identify temporally distinct clusters (observed cases significantly higher than expected cases). Space-time scanning is based on the null hypothesis that cases of infection are randomly distributed over space and time. The analysis was conducted at the monthly scale and at the small area resolution by employing the open access software SaTScan v9.6 (Kulldorf and Information Management Services, Inc., MA, USA) (Kulldorf, 1999). A discrete Poisson model was selected to account for the high spatial resolution (Small Area resolution) and the likely low number of cases per small area unit. Similarly, a minimum of 10 cases per cluster was employed to ensure that only significant clusters were identified, in concurrence with a maximum of 10% of the population at risk and a maximum cluster radius of 50 kilometres.

2.4. Generalised Linear Modelling (GLM)

Generalised Linear Modelling was used to investigate the link between spatial distribution of confirmed human infections and presence/absence of flood risk/surface water proximity. The analyses were undertaken using the high-resolution flood scenario maps produced within the framework of the National Catchment Flood Risk Assessment and Management (CFRAM) consisting of three “risk scenarios” based on estimated flood return period (low: 1000 years, medium: 100 years (fluvial) - 500 years (coastal), and high probability: 10 years) (OPW, 2020). The presence of permanent surface water bodies such as lakes or rivers, were also examined using open access data from the Environmental Protection Agency (EPA).

2.5. Time-Series analysis

The final step of the current study was an exploration of the relationship between the incidence of both infections during the study period and three hydrometeorological variables (rainfall, river discharge and groundwater level). The Shannon River Basin was selected as a case study with regards to its central location within the Republic of Ireland and in concurrence with its spatial significance (15,695km2). Time-series of the hydrometeorological variables were extracted for both Upper and Lower Shannon River Basins (Figure 3), based on the following source of information:

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

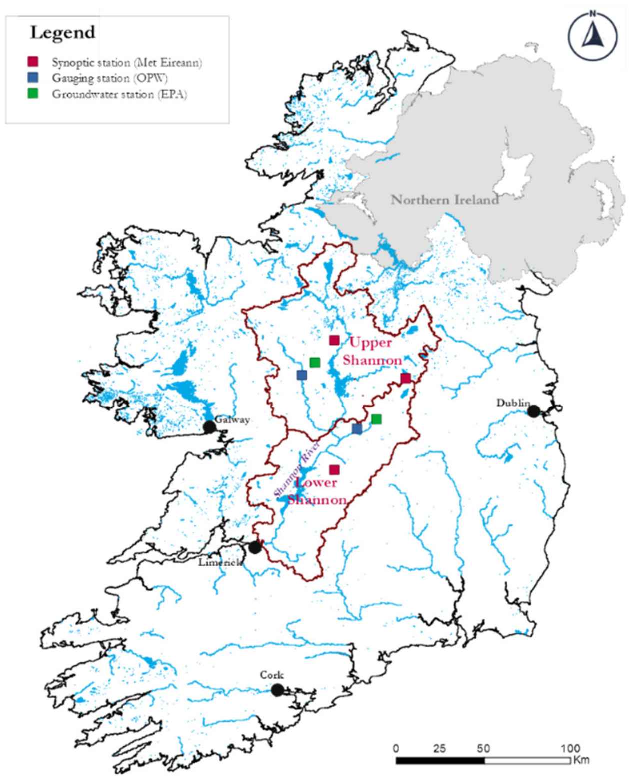


Figure 3: *The Shannon River Basin and measurement stations selected for hydrodynamic data extraction and analyses*

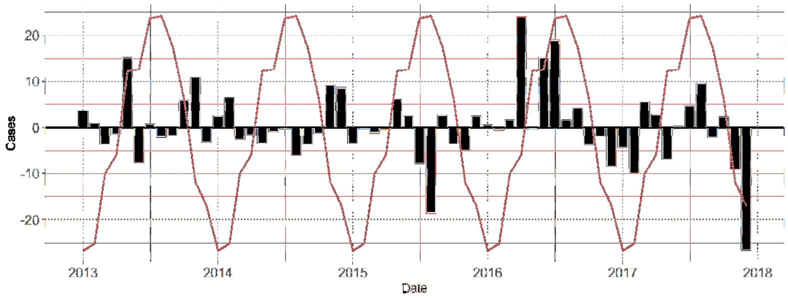
A serial of Spearman's non-parametric matrices were used to assess the level of coherency between the weekly lagged total of infection trends and residuals (selected to account for and exclude usual seasonal patterns of infection) and antecedent weekly hydrometeorological time-series. The infection data for the entire country from July 2015 to July 2016 was employed to conduct the analysis, based on the hypothesis that the Shannon River Basin can be used as a exemplar for both enteric infections. The lag period used was based on a range from 1 to 24 weeks, corresponding with the maximum survival time of *Cryptosporidium* spp. outside a mammalian host (Alum *et al.,* 2014).

3. RESULTS

3.1. Seasonal decomposition

Results obtained from seasonal decomposition identified specific temporal patterns for both infections (Figure 4). In terms of seasonal variation, VTEC exhibits high incidence during mid/late summer (highest peak in July) with a secondary peak in September. Conversely, cryptosporidiosis exhibits higher incidence during spring (from March to May with a highest peak in April). Both infections displayed a generally monotonic increasing trend over the whole duration of the dataset. The highest residuals of both infections were registered during April 2016 with +23 cases for VTEC and +57 cases for cryptosporidiosis, respectively. Secondary significant peaks were recorded in June and July 2016 for VTEC.

(a)



(b)

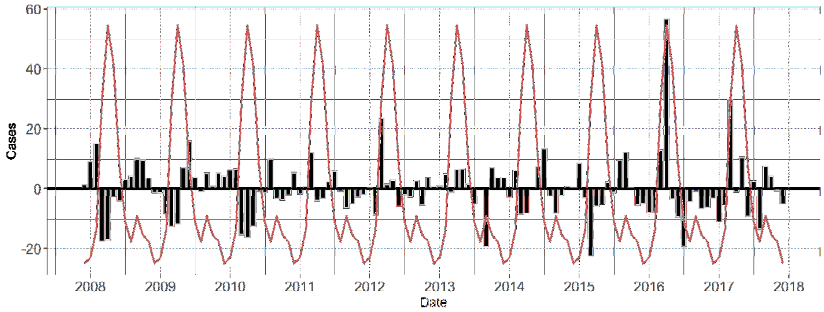


Figure 4: *Residuals (in black) and seasonal variations (in red) obtained from Loess seasonal decomposition VTEC (2013-2018) – (b) Cryptosporidiosis (2008-2018)*

3.2. Space-time scanning

Space-time scanning performed from July 2015 to July 2016 identified space-time clusters for both VTEC and cryptosporidiosis (Figure 5). In total, three significant clusters (p-value < 0.05) were identified for VTEC (83 cases in total). The two largest clusters (cluster 1 & 2) were reported from April to June 2016 and partially located within the Shannon River Basin. A third cluster (cluster 3) was identified in County Cavan during September 2015.

Results of space-time scanning for cryptosporidiosis identified eight clusters (238 cases). The spatial distribution of these clusters was widespread across the country, with four clusters partially occurring within the boundaries of the Shannon River Basin. All identified cryptosporidiosis clusters occurred from March to June 2016.

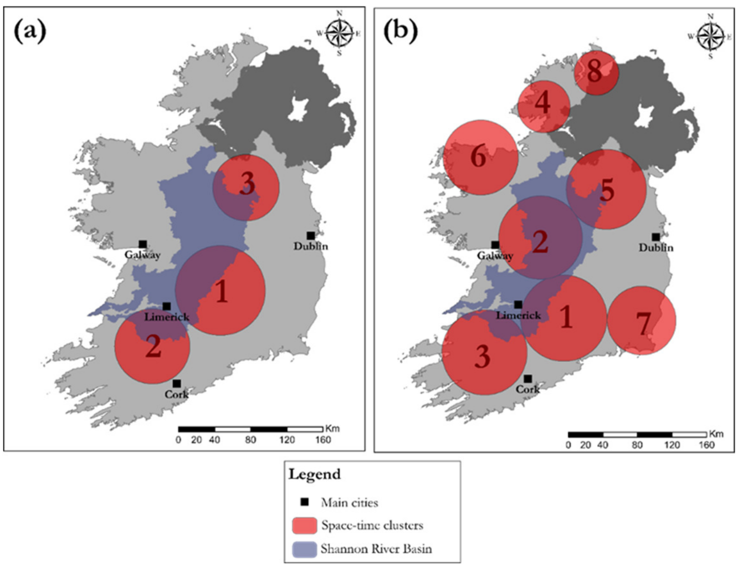


Figure 5: *Space-time clusters from July 2015 to July 2016, (a) VTEC, (b) Cryptosporidiosis*

3.3. Generalised linear modelling

Generalised linear modelling results did not indicate a statistical relationship between flood areas and cryptosporidiosis: no significant p-values were obtained between the cryptosporidiosis incidence rate and simulated flood risk scenarios (Table 1). Conversely, VTEC was found to have a significant positive association with the medium fluvial flood risk scenario (OR: 1.094; p-value: 0.025) (Table 2).

Both infections were found to have a significant positive association with presence of surface water; VTEC enteritis and cryptosporidiosis were 1.2 times (OR: 1.225; p-value: <0.001) and 1.3 times (OR: 1.363; p-value: <0.001) more likely to occur in a small area comprising a surface water body such as a lake or a river, respectively.

Table 1: *Results of generalised linear modelling 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 Std Deviation**	**P Value**	**OR**	**Cl 2,5**	**Cl 97,5**	**Significance**[Error! Bookmark not defined.]
Fluvial – High P.	0,073	0,071	1,076	0,993	1,165	
Fluvial - Medium P.	0,090	0,025	1,094	1,011	1,182	*
Fluvial - Low P.	0,076	0,055	0,998	1,164	1,164	
Coastal – High P.	-0,075	0,262	0,927	0,810	1,055	
Coastal – Medium P.	-0,057	0,373	0,945	0,831	1,068	
Coastal – Low P.	0,066	0,285	0,936	0,827	1,054	
Lakes/Rivers	0,203	> 0,001	1,225	1,10	1,337	***

Table 1: *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 Std Deviation**	**P Value**	**OR**	**Cl 2,5**	**Cl 97,5**	**Significance**[Error! Bookmark not defined.]
Fluvial – High P.	0,050	0,220	1,051	0,970	1,138	
Fluvial - Medium P.	0,040	0,319	1,041	0,962	1,125	
Fluvial - Low P.	0,015	0,698	1,015	0,939	1,097	
Coastal – High P.	-0,036	0,582	0,965	0,847	1,093	
Coastal – Medium P.	-0,069	0,278	0,933	0,821	1,055	
Coastal – Low P.	-0,097	0,121	0,907	0,800	1,023	
Lakes/Rivers	0,310	> 0,001	1,363	1,252	1,483	***

3.4. Time-Series analysis

Results indicate significant positive associations between both infections and all three hydrometeorological variables in both the Lower and Upper Shannon sub-basins (Figure 6 & Figure 7). The results for VTEC exhibits two primary lag periods of correlation ($R_{SP} > 0.4$), from weeks 1 to 5

and from weeks 18 to 19. The strongest associations for each (highest R_{SP} scores) are week 5 for rainfall, week 4 for surface water, week 1 (Lower Shannon) and 4 (Upper Shannon) for groundwater.
The main association periods for cryptosporidiosis were found from weeks 15 and 19 (surface water and groundwater) and from weeks 16 to 20 (rainfall). The highest associations are week 16 (Lower Shannon) and 19 (Upper Shannon) for rainfall, week 16 (Upper Shannon) and 19 (Lower Shannon) for surface water, and week 16 for groundwater.

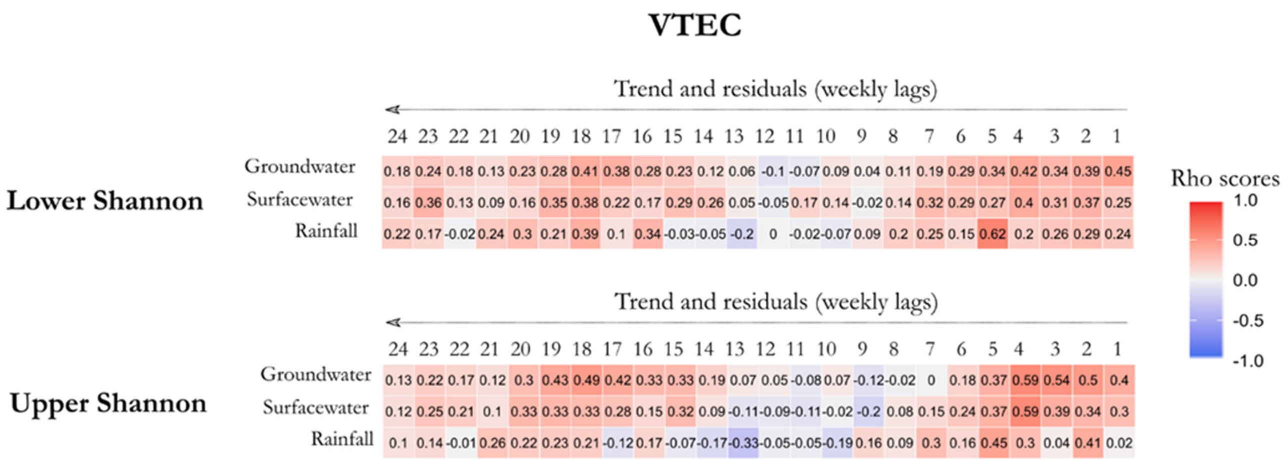


***Figure 6:** Spearman's rank correlation tests for VTEC trend and residuals and hydrometeorological variables*

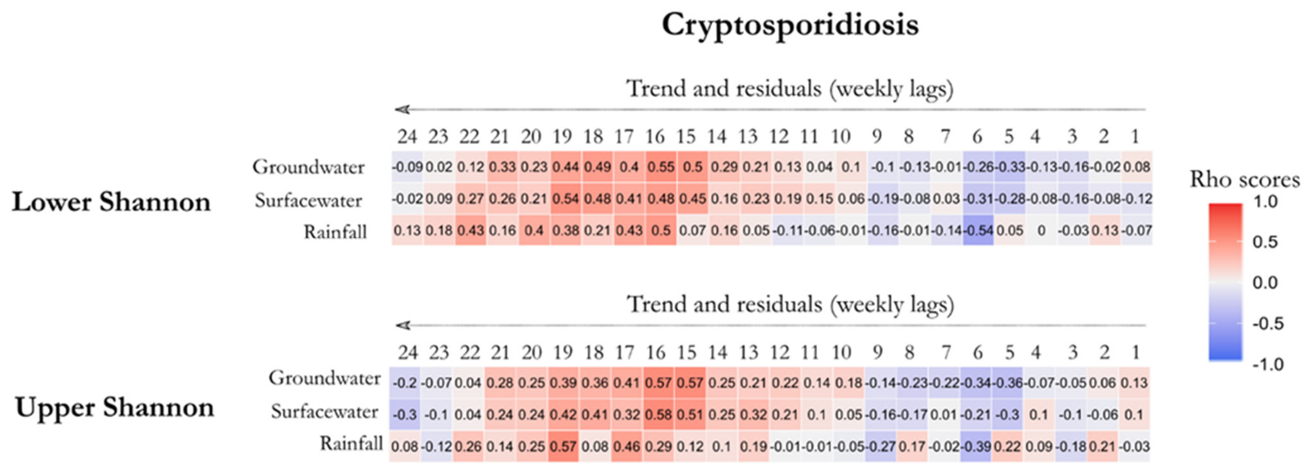


***Figure 7:** Spearman's rank correlation tests for VTEC trend and residuals and hydrometeorological variables*

4. DISCUSSION

4.1. Spatio-temporal patterns of infections in 2015-2016

The seasonal distribution results revealed that the higher residual peak for both infections occurred in April 2016, approximately three months after the 2015/16 flood event. This assessment highlights an atypical pattern of infection during 2016. Indeed, both infections are characterized by different seasonal dynamics: cryptosporidiosis usually peaks in late Spring due to calving, lambing and slurry spreading seasons (Callaghan *et al*., 2009), while VTEC usually marks its highest incidence in late summer due to increased consumption of meat products and livestock grazing (Lal *et al*., 2012; ÓhAiseadha *et al.,* 2017). Accordingly, the atypical and unexpected synchronicity between VTEC and cryptosporidiosis peaks, in addition to the unusual peak of both infections during April 2016 seems to indicate a potentially diffuse outbreak and/or the impact of a significant (indirect with respect to exposure/transmission) environmental or socio-economic event.

Space-time scanning identified 10 clusters of infection which occurred during (i.e. temporally intersecting) April 2016, thus allowing us to reject the hypothesis of an overlooked infection cluster or outbreak (i.e. all primary infections). The spatial distribution of cryptosporidiosis clusters were widespread across the country while VTEC clusters seem to spatially associate with the Shannon River Basin. Previous studies have shown that rural areas in the Irish Midlands and Shannon River Basin may be considered an infection "hotspot" (Boudou *et al.,* 2020; Cleary *et al.,* 2020), due to multiple present risk factors including high cattle density, presence of specific bedrock units (particularly karst areas), and a high reliance of households on untreated private water supplies.

4.2. Infection and flood risk exposure

Generalised linear modelling displayed significant associations between both infections and the presence of a surface water bodies. These results suggest that both infections might be associated with direct or indirect surface water exposures. For example, a study by Graczyk et al. (2004) revealed that *C. Parvum* oocysts were present among zebra mussels sampled across the entire Shannon River drainage area. Similarly, Dwivedi et al., 2016 found high *E. Coli* concentrations in surface water, especially in Winter during groundwater recharge periods.

No significant associations were found between cryptosporidiosis and mapped coastal or fluvial flood risk scenarios during the study period. Conversely, a significant association was found between VTEC and the medium-probability fluvial flood risk scenario, thus suggesting that VTEC enteritis may be more associated with surface water flooding than cryptosporidiosis during significant flood periods. The link between flooding and VTEC has previously been established by Qadri et al., 2005, who found that enterotoxigenic *Escherichia coli* (ETEC) was a major source of acute watery diarrhoea during a flood period in Bangladesh.

4.3. The link between hydrometeorological variables and infections

Spearman's non-parametric matrices showed that VTEC and cryptosporidiosis can be significantly associated with all three hydrometeorological variables, thus confirming findings from previous studies. For example, rainfall has been shown to increase the transport capacity of pathogens via overland flow or resuspension of sediments, subsequently triggering contamination of adjacent groundwater sources (Atherholt et al. 1998; Carlton et al., 2014; Latchmore et al., 2020).

The results obtained via Spearman's tests highlight the varying temporal responses of both infections, indicating a much longer antecedent lag between cryptosporidiosis (maximum $_{RSP}$ scores obtained from week 16 to week 19), than that found for VTEC enteritis (week 1 to week 5). The longer response of cryptosporidiosis to hydrometeorology is likely explained by the longer life expectancy of the pathogens in the aquatic environment: up to 24 weeks (Alum et al., 2014) while VTEC survival is approximately 6 to 12 weeks (Lothigius et al., 2010). Similarly, cryptosporidiosis pathogens were identified to be more persistent in subsurface environments compared to E. Coli pathogens (Bouchier, 1998).

The best lags obtained for cryptosporidiosis (from 16 to 19 weeks) suggest an association of all three hydrometeorological and the flood event of 2015-2016. Accordingly, considering an approximative incubation period of 2 weeks, the April 2016 incidence peak is temporally linked with the hydrometeorological attributes from December 2015 and January 2016 (16 to 17 weeks prior), thus indicating a relatively "direct" link with flooding. A similar association between flooding and cryptosporidiosis has been presented in a study from Germany (Gertler et al., 2015): this study found that a cryptosporidiosis outbreak in the city of Halle could be linked to a flood event occurring on the Saale River approximately 10 weeks prior.

Contrastingly, Spearman's tests results are not sufficient to demonstrate a direct link between the timing of VTEC incidence and the 2015-2016 flood: the best lags found, comprised between week 1 to week 5, are too quick to be associated with the timing of the flood event. However, additional and more complete time-series modelling analyses may be required to fully explore and reject the potential link between VTEC and flooding.

5. CONCLUSIONS AND PERSPECTIVES

The presented study sought to investigate the link between the incidence of cryptosporidiosis and VTEC enteritis with the Winter 2015/16 flood in Ireland. Results show that atypical patterns of infections occurred during Spring/Summer 2016, with particularly unusual and unseasonal infection peaks identified during April of that year. 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 infection. Findings demonstrate the impact of an extreme weather event and sporadic cases of infection, even several months after the occurrence of the event. Accordingly, the incidence of waterborne infections within a flood period should be monitor closely, as such as the water quality. This is especially the case in rural areas of the Midlands considered as a hotspot for both infections. This study finally indicates that a major flood event is susceptible to trigger indirect and long- term effects on population health, raising concerns especially with regards to climate change projections. As such, a multidisciplinary approach, combining hydrology, meteorology and epidemiology, is required to fully understand the complex system of a major flood event and its long-term impacts on the population.

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