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Surface water flooding, groundwater contamination, and enteric disease in developed countries: A scoping review of connections and consequences☆

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ABSTRACT

Significant volumes of research over the past four decades has sought to elucidate the social, infrastructural, economic, and human health effects of climate change induced surface flooding. To date, epidemiological and public health studies of flooding events have focused on mental health effects, vector-borne diseases, and infectious enteric disease due to floodwater contact (i.e. typically low consumption rates). The inherent nature of groundwater (i.e. out of sight, out of mind) and the widely held belief that aquifers represent a pristine source of drinking water due to natural attenuation may represent the "perfect storm" causing direct consumption of relatively large volumes of surface flood-contaminated groundwater. Accordingly, the current study sought to systematically identify and synthesize all available peer-reviewed literature pertaining to the nexus between surface flooding, groundwater contamination and human gastroenteric outcomes. Just 14 relevant studies were found to have been published during the period 1980–2017, thus highlighting the fact that this potentially significant source of climate-related exposure to environmental infection has remained understudied to date. Studies differed significantly in terms of type and data reporting procedures, making it difficult to discern clear trends and patterns. Approximately 945 confirmed cases of flood-related enteric disease were examined across studies; these concurred with almost 10,000 suspected cases, equating to approximately 20 suspected cases per confirmed case. As such, no regional, national or global estimates are available for the human gastrointestinal health burden of flood-related groundwater contamination. In light of the demonstrable public health significance of the concurrent impacts of groundwater susceptibility and climate change exacerbation, strategies to increase awareness about potential sources of contamination and motivate precautionary behaviour (e.g. drinking water testing and treatment, supply interruptions) are necessary. Mainstreaming climate adaptation concerns into planning policies will also be necessary to reduce human exposure to waterborne sources of enteric infection.

1. Introduction

Flooding represents one of the most devastating naturally occurring environmental hazards and has the potential to inflict major societal, infrastructural, and environmental damage (Barredo, 2007; Owrangi et al., 2014). Moreover, it is now widely accepted that climate change will exacerbate the frequency and intensity of significant flood events into the future (Mousavi et al., 2011; Pall et al., 2011; Arnell and Gosling, 2016). For example, a recent high-resolution (1.5 km grid spacing) hydrological modelling study in the UK predicts increasing hourly rainfall during winter months, in addition to intensification of short-duration high-threshold rainfall events during summer periods, indicative of significant flash flooding (Kendon et al., 2014). Similarly, Arnell and Gosling (2016) used the $HadCM_3$ and SRES A_1b climate models to predict that current 100-year floods will occur at least twice as frequently across 40% of the world, with approximately 450 million people and 430,000 km^2 rural land affected by 2050.

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While the structural damage and subsequent costs associated with flood events have and will likely continue to receive widespread media attention, (Devitt and O'Neill, 2017), far less attention is given to the potential adverse human health effects of these climatic events (Semenza et al., 2012).

Within the context of increasing flood frequency and severity, the subsequent mobilization of enteric pathogens within the environment, and particularly those from anthropogenic sources (e.g. inundated water treatment systems, septic tanks, and farmyards), followed by transmission of microbiologically rich material to rivers, coastal waters, and groundwater, represents an area of particular concern (Ivers and Ryan, 2006; Ten Veldhuis et al., 2010; De Man et al., 2014). The impact of extreme weather events has been shown to trigger waterborne disease outbreaks via infrastructural inundation, hydrological short circuiting/preferential flow, and subsequent consumption of contaminated water (Curriero et al., 2001; O'Dwyer et al., 2016). However, compared with flood-related infrastructural impacts, the increased exposure to waterborne pathogens is less well understood. Similarly, work on the socioeconomic costs of flooding events and climate change adaptation have tended to focus on river and coastal flooding (Rojas et al., 2013), with far less information available pertaining to public and private groundwater sources.

Groundwater represents the world's most extracted raw material (≈982 km^3/annum), and supplies approximately 31.5% (2.2 billion people) of the global population with domestic drinking water (Margat and Van der Gun, 2013; Murphy et al., 2017). For example, presently, 138.5 million Americans derive their daily drinking water from a groundwater source (US EPA, 2015). In high income countries, the widely held presumption that groundwater is a universally safe resource has resulted in undesirable practises (Charrois, 2010; Kreutzwiser et al., 2011; Hynds et al., 2013). Jin and Flury (2002) have shown that groundwater supplies are responsible for a disproportionate number of reported waterborne disease outbreaks. During the period 1971 to 2008, Wallender et al. (2014) identified at least 36 waterborne outbreaks reported to the Center for Disease Control and Prevention (CDC) Waterborne Disease and Outbreak Surveillance System (WBDOSS) which were associated with preceding heavy rainfall or flooding. Similar studies have shown that, even during relatively "normal" meteorological conditions, the contamination mechanisms associated with groundwater sources are intricate, temporal, localised, and frequently source-specific (Howard et al., 2003; Engström et al., 2017).

Notwithstanding the global importance of groundwater, the inherent complexities (and lack of understanding) associated with groundwater contamination mechanisms, and the increasing frequency and severity of flood events, to date, no comprehensive synthesis of the nexus between surface flooding, groundwater contamination, and the incidence of enteric disease has been published in the scientific literature. In isolation, these represent separate water security issues, however, in light of the potentially significant public health impacts of climate change, such a review is undoubtedly warranted. Accordingly, in order to acquire an improved understanding of the sources, pathways and receptors present at the interface between flooding, groundwater contamination and human gastrointestinal health, an exhaustive scoping review of relevant epidemiological and hydro (geo)logical studies has been undertaken. All pertinent data associated with exposures, mechanisms, and risk factors associated with flood-related, groundwater-borne enteric illness were extracted and homogenised. Due to a lack of consistent reporting and surveillance, in addition to auxiliary issues associated with waterborne infection in regions characterised by low levels of economic and social development (e.g. hygiene, (mal)nutrition, availability of healthcare services, etc.), the current review focused on high income regions, defined as developed economies, according to the World Economic Situation and Prospects (WESP) 2017 Report (United Nations, 2017). Identification of the causative factors associated with flood-related, groundwater-borne enteric illness will aid development of evidence-based practises, policies and procedures to mitigate future public health risks.

2. Methods

2.1. Literature identification, data sources, and searches

The overarching review protocol has been adapted from several previous studies (Sargeant et al., 2006; Graham and Polizzotto, 2013; Hynds et al., 2014a). The developed primary research question guiding the review was:

> *What are the incidence, frequency, causative organism(s), and mechanism(s) associated with outbreaks of communicable/notifiable enteric infection caused by consumption of groundwater affected by surface water flooding in developed countries/regions?*

Both Scopus and Web of Science databases were searched on June 22nd, 2017 (author LAA), with the Source-Pathway-Receptor-Consequence (SPRC) Model employed for search term development and literature identification (Fig. 1). The search was limited to papers in English and published from 1980 until present (Table 1). Literature scans employed Boolean positional operators ("AND", "OR", "SAME", "WITH", "ADJ") to appropriately refine literature identification, with supplementary legacy searches of article bibliographies (n = 12) and grey literature sources performed manually (LAA). Article inclusion required confirmation of infection via stool sampling, and/or confirmation of microbial groundwater contamination (faecal indicator organisms (FIO) or enteric pathogens) during or soon after a surface water flooding event. Epidemiological studies, whether descriptive or analytical, were considered eligible once a groundwater source directly contaminated by surface flooding was designated the primary source of enteric infection.

2.2. Study selection

As shown (Fig. 2; Identification), 4806 potentially appropriate articles were identified via the first (ID) review phase, decreasing to 3477 upon de-duplication (Fig. 2; Screening). The first phase of screening was undertaken via an assessment of article title, year, and abstract, and based upon developed eligibility criteria (Table 2), resulting in 112 articles going forward for eligibility assessment (Fig. 2; Eligibility). Full-texts were independently and concomitantly analysed by two researchers, again using developed inclusion/exclusion (eligibility) criteria. Abstracts without a full text (e.g. conference proceedings) were excluded at this stage. The primary inclusion criteria were: i) English-language articles only, ii) articles published after January 1st, 1980, iii) events occurring in high economies as defined in the WESP Report (United Nations, 2017), iv) groundwater-related outbreaks or groundwater source contamination triggered/caused by flooding events, v) groundwater consumption as the pathway of infection, vi) presence of post-event measurement of waterborne enteric pathogens (infection/contamination) or FIO (contamination), and vii) confirmed enteric waterborne illnesses in human population(s) (e.g. verotoxigenic *E. coli* (VTEC)/shiga-toxin producing *E. coli* (STEC), *Cryptosporidium, Campylobacter, Salmonella, Giardia*, norovirus, etc.).

Articles excluded during this phase were those that: i) reviewed results of previously published studies, ii) failed to establish a