

Water, sanitation and hygiene risk factors for the transmission of cholera in a changing climate: using a systematic review to develop a causal process diagram

Natalia Jones, Maha Bouzid, Roger Few, Paul Hunter  and Iain Lake

ABSTRACT

Cholera is a severe diarrhoeal disease affecting vulnerable communities. A long-term solution to cholera transmission is improved access to and uptake of water, sanitation and hygiene (WASH). Climate change threatens WASH. A systematic review and meta-analysis determined five overarching WASH factors incorporating 17 specific WASH factors associated with cholera transmission, focussing upon community cases. Eight WASH factors showed lower odds and six showed higher odds for cholera transmission. These results were combined with findings in the climate change and WASH literature, to propose a health impact pathway illustrating potential routes through which climate change dynamics (e.g. drought, flooding) impact on WASH and cholera transmission. A causal process diagram visualising links between climate change dynamics, WASH factors, and cholera transmission was developed. Climate change dynamics can potentially affect multiple WASH factors (e.g. drought-induced reductions in handwashing and rainwater use). Multiple climate change dynamics can influence WASH factors (e.g. flooding and sea-level rise affect piped water usage). The influence of climate change dynamics on WASH factors can be negative or positive for cholera transmission (e.g. drought could increase pathogen desiccation but reduce rainwater harvesting). Identifying risk pathways helps policymakers focus on cholera risk mitigation, now and in the future.


Key words | causal process diagram, cholera, climate change, health impact pathway, systematic review, WASH

Natalia Jones (corresponding author)

Iain Lake

School of Environmental Sciences,
University of East Anglia UEA,
Norwich NR4 7TJ,
UK
E-mail: n.jones@uea.ac.uk

Maha Bouzid

Paul Hunter 

Norwich Medical School,
University of East Anglia UEA,
Norwich NR4 7TJ,
UK

Roger Few

School of International Development,
University of East Anglia UEA,
Norwich NR4 7TJ,
UK

INTRODUCTION

Cholera is a contagious diarrhoeal disease caused by the bacterium *Vibrio cholera*. It is mainly transferred through the faecal–oral route (Clemens *et al.* 2017), with human-to-human transmission and the consumption of contaminated water or food the main routes of transmission (Sack *et al.* 2004). Globally, cholera affects 1.3–4 million people per annum and kills between 21,000 and 143,000 (World

Health Organization 2018b). In October 2017, the World Health Organization (WHO) Global Task Force on Cholera Control (a network of 50 United Nations (UN) and international agencies, academic institutions, and Non-Governmental Organizations (NGOs)) committed to reducing deaths from cholera by 90% by 2030 (World Health Organization 2017a). A cholera vaccine is available but is mostly used as a response to large outbreaks (Kupferschmidt 2018). Population-wide vaccination is not usually undertaken (World Health Organization 2018a), as the vaccine only lasts around 3 years and is relatively

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (<http://creativecommons.org/licenses/by/4.0/>).

doi: 10.2166/wh.2020.088

ineffective in children under 5 years (Bi *et al.* 2017; Lessler *et al.* 2018). Also, there are insufficient supplies of vaccine for population-wide administrations (Lessler *et al.* 2018).

For a more long-term solution, the provision of Water, Sanitation and Hygiene (WASH) infrastructure is central to the prevention of cholera transmission (Hutton & Chase 2016; Lessler *et al.* 2018; UNICEF 2018a). Access to clean water, the availability of adequate sanitation, such as basic toilets, and good hygiene practices, especially hand-washing with soap, can prevent cholera outbreaks by breaking transmission routes (Yates *et al.* 2018).

Intervention studies investigating how WASH improvements can reduce the risk of cholera are widely reported in the literature (e.g. Azurin & Alvero 1974; Conroy *et al.* 2001; Dunston *et al.* 2001; Cavallaro *et al.* 2011), although the effectiveness of these interventions is uncertain (Fewtrell *et al.* 2005; Hunter 2009; Taylor *et al.* 2015). Case-control studies have investigated whether individual WASH factors, such as handwashing (O'Connor *et al.* 2011; Zohura *et al.* 2016; Burrowes *et al.* 2017), latrines (Sasaki *et al.* 2008; Grandesso *et al.* 2014), and water storage (Beatty *et al.* 2004; Kirk *et al.* 2005; Bhunia & Ghosh 2011), are associated with cholera infections. Wolfe *et al.* (2018) performed a systematic review to establish which WASH factors are the most relevant to cholera transmission.

Climate change is a threat to WASH infrastructure and services (Alhassan & Hadwen 2017) because water and climate change are intrinsically linked (Jiménez Cisneros *et al.* 2014; Settele *et al.* 2014), as are water and WASH (Alhassan & Hadwen 2017; UNICEF 2018b). Climate change has already, and will continue to, change the water available in rivers, lakes and underground aquifers, alter precipitation patterns, and increase the frequency and intensity of extreme events (such as floods and droughts) (IPCC 2014; Jiménez Cisneros *et al.* 2014). Although there have been investigations into the impact of climate change on drinking water (World Health Organization 2009; Howard & Bartram 2010; Dai 2011; Jiménez Cisneros *et al.* 2014; Ghosh *et al.* 2015; Smajgl *et al.* 2015), few studies have examined how sanitation and hygiene facilities may be vulnerable to climate change (Howard *et al.* 2010). To our knowledge, no study has examined the impact of climate change on the WASH factors most relevant to cholera transmission.

In this study, we perform a systematic review and meta-analysis examining the main WASH factors associated with cholera transmission, focussing upon cases in community settings. This work provides independent corroboration of Wolfe *et al.* (2018) and includes methodological developments such as adjustment for multiple studies in the same paper and enhanced categorisation of studies to a common baseline (see Supplementary file 1). The majority of this paper uses these results to develop, for the first time to our knowledge, a health impact pathway and a causal process diagram examining how climate change may impact on WASH factors. These can be used by decision-makers to provide information on the impact of specific climate change dynamics on WASH infrastructure and behaviour.

The paper briefly outlines the methods and findings of the systematic review, and then focuses on the development of the health impact pathway and causal process diagram examining the links between climate change dynamics and five general and 17 specific WASH factors.

METHODS

The first step in our analysis was to undertake a systematic review on cholera and WASH to identify the key WASH factors associated with cholera transmission. A paucity of the literature on climate change and cholera meant it was not possible to directly review this relationship, and thus, a two-stage process was undertaken. Full details of the systematic review including detailed methods and results can be found in Supplementary file 1. In summary, using Scopus, Science Direct, Medline, and six grey literature sources, 37 search terms associated with WASH were combined with cholera (see Supplementary Table S1). Initially, 8,410 papers were retrieved; after screening and eligibility assessment, 53 papers were selected for qualitative synthesis and meta-analysis (see Supplementary Figure S1).

WASH factors were categorised as follows: (1) water treatment (untreated water, boiling, chlorination), (2) water source (all municipal/piped, municipal/piped (no waterborne outbreak), surface water, rainwater, well water), (3) sanitation (open defaecation, shared facilities, improved sanitation), (4) hand hygiene (all handwashing,

handwashing before food, handwashing after defaecation, presence of soap), and (5) water storage (narrow-mouthed container, other containers) that may lead to contamination post collection.

Health impact pathways are descriptive models which illustrate the possible routes of the impacts of hazards through to potential health outcomes (Few 2007). They are a form of adaptive pathways, an approach which has been used extensively in climate adaptation research (e.g. Few 2007; Ren *et al.* 2011; Smith *et al.* 2011; Rosenzweig & Solecki 2014; Jacobs *et al.* 2018). Health impact pathways highlight the key mechanisms that can drive health outcomes and the points where it may be possible to break the flow of impact. These pathways are useful for clarifying the association between risks and health impacts (Few 2007). In this study, a health impact pathway was developed during a 90-minute focussed discussion between three paper authors (R.F., N.J., and I.L.), based on the generalised health impact pathway developed by Few (2007) and drawing on the findings of the systematic review. This provides an overview of how climate change may influence the five overarching WASH factors important for cholera transmission highlighted in the systematic review, and the mechanisms through which this could occur. The discussion drew on the findings of the systematic review and the published literature on climate change and health. At the conclusion of this meeting, a health impact pathway for climate change and WASH was proposed which was further discussed with all authors, resulting in the final health impact pathway for climate change and WASH reported here.

Following this, a more detailed causal process diagram was constructed by N.J. in consultation with the other authors. Causal process diagrams are a way of summarising causal relationships and visualising the links in complex systems (Joffe & Mindell 2006; Joffe *et al.* 2012). They have been used to examine a variety of health outcomes (e.g. Rehfuss *et al.* 2013; Vins *et al.* 2015; Friel *et al.* 2017). In this study, a causal process diagram was developed based on the relationships between climate change dynamics, WASH factors, and cholera, drawing on the findings of the first part of the study. All of the 17 WASH factors identified in the systematic review (14 of which were shown to be significantly associated with cholera transmission) were included in the causal process model. Using specific focussed literature

searches in Scopus and Google Scholar, plus snowballing literature, the links between climate change dynamics and WASH factors were determined. These were drawn from a variety of the published literature from both the academic and grey fields and included reviews, reports, and observational studies. The diagram indicates how specific climate change dynamics (e.g. drought, flooding, sea-level rise, etc.) may impact on the individual WASH factors and thus cholera transmission. Within the diagram, the direction of the association between climate change dynamics and WASH factors (either a positive or negative impact) is highlighted. There are few observational studies reporting measures of impact between WASH factors and climate change, so the strength of associations cannot be determined. The relationship between WASH factors and cholera transmission (either a risky or protective relationship), as found in the systematic review is also shown. In this study, a lower odds ratio (less than one) for a WASH factor and cholera transmission from the systematic review is indicative of a more protective relationship on the causal process diagram, whilst a higher odds ratio (greater than one) is indicative of a more risky relationship.

RESULTS AND DISCUSSION

Table 1 shows the pooled odds ratios for cholera risk factors taking into account multiple studies within the same paper. The findings showed that boiling water, chlorinating water, sourcing municipal/piped water with no waterborne outbreak (water which has no cholera epidemic associated with it), and rainwater all showed lower odds of cholera transmission. Similarly, all handwashing and specific handwashing before food and after defaecation also showed lower odds, as did using soap. However, drinking untreated water, using surface water as a water source and well water as a water source, showed higher odds of cholera transmission. Open defaecation and shared sanitation facilities also showed higher odds of cholera transmission, as did storing water in containers that were not narrow-mouthed. The remaining WASH factors did not show a significant relationship with cholera risk. These findings are broadly similar to those found by Wolfe *et al.* (2018), although their study categorised the WASH factors differently and did not combine

Table 1 | Pooled odds ratios for cholera risk factors – adjusted for multiple studies within the same paper^a

Risk factor category	Risk factor	OR	Lower 95%CI	Upper 95%CI	P-value
Water treatment	Untreated water	2.80	1.82	4.29	<0.001
	Boiling	0.44	0.33	0.60	<0.001
	Chlorination	0.47	0.23	0.98	0.043
Water source	All Municipal/piped	0.90	0.42	1.95	0.790
	Municipal/piped – no waterborne outbreak	0.42	0.26	0.70	0.001
	Surface water	2.88	1.69	4.90	<0.001
	Rainwater	0.34	0.21	0.60	<0.001
	Well water	3.01	1.08	8.39	0.035
Sanitation	Open defaecation	2.64	1.58	4.39	<0.001
	Shared facilities	1.82	1.33	2.51	<0.001
	Improved sanitation	0.69	0.44	1.08	0.110
Hand hygiene	All handwashing	0.36	0.25	0.52	<0.001
	Handwashing before food	0.45	0.32	0.65	<0.001
	Handwashing after defaecation	0.28	0.17	0.45	<0.001
	Presence of soap	0.31	0.22	0.45	<0.001
Water storage	Narrow-mouthed container	0.61	0.12	3.10	0.550
	Other containers	2.02	1.15	3.57	0.015

^aBrief methods for obtaining odds ratios in the 'Methods' section, full methods detailed in Supplementary file 1.

studies with different orders of categories in the same predictor variable. Also, Wolfe *et al.* (2018) did not adjust for multiple studies in the same paper.

Figure 1 shows how, through a variety of possible mechanisms, climate change, in the form of multiple climate change dynamics, may impact on WASH factors. It is important to note some key points about this diagram. First, each climate change dynamic has the potential to impact on multiple WASH factors. For example, sea-level rise may result in the salinisation of water sources (IPCC 2014), which can impact on both sanitation (Few *et al.* 2004; Howard & Bartram 2010) and water sources (Howard *et al.* 2010; Ghosh *et al.* 2015; Smajgl *et al.* 2015). Extreme events, such as floods, may result in the contamination of water sources (Jean *et al.* 2006) and the destruction of sanitation infrastructure (Heath *et al.* 2012; Sherpa *et al.* 2014). Second, the influence on WASH factors can be either negative or positive for health outcomes and which, if any, of these will dominate is unknown. For example,

reduced rainfall may lead to increased desiccation of pathogens and faecal matter as a result of drier environments (Howard & Bartram 2010), but could reduce rainwater harvesting, pushing individuals to riskier sources (Howard *et al.* 2010; Asadieh & Krakauer 2016). Figure 1 does not show every plausible association between climate change dynamics and WASH factors. There may be other climate change dynamics which are not listed that could impact on WASH factors. The mechanisms shown are a summary of those for which it was possible to determine potential linkages between climate change dynamics and WASH factors, using the published literature.

Five general WASH factors, incorporating 17 specific factors were highlighted in the systematic review and meta-analysis (see Table 1) as being important in the transmission of cholera. The dynamics of climate change can potentially impact all of these in varying ways. In Figure 2, the possible relationships between specific climate change dynamics and the 17 defined WASH factors are detailed, drawn from a review of the literature. Where lower odds for a WASH factor and cholera transmission relationship were found in the systematic review, this is shown as a more protective relationship in Figure 2, whilst higher odds for a WASH factor and cholera transmission relationship in the systematic review is indicative of a more risky relationship in Figure 2. Similarly, the relationships between climate change dynamics and WASH factors are described as negative (likely to damage the impact of a protective WASH factor or increase the impact of a risky WASH factor) or positive (likely to enhance the impact of a protective WASH factor or reduce the impact of a risky WASH factor) in Figure 2. The following paragraphs discuss the potential relationships between WASH factors and climate change dynamics indicated in Figure 2.

Water treatment: Untreated water. Within the meta-analysis, drinking untreated water was shown to have higher odds of cholera transmission (OR 2.8; 95%CI 1.82–4.29). There exists a desire to end the consumption of untreated water worldwide (United Nations 2015); however, there is potential for the dynamics of climate change to impact on this. Evidence suggests that improved water supplies will be negatively affected by the dynamics of climate change such as flooding, extreme rainfall, drought, increased temperatures, and sea-level rise (World Health

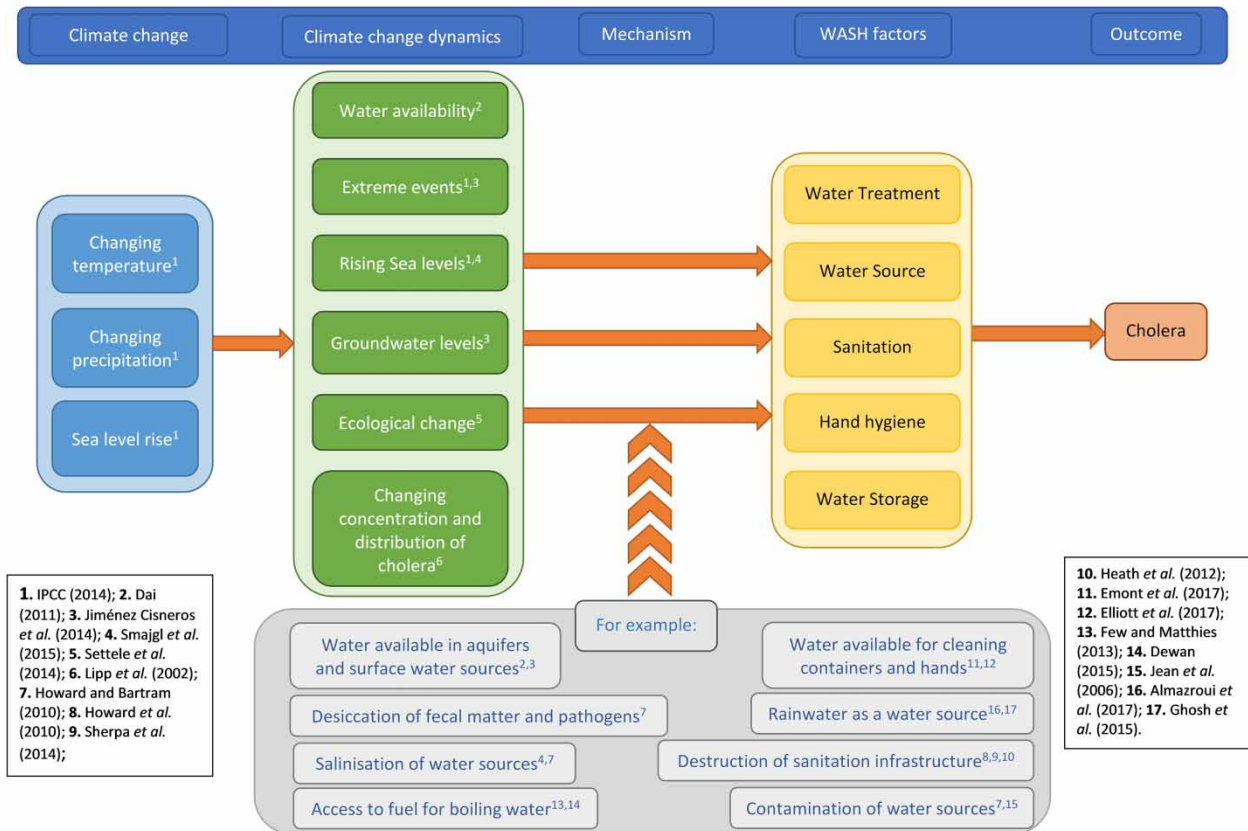


Figure 1 | Health impact pathway for climate change and WASH.

Organization 2009; Howard & Bartram 2010; Dai 2011; Jiménez Cisneros et al. 2014; Ghosh et al. 2015; Smajgl et al. 2015). Any reduction in the availability of improved water supplies may result in an increase in the drinking of untreated water, thus increasing the risk of cholera.

Water treatment: Boiling. The meta-analysis showed that boiling water had lower odds of cholera transmission (OR 0.44; 95%CI 0.33–0.60). There has been no investigation into how climate change might specifically affect the usage of boiled water. However, boiling water requires energy and thus any interruptions in energy supply, such as disruption to energy infrastructure due to flooding (Del Ninno et al. 2001; Few & Matthies 2013; Dewan 2015), could result in less boiling of water. In areas where there is a reliance on resources, such as wood, animal waste, and jute sticks, as a fuel for boiling water, any impact on the availability of these fuels, such as extreme flooding events or increased desertification, will reduce the potential for boiling water (Del Ninno et al. 2001; Dewan 2015).

Water treatment: Chlorination. Chlorination was found to show lower odds of cholera transmission in the meta-analysis (OR 0.47; 95%CI 0.23–0.98). Chlorination is widely used as a water treatment, despite its limitations (such as the risk of over-chlorinated water and the potential for long-term health effects) (Zinn et al. 2018). In particular, chlorination is often used as a water treatment after extreme events, such as floods (Branz et al. 2017); thus, there is potential for a short-term increase in the use of chlorination as a result of certain climate change dynamics. However, we found no literature that examines the potential associations between climate change and the use of chlorination as a water treatment. Heavy rainfall can result in river water becoming more turbid (World Health Organization 2009), which may impact on the use of chlorine as a water treatment. Turbid water is challenging to chlorinate (Branz et al. 2017), as particulate matter can potentially shield organisms from disinfection (Keegan et al. 2012; World Health Organization 2017b). Highly turbid water can require

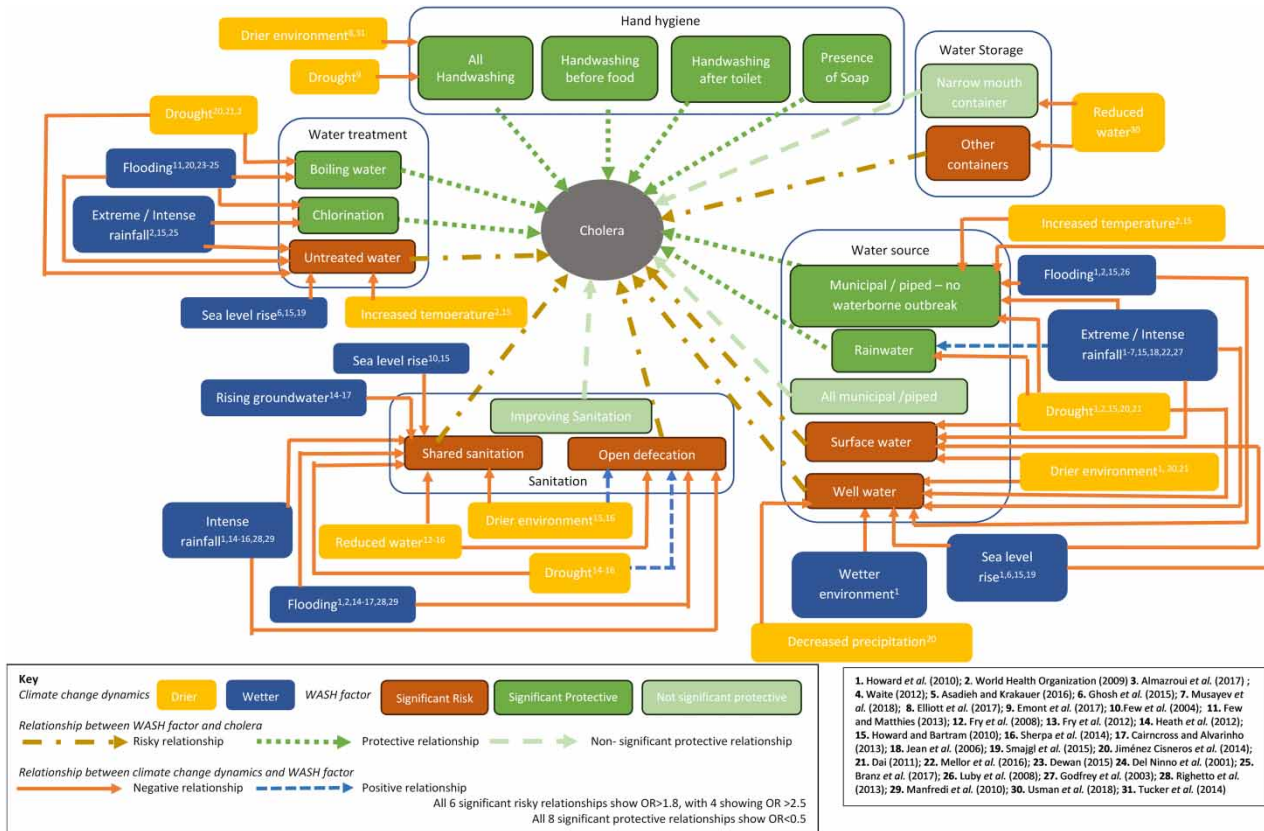


Figure 2 | Causal process diagram showing the links, from the literature, between climate change dynamics and WASH influences on cholera transmission.

higher doses of chlorine than non-turbid water (Branz et al. 2017), which can result in the formation of unsafe levels of disinfection by-products, such as trihalomethanes and haloacetic acids (Lantagne et al. 2007).

Water source: All municipal/piped water and Municipal/piped water – no waterborne outbreak. The findings from the meta-analysis showed drinking piped water where there is no waterborne outbreak of cholera associated with the water supply, was found to show lower odds of cholera transmission (OR 0.42; 95%CI 0.26–0.70), while any piped water source, whether or not there is an outbreak, showed lower odds but was not significant (OR 0.90; 95%CI 0.42–1.95). Though more resilient than most other water sources (Luh et al. 2017), piped water systems can be disrupted by the effects of climate change because they are made up of many components (depending on the circumstances) all of which can be at risk (Howard et al. 2010). Municipal piped systems are at risk of contamination and this may increase with increased temperatures and

more extreme rainfall and flooding events (World Health Organization 2009; Howard & Bartram 2010). After heavy rain, an outcome of extreme rainfall events, river water may become more turbulent, damaging intake points and compromising treatment (World Health Organization 2009; Howard & Bartram 2010). In times of drought, water supplies provided through piped networks may become less secure due to less water being available (World Health Organization 2009). Rising sea level may result in piped water supplies becoming more saline (Howard & Bartram 2010), while interruptions in energy supplies caused by extreme weather events may result in piped water supplies becoming unreliable (World Health Organization 2009). Any damage to municipal/piped water supplies may result in people using alternative, potentially less safe, water sources.

Water source: Surface water. Surface water showed higher odds of cholera transmission (OR 2.88; 95%CI 1.69–4.90). Studies generally indicate that this water

supply will be affected by climate change, potentially making it less suitable as a water source. In areas where drought or drier environments are anticipated, surface water sources may dry up and there is likely to be less water flowing through rivers and streams for longer periods of time (Dai 2011; Jiménez Cisneros *et al.* 2014). In coastal areas, there is evidence that some surface water sources are becoming saline as a result of the intrusion of saltwater caused by sea-level rise (Ghosh *et al.* 2015; Smajgl *et al.* 2015), thus making them undrinkable. In areas where more extreme rainfall events are expected, there may be an increase in the contamination of surface water sources due to the concentration of pathogens and the effect of runoff (Mellor *et al.* 2016).

Water source: Rainwater. The meta-analysis showed that rainwater as a water source has lower odds of cholera transmission (OR 0.34; 95%CI 0.21–0.60). In areas where elevated precipitation is expected, there is potential for rainwater harvesting to become a useful and safer water supply (Howard *et al.* 2010; Waite 2012; Asadieh & Krakauer 2016; Almazroui *et al.* 2017). However, this will be dependent on sufficient storage being available (Howard *et al.* 2010). Studies have shown that, in areas where other water supplies are vulnerable to climate change dynamics, rainwater harvesting has the potential to be used as a constant and reliable alternative water supply as long as appropriate storage is in place (Ghosh *et al.* 2015; Musayev *et al.* 2018). However, in areas where more intense and longer periods of drought will occur, rainwater harvesting will become a more vulnerable source of drinking water (World Health Organization 2009; Howard *et al.* 2010); thus, people may turn to less safe water sources.

Water source: Well water. Within the meta-analysis, using well water as a water source showed higher odds of cholera transmission (OR 3.01; 95%CI 1.08–8.39). The water found in wells is usually drawn from aquifers or groundwater sources and can be improved or unimproved (UNICEF 2015). The majority of studies examined in the meta-analysis looked at unimproved wells, although in some studies, it was unclear whether the wells were improved or not. It is difficult to attribute the effects of climate change on groundwater sources (Stoll *et al.* 2011); however, there is evidence that decreased precipitation is associated with reduced discharge and recharge of

groundwater (Jiménez Cisneros *et al.* 2014), while sea-level rise is resulting in the saline intrusion of groundwater (Howard *et al.* 2010). Studies have shown that after extreme rainfall events, well water supplies can suffer from increased microbial contamination (Jean *et al.* 2006). Unimproved wells, such as dug wells, are at risk of contamination after intense rainfall and flooding (Godfrey *et al.* 2003; World Health Organization 2009; Howard & Bartram 2010; Howard *et al.* 2010), and in areas which are getting wetter (Howard *et al.* 2010). Unimproved wells are also at risk of drying up in areas of drought (Howard & Bartram 2010) and drier environments (Howard *et al.* 2010) leading to the use of more hazardous water sources or the reduction in water use for some activities (e.g. bathing and washing clothes) (Elliott *et al.* 2017). Improved wells, such as tube-wells (which have protective casing), are considered fairly resilient to the impacts of climate change, as they are not very vulnerable to contamination and are capable of being adapted (Howard & Bartram 2010). However, they too can be vulnerable to drought, as decreased water levels in the water table can result in drying up (Howard *et al.* 2010), with any remaining water having a higher concentration of pathogens (Howard & Bartram 2010). They are also at risk from the intrusion of contaminated water as a result of flooding events (Luby *et al.* 2008; World Health Organization 2009; Howard *et al.* 2010) and of salinisation from rising sea levels (Howard *et al.* 2010).

Sanitation: Open defaecation. Defecating in the open showed higher odds of cholera transmission in the meta-analysis (OR 2.64; 95%CI 1.58–4.39). The solution to ending open defaecation is to improve sanitation facilities (UNICEF 2015). However, many improved sanitation facilities require a sufficient supply of water (Fry *et al.* 2008). An increase in water stress as a result of climate change could restrict the development of improved sanitation facilities (Fry *et al.* 2012), thus effecting a continuation of the practice of open defaecation. In places where improved sanitation is in place, extreme events such as flooding can destroy sanitary facilities, resulting in an increase in the practice of open defaecation (Heath *et al.* 2012). Microbial contamination of water has been shown to be associated with open defaecation (Manfredi *et al.* 2010) with rainfall causing washout from open defaecation sites into water-courses (Righetto *et al.* 2013). Therefore, increased flooding

and more intense rainfall due to climate change could result in more faeces left from open defaecation being washed into watercourses, thus increasing the contamination of water supplies. In areas where climate change is resulting in drier environments, there may be some positive impacts on open defaecation. Evidence suggests that dry pit latrines are resilient to drier environments as the drier conditions result in the attenuation or death of pathogens (Howard & Bartram 2010). This consequence may also be relevant to waste from open defaecation, although there is no literature to support this theory.

Sanitation: Shared facilities and Improved sanitation.

The meta-analysis found improved sanitation was not significantly associated with cholera transmission (OR 0.69; 95% CI 0.44–1.08), although the direction indicated lower odds. Sharing sanitation facilities with other households showed higher odds of cholera transmission (OR 1.82; 95%CI 1.33–2.51). Shared sanitation facilities can be of an acceptable standard but are classed as unimproved because they are shared (UNICEF 2015). Both improved and unimproved facilities, shared or not, can be impacted by the effects of climate change. Pit latrines are reasonably resilient to the impacts of droughts and drier climates (Howard & Bartram 2010), and drier conditions can result in the death or attenuation of pathogens (Howard & Bartram 2010), reducing the risk of contamination. Waterless pit latrines dry up faster under drier conditions, making them easier to empty (Sherpa *et al.* 2014). However, pit latrines are vulnerable to wetter conditions, as flooding and intense rainfall can cause collapse, flooding, inaccessibility, or total destruction (Howard *et al.* 2010; Heath *et al.* 2012; Sherpa *et al.* 2014). Intense rainfall and flooding can wash waste from pit latrines into watercourses (Howard *et al.* 2010; Heath *et al.* 2012; Sherpa *et al.* 2014), while rising groundwater can result in increased contamination from these facilities (Howard & Bartram 2010; Cairncross & Alvarinho 2013). Shared facilities may use septic tanks which have been shown to overflow or back flood causing contamination if flooding occurs (Cairncross & Alvarinho 2013; Sherpa *et al.* 2014). These facilities rely on large volumes of water so may be particularly vulnerable in areas where climate change reduces water supply (Howard *et al.* 2010).

Facilities which use a sewerage system are vulnerable to severe rainfall and flooding which can cause systems to

overflow or back flood. This can result in contamination, increase the risk of cholera transmission and can affect use (Howard & Bartram 2010; Sherpa *et al.* 2014). Where sea-level rise occurs, sewers which discharge into the sea can backup and flood (Few *et al.* 2004; Howard & Bartram 2010). In environments where there are drought conditions and reduced water supply due to climate change, the ability of sewerage systems to work effectively will be reduced due to their reliance on large quantities of water (Howard & Bartram 2010; Howard *et al.* 2010; Sherpa *et al.* 2014). More indirectly, interruptions in the energy supply can occur with extreme events, such as flooding, which can impact on the ability of sewerage systems to function (World Health Organization 2009). Any disruption to shared sanitation facilities will likely result in people moving to less sanitary methods, such as open defaecation (Heath *et al.* 2012).

Hand hygiene: All Handwashing/Handwashing before food/Handwashing after defaecation/Presence of soap.

Handwashing in all forms (all handwashing, before food, and after defaecation) and the presence of soap all showed lower odds of cholera transmission in the meta-analysis (All – OR 0.36; 95%CI 0.25–0.52; Food – OR 0.45 95%CI 0.32–0.65; Defaecation – OR 0.28; 95%CI 0.17–0.45; Soap – OR 0.31 95%CI 0.22–0.45). Studies have shown that in areas where there are wet and dry seasons, the frequency of handwashing declines significantly in the dry season (Elliott *et al.* 2017). In some areas, the amount of water available for personal hygiene, such as handwashing, is rationed during dry periods (Tucker *et al.* 2014), while in other places, the number of people not handwashing significantly increases in the dry season compared with the wet season (Elliott *et al.* 2017). In periods of drought, handwashing is significantly less frequent than at other times and associated with reduced water supply (Emont *et al.* 2017). Therefore, where climate change results in drought, drier environments, or decreased water availability, there is likely to be less frequent handwashing. No studies have examined the dynamics of climate change and the specifics of handwashing either before eating or after using the toilet. The evidence for which of these is more common is unclear, as some studies suggest more people wash their hands before preparing and eating food than after using the toilet (Phillips *et al.* 2015), while others show washing hands after using the toilet

is more common than before preparing and eating food (Luby *et al.* 2011). Therefore, it is not possible to determine which may be more affected with reduced water availability. The presence of soap showed lower odds of cholera transmission. However, there is no published evidence or comment on how the presence of soap may be affected by climate change.

Water storage: In containers other than narrow-mouthed/Narrow-mouthed containers. The type of container used to store water has been shown to impact on the transmission of cholera, with containers which are not narrow-mouthed showed higher odds of cholera transmission (OR 2.02; 95% CI 1.15–3.57). Narrow-mouthed containers did not show a significant relationship but indicated lower odds (OR 0.61; 95%CI 0.12–3.10). There is no published evidence on the impacts of climate change and the use of household containers. However, water storage containers which are not adequately cleaned can result in increased contamination (Usman *et al.* 2018). Therefore, any reduction in water availability caused by climate change could result in less potential for people to clean water storage containers, thus increasing the potential for water contamination and cholera transmission.

Implications for policy and research. The impacts of climate change are place and time-dependent; in some areas, sea-level rise is a key concern, and in others, it may be drought (IPCC 2014). Within one place, these concerns may change with different seasons. The health impact pathway and causal process diagram can help to better understand how climate change dynamics impact on WASH factors and ultimately cholera transmission, and assist those dealing with the consequences of both long-term climate change and extreme events to prioritise systems and behaviour. In the absence of a ‘gold standard’ evidence base for dealing with the epidemiological implications of climate change, the health impact pathway and causal process diagram can help decision-makers (such as NGOs, the World Bank, national governments, and local water and wastewater authorities) judge what the likely impact of certain climate change dynamics could be on WASH in specific settings and focus on implementing appropriate system and behaviour changes. These parties may find the health impact pathway and causal process diagram useful frameworks for discussion around increasing

the likelihood of ‘reduced cholera transmission’ pathways by making specific WASH adaptations while reducing the likelihood of ‘promotion of cholera transmission’ WASH pathways. For example, in areas where increasing drought is a problem, decision-makers could focus on adaptations to shared sanitation, municipal, surface and rainwater sources, and handwashing behaviour. Such decision tools are likely to be especially key in data-poor and resource-constrained contexts where public health institutions have to base their priorities and policies on limited available data.

In terms of further research, the development of the health impact pathway and causal process diagram has highlighted the gaps in knowledge of the links between climate change dynamics and WASH factors. For example, there is little or no research into the impact of climate change on handwashing and water containers, and no focussed analysis on the impact of climate change on sanitation. There is a need for large-scale modelling of the specific impacts of different climate change dynamics on various geographic locations. Future research into the impacts of climate change on WASH factors could further strengthen the ability to use the health impact pathway and causal process diagram in policymaking and implementation.

CONCLUSIONS

In this study, we undertook a novel approach to examining many of the possible links between climate change, WASH factors, and cholera transmission. Some of these links anticipate increased cholera transmission, while others suggest reduced cholera transmission. The relative likelihood of the opposing impacts is unknown at this time. We carried out a systematic review to determine the WASH factors associated with cholera transmission. Based on the results of this, we examined the published literature on climate change and WASH factors to investigate how the dynamics of climate change may impact on the key WASH factors associated with cholera transmission. Finally, we developed a health impact pathway and causal process diagram indicating how climate change may influence WASH and thus cholera transmission.

Five general WASH factors (water source, water treatment, sanitation, hand hygiene, water storage), incorporating

17 specific factors were highlighted in the systematic review and meta-analysis as being important in the transmission of cholera. Of these, 14 were significantly associated with cholera risk. Eight of these showed lower odds of cholera transmission (boiling water, chlorinating water, sourcing municipal/piped water with no waterborne outbreak – water which has no cholera epidemic associated with it – drinking rainwater, all handwashing, handwashing before food, handwashing after defaecation, presence of soap). The remaining six showed higher odds of cholera transmission (drinking untreated water, using surface water as a water source, using well water as a water source, open defaecation, shared sanitation facilities, storing water in containers that were not narrow-mouthed).

A health impact pathway was subsequently developed illustrating the possible routes through which climate change may affect climate change dynamics, WASH, and cholera outcomes. Building upon this pathway, a causal process diagram was created with the eight WASH factors showing lower odds of cholera transmission described as showing a more protective relationship, while the six WASH factors which showed higher odds of cholera transmission were described as showing a more risky relationship. This divide highlights the complexity of the factors which drive the transmission of cholera, indicating that there is not a simple solution to this health issue. An examination of the literature indicated associations between climate change dynamics and WASH factors significantly associated with cholera transmission. For the majority of WASH factors, there was evidence of associations with climate change dynamics. For others, there was no published evidence of an association. The causal process diagram indicates how climate change may influence cholera transmission through WASH.

Each climate change dynamic is likely to impact on multiple WASH factors. For example, flooding can affect water treatment, water sources, and sanitation, whilst drought may affect water sources, hand hygiene, and water storage. In addition, multiple climate change dynamics may influence the same WASH factor. For example, the choice of a water source may be affected by sea-level rise, flooding, and changing drought intensity. Finally, the influence of climate change dynamics on WASH factors can be both negative and positive for health outcomes. For example,

reduced rainfall may lead to increased desiccation of pathogens and faecal matter as a result of drier environments lowering cholera risk. However, it could also reduce rainwater harvesting, pushing individuals to riskier sources of drinking water.

The findings of this study must be viewed in a context of uncertainty. Our findings indicate the potential relationships between climate change dynamics, WASH factors, and cholera transmission, but there is much uncertainty around how these relationships may develop. Alongside this, while there is the confidence that the global mean temperature will continue to rise under current conditions (IPCC 2014), how this will manifest is less certain. It is expected that the intensity and frequency of extreme events will alter (IPCC 2014; Jiménez Cisneros *et al.* 2014), but specific impacts in any one location are more uncertain.

Cholera affects some of the most vulnerable communities (World Health Organization 2017a), and this group are often at great risk from the dynamics of climate change (World Health Organization 2009). In addition, such communities are often those least well served by health systems, exacerbating the health burden of any cholera increase. The health impact pathway and causal process diagram developed in this paper indicate how climate change may affect cholera risk in such communities through WASH. These can help better understand how climate change dynamics impact on WASH factors and ultimately cholera transmission. The health impact pathway and causal process diagram can be used to help decision-makers prioritise system and behavioural changes to WASH factors, based on the climate change dynamics that impact specific areas. Future research needs to focus on the missing links between WASH factors and climate change dynamics and to identify communities potentially at increased risk of cholera as a consequence of climate change and strengthen WASH in such locations.

ACKNOWLEDGEMENTS

This research was funded by WaterAid, grant number R205748. I.L., R.F. and P.H. received support from grant NE/E009042/1, funded by the Natural Environment Research Council. I.L. and P.H. are partly funded by the

National Institute for Health Research, Health Protection Research Unit in Emergency Preparedness and Response at King's College London. I.L. and P.H. are also funded in part by the NIHR Health Protection Research Unit in Gastrointestinal Infection at the University of Liverpool.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at <https://dx.doi.org/10.2166/wh.2020.088>.

REFERENCES

- Alhassan, S. & Hadwen, W. L. 2017 Challenges and opportunities for mainstreaming climate change adaptation into WASH development planning in Ghana. *International Journal of Environmental Research and Public Health* **14**, 749.
- Almazroui, M., Islam, M. N., Balkhair, K. S., Şen, Z. & Masood, A. 2017 Rainwater harvesting possibility under climate change: a basin-scale case study over western province of Saudi Arabia. *Atmospheric Research* **189**, 11–23.
- Asadieh, B. & Krakauer, N. Y. 2016 Impacts of changes in precipitation amount and distribution on water resources studied using a model rainwater harvesting system. *Journal of the American Water Resources Association* **52**, 1450–1471.
- Azurin, J. C. & Alvero, M. 1974 Field evaluation of environmental sanitation measures against cholera. *Bulletin of the World Health Organization* **51**, 19–26.
- Beatty, M. E., Jack, T., Sivapalasingam, S., Yao, S. S., Paul, I., Bibb, B., Greene, K. D., Kubota, K., Mintz, E. D. & Brooks, J. T. 2004 An outbreak of *Vibrio cholerae* O1 infections on Ebeye Island, Republic of the Marshall Islands, associated with use of an adequately chlorinated water source. *Clinical Infectious Diseases* **38**, 1–9.
- Bhunia, R. & Ghosh, S. 2011 Waterborne cholera outbreak following Cyclone Aila in Sundarban area of West Bengal, India, 2009. *Transactions of the Royal Society of Tropical Medicine and Hygiene* **105**, 214–219.
- Bi, Q., Ferreras, E., Pezzoli, L., Legros, D., Ivers, L. C., Date, K., Qadri, F., Digilio, L., Sack, D. A., Ali, M., Lessler, J., Luquero, F. J., Azman, A. S., Cavaller, P., Date, K., Sreenivasan, N., Matzger, H., Luquero, F., Grais, R., Wiesner, L., Ko, M., Rouzier, V., Peak, C., Qadri, F., Landegger, J., Lynch, J., Azman, A., Sack, D., Henkens, M., Ciglenecki, I., Ivers, L., Diggle, E., Weiss, M., Hinman, A., Maina, K., Mirza, I., Gimeno, G. & Levine, M. 2017 Protection against cholera from killed whole-cell oral cholera vaccines: a systematic review and meta-analysis. *The Lancet Infectious Diseases* **17**, 1080–1088.
- Branz, A., Levine, M., Lehmann, L., Bastable, A., Ali, S. I., Kadir, K., Yates, T., Bloom, D. & Lantagne, D. 2017 Chlorination of drinking water in emergencies: a review of knowledge to develop recommendations for implementation and research needed. *Waterlines* **36**, 4–39.
- Burrowes, V., Perin, J., Monira, S., Sack, D. A., Rashid, M. U., Mahamud, T., Rahman, Z., Mustafiz, M., Bhuyian, S. I., Begum, F., Zohura, F., Biswas, S., Parvin, T., Hasan, T., Zhang, X., Sack, B. R., Saif-Ur-Rahman, K. M., Alam, M. & George, C. M. 2017 Risk factors for household transmission of *Vibrio cholerae* in Dhaka, Bangladesh (CHOBI7 Trial). *The American Journal of Tropical Medicine and Hygiene* **96**, 1382–1387.
- Cairncross, S. & Alvarinho, M. 2013 The Mozambique floods of 2000: health impact and response. In: *Flood Hazards and Health: Responding to Present and Future Risks*. Routledge, London.
- Cavallaro, E. C., Harris, J. R., Da Goia, M. S., Dos Santos Barrado, J. C., Da Nóbrega, A. A., De Alvarenga Jr., I. C., Silva, A. P., Sobel, J. & Mintz, E. 2011 Evaluation of pot-chlorination of wells during a cholera outbreak, Bissau, Guinea-Bissau, 2008. *Journal of Water and Health* **9**, 394–402.
- Clemens, J. D., Nair, G. B., Ahmed, T., Qadri, F. & Holmgren, J. 2017 Cholera. *The Lancet* **390**, 1539–1549.
- Conroy, R. M., Meegan, M. E., Joyce, T., Mcguigan, K. & Barnes, J. 2001 Solar disinfection of drinking water protects against cholera in children under 6 years of age. *Archives of Disease in Childhood* **85**, 293–295.
- Dai, A. 2011 Drought under global warming: a review. *Wiley Interdisciplinary Reviews: Climate Change* **2**, 45–65.
- Del Ninno, C., Dorosh, P. A., Smith, L. C. & Roy, D. K. 2001 The 1998 floods in Bangladesh: disaster impacts, households coping strategies, and response. *Research Report of the International Food Policy Research Institute* Report 122, 1–114.
- Dewan, T. H. 2015 Societal impacts and vulnerability to floods in Bangladesh and Nepal. *Weather and Climate Extremes* **7**, 36–42.
- Dunston, C., McAfee, D., Kaiser, R., Rakotoarison, D., Rambeloson, L., Anh Thu, H. & Quick, R. E. 2001 Collaboration, cholera, and cyclones: a project to improve point-of-use water quality in Madagascar. *American Journal of Public Health* **91**, 1574–1576.
- Elliott, M., Macdonald, M. C., Chan, T., Kearton, A., Shields, K. F., Bartram, J. K. & Hadwen, W. L. 2017 Multiple household water sources and their use in remote communities with evidence from Pacific Island countries. *Water Resources Research* **53**, 9106–9117.
- Emont, J. P., Ko, A. I., Homasi-Paelate, A., Ituaso-Conway, N. & Nilles, E. J. 2017 Epidemiological investigation of a diarrhoea outbreak in the South Pacific Island nation of Tuvalu during a Severe la Niña-associated drought emergency in 2011. *The American Journal of Tropical Medicine and Hygiene* **96**, 576–582.

- Few, R. 2007 Health and climatic hazards: framing social research on vulnerability, response and adaptation. *Global Environmental Change* **17**, 281–295.
- Few, R. & Matthies, F. 2013 Responses to the health risks from flooding. In: *Flood Hazards and Health: Responding to Present and Future Risks*. Routledge, London.
- Few, R., Ahern, M., Matthies, F. & Kovats, S. 2004 *Floods, Health and Climate Change: A Strategic Review*. Tyndall Centre Working Paper No. 63. University of East Anglia, Norwich.
- Fewtrell, L., Kaufmann, R. B., Kay, D., Enanoria, W., Haller, L. & Colford Jr., J. M. 2005 Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis. *The Lancet Infectious Diseases* **5**, 42–52.
- Friel, S., Pescud, M., Malbon, E., Lee, A., Carter, R., Greenfield, J., Cobcroft, M., Potter, J., Rychetnik, L. & Meertens, B. 2017 Using systems science to understand the determinants of inequities in healthy eating. *PLoS ONE* **12**, e0188872–e0188872.
- Fry, L. M., Mihelcic, J. R. & Watkins, D. W. 2008 Water and nonwater-related challenges of achieving global sanitation coverage. *Environmental Science & Technology* **42**, 4298–4304.
- Fry, L. M., Watkins, D. W., Reents, N., Rowe, M. D. & Mihelcic, J. R. 2012 Climate change and development impacts on the sustainability of spring-fed water supply systems in the Alto Beni region of Bolivia. *Journal of Hydrology* **468–469**, 120–129.
- Ghosh, G. C., Jahan, S., Chakraborty, B. & Akter, A. 2015 Potential of household rainwater harvesting for drinking water supply in Hazard Prone Coastal area of Bangladesh. *Nature Environment and Pollution Technology* **14**, 937–942.
- Godfrey, S., Mccaffery, L., Obika, A. & Becks, M. 2003 The effectiveness of point-source chlorination in improving water quality in internally displaced communities in Angola. *Water and Environment Journal* **17**, 149–151.
- Grandesso, F., Allan, M., Jean-Simon, P. S. J., Boncy, J., Blake, A., Pierre, R., Alberti, K. P., Munger, A., Elder, G., Olson, D., Porten, K. & Luquero, F. J. 2014 Risk factors for cholera transmission in Haiti during inter-peak periods: insights to improve current control strategies from two case-control studies. *Epidemiology and Infection* **142**, 1625–1635.
- Heath, T. T., Parker, A. H. & Weatherhead, E. K. 2012 Testing a rapid climate change adaptation assessment for water and sanitation providers in informal settlements in three cities in sub-Saharan Africa. *Environment and Urbanization* **24**, 619–637.
- Howard, G. & Bartram, J. 2010 *Vision 2030. The Resilience of Water Supply and Sanitation in the Face of Climate Change*. Technical Report. World Health Organization.
- Howard, G., Katrina, C., Pond, K., Brookshaw, A., Hossain, H. & Bartram, J. 2010 Securing 2020 vision for 2030: climate change and ensuring resilience in water and sanitation services. *Journal of Water and Climate Change* **1**, 2–16.
- Hunter, P. R. 2009 Household water treatment in developing countries: comparing different intervention types using meta-regression. *Environmental Science & Technology* **43**, 8991–8997.
- Hutton, G. & Chase, C. 2016 The knowledge base for achieving the sustainable development goal targets on water supply, sanitation and hygiene. *International Journal of Environmental Research and Public Health* **13**, 536.
- IPCC 2014 *Climate Change 2014. Synthesis Report: Summary for Policymakers*. Intergovernmental Panel on Climate Change.
- Jacobs, B., Boronyak, L., Mitchell, P., Vandenberg, M. & Batten, B. 2018 Towards a climate change adaptation strategy for national parks: adaptive management pathways under dynamic risk. *Environmental Science & Policy* **89**, 206–215.
- Jean, J. S., Guo, H. R., Chen, S. H., Liu, C. C., Chang, W. T., Yang, Y. J. & Huang, M. C. 2006 The association between rainfall rate and occurrence of an enterovirus epidemic due to a contaminated well. *Journal of Applied Microbiology* **101**, 1224–1231.
- Jiménez Cisneros, B. E., Oki, T., Arnell, N. W., Benito, G., Cogley, J. G., Döll, P., Jiang, T. & Mwakalila, S. S. 2014 Freshwater resources. 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* (C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. Maccracken, P. R. Mastrandrea & L. L. White, eds). Cambridge University Press, Cambridge, UK, and New York, NY, USA.
- Joffe, M. & Mindell, J. 2006 Complex causal process diagrams for analyzing the health impacts of policy interventions. *American Journal of Public Health* **96**, 473–479.
- Joffe, M., Gambhir, M., Chadeau-Hyam, M. & Vineis, P. 2012 Causal diagrams in systems epidemiology. *Emerging Themes in Epidemiology* **9**, 1–1.
- Keegan, A., Wati, S. & Robinson, B. 2012 Chlor(am)ine disinfection of human pathogenic viruses in recycled waters (SWF 62M-2114). In: *Smart Water Fund*. Smart Water Fund, Victoria, Melbourne.
- Kirk, M. D., Kiedrzyński, T., Johnson, E., Elymore, A. & Wainiqolo, I. 2005 Risk factors for cholera in Pohnpei during an outbreak in 2000: lessons for Pacific countries and territories. *Pacific Health Dialog* **12**, 17–22.
- Kupferschmidt, K. 2018 Use of cholera vaccines expands, raising hopes: swelling supplies and a better formulation bolster response to widespread outbreaks. *Science* **359**, 620–621.
- Lantagne, D. S., Blount, B. C., Cardinali, F. & Quick, R. 2007 Disinfection by-product formation and mitigation strategies in point-of-use chlorination of turbid and non-turbid waters in western Kenya. *Journal of Water and Health* **6**, 67–82.
- Lessler, J., Moore, S. M., Luquero, F. J., McKay, H. S., Grais, R., Hens, M., Mengel, M., Dunoyer, J., M'bangombe, M., Lee, E. C., Djingarey, M. H., Sudre, B., Bompangue, D., Fraser, R. S. M., Abubakar, A., Perea, W., Legros, D. & Azman, A. S.

- 2018 Mapping the burden of cholera in sub-Saharan Africa and implications for control: an analysis of data across geographical scales. *The Lancet* **391**, 1908–1915.
- Luby, S. P., Gupta, S. K., Sheikh, M. A., Johnston, R. B., Ram, P. K. & Islam, M. S. 2008 Tubewell water quality and predictors of contamination in three flood-prone areas in Bangladesh. *Journal of Applied Microbiology* **105**, 1002–1008.
- Luby, S. P., Halder, A. K., Huda, T., Unicomb, L. & Johnston, R. B. 2011 The effect of handwashing at recommended times with water alone and with soap on child diarrhea in rural Bangladesh: an observational study. *PLoS Medicine* **8**, e1001052.
- Luh, J., Royster, S., Sebastian, D., Ojomo, E. & Bartram, J. 2017 Expert assessment of the resilience of drinking water and sanitation systems to climate-related hazards. *Science of the Total Environment* **592**, 334–344.
- Manfredi, E. C., Flury, B., Viviano, G., Thakuri, S., Khanal, S. N., Jha, P. K., Maskey, R. K., Kayastha, R. B., Kafle, K. R., Bhochhibhoya, S., Ghimire, N. P., Shrestha, B. B., Chaudhary, G., Giannino, F., Carten, F., Mazzoleni, S. & Salerno, F. 2010 Solid waste and water quality management models for Sagarmatha National Park and Buffer Zone, Nepal. *Mountain Research and Development* **30**, 127–142.
- Mellor, J. E., Levy, K., Zimmerman, J., Elliott, M., Bartram, J., Carlton, E., Clasen, T., Dillingham, R., Eisenberg, J., Guerrant, R., Lantagne, D., Mihelcic, J. & Nelson, K. 2016 Planning for climate change: the need for mechanistic systems-based approaches to study climate change impacts on diarrheal diseases. *Science of the Total Environment* **548–549**, 82–90.
- Musayev, S., Burgess, E. & Mellor, J. 2018 A global performance assessment of rainwater harvesting under climate change. *Resources, Conservation & Recycling* **132**, 62–70.
- O'Connor, K. A., Cartwright, E., Loharikar, A., Routh, J., Gaines, J., Fouché, M. D. B., Jean-Louis, R., Ayers, T., Johnson, D., Tappero, J. W., Roels, T. H., Archer, W. R., Dahourou, G. A., Mintz, E., Quick, R. & Mahon, B. E. 2011 Risk factors early in the 2010 cholera epidemic, Haiti. *Emerging Infectious Diseases* **17**, 2136–2138.
- Phillips, R. M., Vujcic, J., Boscoe, A., Handzel, T., Aninyasi, M., Cookson, S. T., Blanton, C., Blum, L. S. & Ram, P. K. 2015 Soap is not enough: handwashing practices and knowledge in refugee camps, Maban County, South Sudan. *Conflict and Health* **9**, 39.
- Rehfuess, E. A., Best, N., Briggs, D. J. & Joffe, M. 2013 Diagram-based analysis of causal systems (DACS): elucidating inter-relationships between determinants of acute lower respiratory infections among children in sub-Saharan Africa. *Emerging Themes in Epidemiology* **10**, 13–13.
- Ren, Z., Chen, Z. & Wang, X. 2011 Climate change adaptation pathways for Australian residential buildings. *Building and Environment* **46**, 2398–2412.
- Righetto, L., Bertuzzo, E., Mari, L., Schild, E., Casagrandi, R., Gatto, M., Rodriguez-Iturbe, I. & Rinaldo, A. 2013 Rainfall mediations in the spreading of epidemic cholera. *Advances in Water Resources* **60**, 34–46.
- Rosenzweig, C. & Solecki, W. 2014 Hurricane sandy and adaptation pathways in New York: lessons from a first-responder city. *Global Environmental Change* **28**, 395–408.
- Sack, D. A., Sack, R. B., Nair, G. B. & Siddique, A. K. 2004 Cholera. *The Lancet* **363**, 223–233.
- Sasaki, S., Suzuki, H., Igarashi, K., Tambatamba, B. & Mulenga, P. 2008 Spatial analysis of risk factor of cholera outbreak for 2003–2004 in a peri-urban area of Lusaka, Zambia. *The American Journal of Tropical Medicine and Hygiene* **79**, 414–421.
- Settele, J., Scholes, R., Betts, R., Bunn, S., Leadley, P., Nepstad, D., Overpeck, J. T. & Taboada, M. A. 2014 Terrestrial and inland water systems. 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* (C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea & L. L. White, eds). Cambridge University Press, Cambridge, UK, and New York, NY, USA.
- Sherpa, A. M., Koottatep, T., Zurbrugg, C. & Cissé, G. 2014 Vulnerability and adaptability of sanitation systems to climate change. *Journal of Water and Climate Change* **5**, 487–495.
- Smaajl, A., Toan, T. Q., Nhan, D. K., Ward, J., Trung, N. H., Tri, L. Q., Tri, V. P. D. & Vu, P. T. 2015 Responding to rising sea levels in the Mekong Delta. *Nature Climate Change* **5**, 167–174.
- Smith, M. S., Horrocks, L., Harvey, A. & Hamilton, C. 2011 Rethinking adaptation for a 4 °C world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **369**, 196–216.
- Stoll, S., Hendricks Franssen, H. J., Barthel, R. & Kinzelbach, W. 2011 What can we learn from long-term groundwater data to improve climate change impact studies? *Hydrology and Earth System Sciences* **15**, 3861–3875.
- Taylor, D. L., Kahawita, T. M., Cairncross, S. & Ensink, J. H. 2015 The impact of water, sanitation and hygiene interventions to control cholera: a systematic review. *PLoS ONE* **10**, e0135676.
- Tucker, J., Macdonald, A., Coulter, L. & Calow, R. C. 2014 Household water use, poverty and seasonality: wealth effects, labour constraints, and minimal consumption in Ethiopia. *Water Resources and Rural Development* **3**, 27–47.
- UNICEF 2015 *Progress on Sanitation and Drinking Water – 2015 Update and MDG Assessment*. UNICEF.
- UNICEF 2018a *Cholera: WASH*. UNICEF. Available from: https://www.unicef.org/cholera/index_71218.html (accessed 27 June 2018).
- UNICEF 2018b *Water, Sanitation and Hygiene: Climate Change*. Available from: https://www.unicef.org/wash/3942_4472.html (accessed 27 June 2018).

- United Nations 2015 *Transforming Our World: The 2030 Agenda for Sustainable Development*. United Nations.
- Usman, M. A., Gerber, N. & Pangaribowo, E. H. 2018 Drivers of microbiological quality of household drinking water – a case study in rural Ethiopia. *Journal of Water and Health* **16**, 275–288.
- Vins, H., Bell, J., Saha, S. & Hess, J. J. 2015 The mental health outcomes of drought: a systematic review and causal process diagram. *International Journal of Environmental Research and Public Health* **12**, 13251–13275.
- Waite, M. 2012 Climate-change mitigation and adaptation in small island developing states: the case of rainwater harvesting in Jamaica. *Sustainability: Science, Practice and Policy* **8**, 81–87.
- Wolfe, M., Kaur, M., Yates, T., Woodin, M. & Lantagne, D. 2018 A systematic review and meta-analysis of the association between water, sanitation, and hygiene exposures and cholera in case-control studies. *The American Journal of Tropical Medicine and Hygiene* **99**, 534–545.
- World Health Organization 2009 *Vision 2030: The Resilience of Water Supply and Sanitation in the Face of Climate Change*. World Health Organization.
- World Health Organization 2017a *Declaration to Ending Cholera. Global Task Force on Cholera Control*. World Health Organization.
- World Health Organization 2017b *Water Quality and Health – Review of Turbidity: Information for Regulators and Water Suppliers*. World Health Organization.
- World Health Organization 2018a *Cholera vaccine: WHO position paper, August 2017 – recommendations*. *Vaccine* **36**, 3418–3420.
- World Health Organization 2018b *Cholera: Key Facts*. World Health Organization. Available from: <http://www.who.int/news-room/fact-sheets/detail/cholera> (accessed 27 June 2018).
- Yates, T., Vujcic, J. A., Joseph, M. L., Gallandat, K. & Lantagne, D. 2018 Water, sanitation, and hygiene interventions in outbreak response: a synthesis of evidence. *Waterlines* **37**, 5–30.
- Zinn, C., Bailey, R., Barkley, N., Walsh, M. R., Hynes, A., Coleman, T., Savic, G., Soltis, K., Primm, S. & Haque, U. 2018 How are water treatment technologies used in developing countries and which are the most effective? An implication to improve global health. *Journal of Public Health and Emergency* **2**, 25.
- Zohura, F., Bhuyian, S. I., Monira, S., Begum, F., Biswas, S. K., Parvin, T., Sack, D., Sack, R. B., Leontsini, E., Saif-Ur-Rahman, K. M., Rashid, M. U., Sharmin, R., Zhang, X., Alam, M. & George, C. M. 2016 Observed handwashing with soap practices among cholera patients and accompanying household members in a hospital setting (CHoBI7 Trial). *The American Journal of Tropical Medicine and Hygiene* **95**, 1314–1318.

First received 27 March 2019; accepted in revised form 28 October 2019. Available online 27 January 2020