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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

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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

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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

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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 handwashing 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. Rehfuess *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 were 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

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

[a]Brief methods for obtaining odds ratios in the 'Methods' section, full methods detailed in Supplementary file 1.

and did not combine 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 risker 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

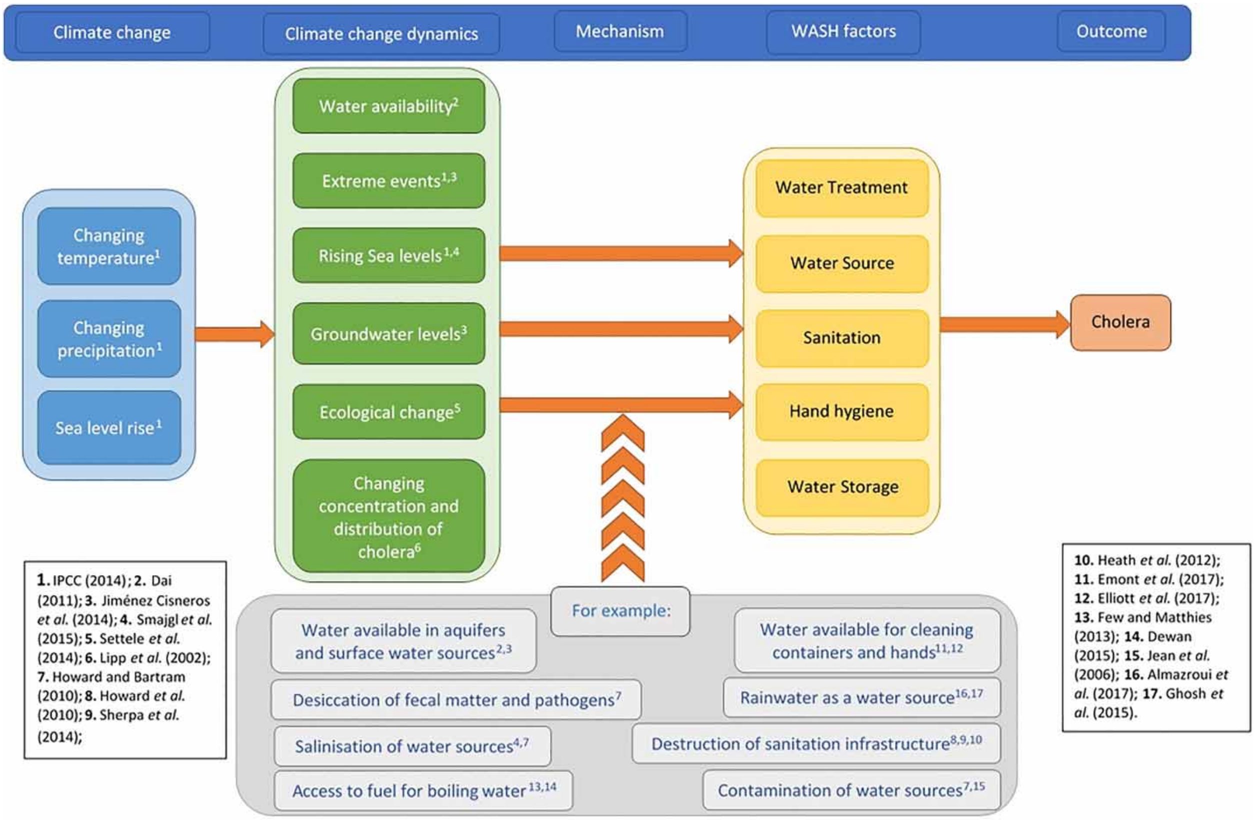

Figure 1 | Health impact pathway for climate change and WASH.

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

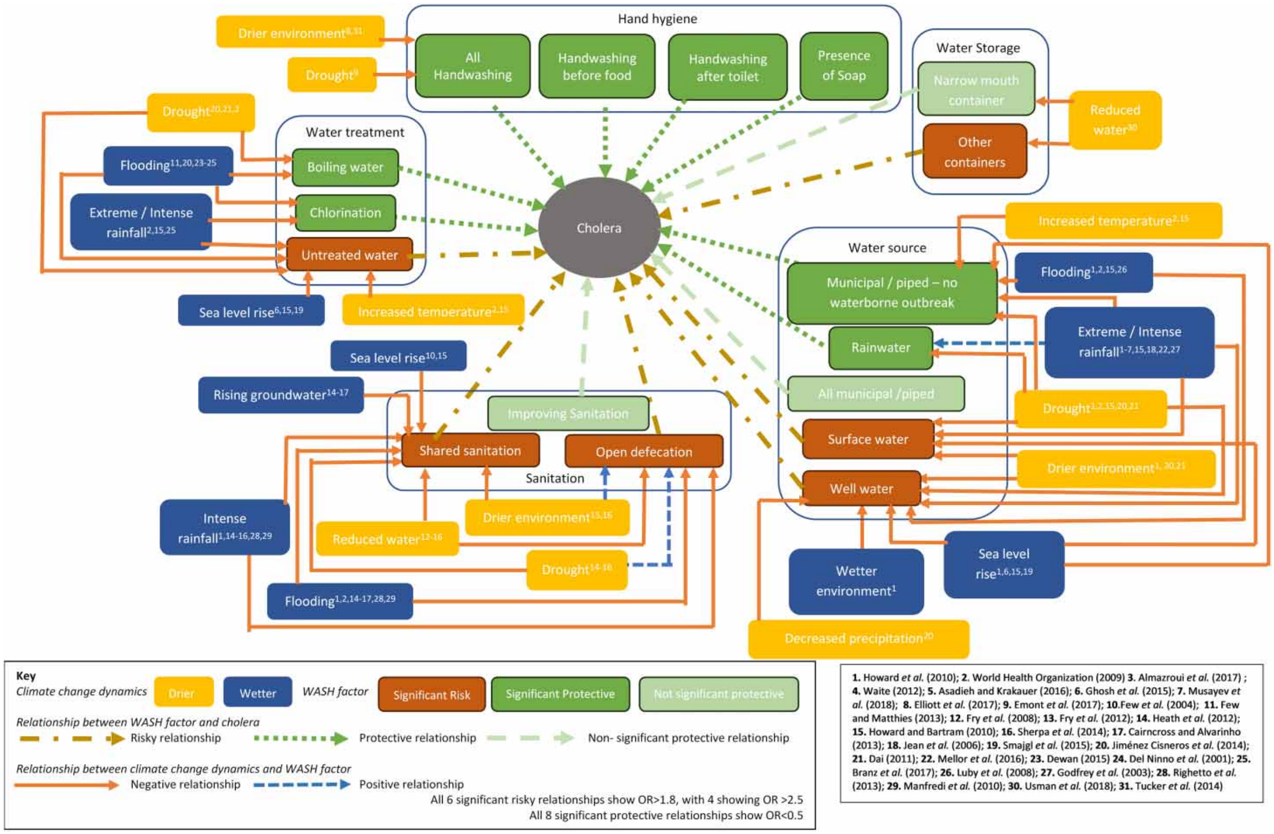

Figure 2 | Causal process diagram showing the links, from the literature, between climate change dynamics and WASH influences on cholera transmission.

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 aquafers 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 tubewells (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 defection. 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 watercourses (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 such 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 risker 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 at risk of cholera as a consequence of climate change and strengthen WASH in such locations.

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SUPPLEMENTARY MATERIAL

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