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Infrastructure alone cannot ensure resilience to weather events in drinking water supplies

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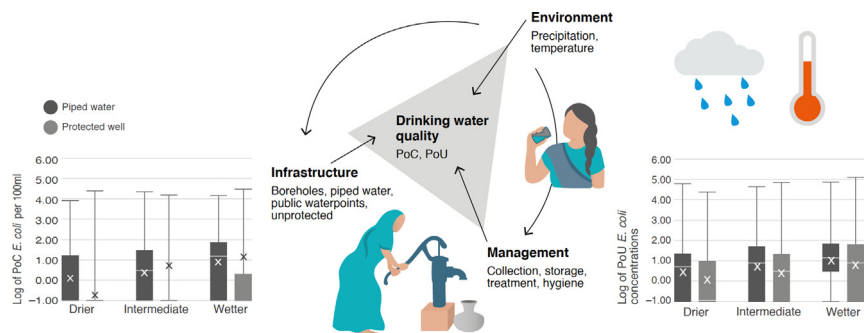
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HIGHLIGHTS

- Weather-related shocks affect drinking water quality, impacting health.
- Novel multi-country empirical study measured weather impact on water quality.
- Rainfall and temperature extremes affected water quality at source and household.
- GEE analysis demonstrated water management behaviour varies with weather.
- Strengthening climate resilience needs to address management and infrastructure.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate resilient water supplies are those that provide access to drinking water that is sustained through seasons and through extreme events, and where good water quality is also sustained. While surface and groundwater quality are widely understood to vary with rainfall, there is a gap in the evidence on the impact of weather and extremes in rainfall and temperature on drinking water quality, and the role of changes in water system management. A three-country

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(Bangladesh, Nepal and Tanzania) observational field study tracked 2353 households clustered around 685 water sources across seven different geographies over 14 months. Water quality (*E. coli*) data was modelled using GEE to account for clustering effects and repeated measures at households. All types of infrastructure were vulnerable to changes in weather, with differences varying between geographies; protected boreholes provided the greatest protection at the point of collection (PoC). Water quality at the point of use (PoU) was vulnerable to changes in weather, through changes in PoC water quality as well as changes in management behaviours, such as safe storage, treatment and cleaning. This is the first study to demonstrate the impact of rainfall and temperature extremes on water quality at the PoC, and the role that weather has on PoU water quality via management behaviours. Climate resilience for water supplies needs to consider the infrastructure as well as the management decisions that are taking place at a community and household level.

1. Introduction

The Inter-Governmental Panel on Climate Change (IPCC and White, 2014) defines resilience as *'The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation'*. The nature of systems covered by this definition vary enormously but include a large proportion that focus on the delivery of goods and services for people. In these cases, resilience relates to the whole system, including socio-economic factors (in particular management systems), infrastructure and the environment. In this paper we look at household drinking water services, and in particular the ability of these systems to provide safe drinking water during weather-related shocks.

Weather-related shocks are widely reported to increase waterborne diseases and affect health, for which drinking water is a likely pathway but often not explicitly studied. Heavy rainfall has been associated with a number of major outbreaks, such as the Yemen cholera epidemic between 2016 and 2018 (Camacho et al., 2018) and the cholera outbreak in Juba, South Sudan in 2015 (Lemaitre et al., 2019). In Haiti, heavy rainfall was associated with incidence of cholera cases within the 2010/11 outbreak (Eisenberg et al., 2013). Floods have been reported to increase incidence of gastrointestinal diseases, such as rotavirus, cryptosporidiosis and cholera (Ahern et al., 2005; Alderman et al., 2012). Droughts have been linked with long term impacts on stunting in children (Cooper et al., 2019) and, in Africa, has been associated with cholera (Rebaudet et al., 2013). The mechanisms by which these weather-related shocks influence health are varied, and relate to behaviour changes as well as environmental change. Outbreaks from floods are commonly associated with contamination of drinking water supplies (Cann et al., 2013), but have also been observed after the water has receded due to children playing in recently flooded areas (Gertler et al., 2015). Droughts are linked to increases in diarrhoeal disease because hygiene is compromised as water availability decreases, and have been associated with increases in vector-borne diseases due to increased breeding sites near houses in water storage vessels (Stanke et al., 2013).

Weather-related shocks impact water supplies through various mechanisms, with potential to affect the health of users. Primary impacts include damage to infrastructure from erosion under heavy rainfall and floods, loss of water sources in droughts, and deterioration of water quality (Charles et al., 2009; Howard et al., 2010). There is strong evidence of the impact of weather on water quality in the environment and in drinking water supplies, with increases in faecal contamination linked to rainfall (Kostyla et al., 2015; WHO, 2011). Heavy rainfall can have a rapid impact on water quality in rivers, that is delayed but still significant in reservoirs (Brookes et al., 2004). It may also be rapid for shallow groundwater (Chilton and Seiler, 2006), although more limited in deeper, unfractured aquifers. The impact of antecedent dry periods on the accumulation of pollutants and subsequently on water quality is well understood in terms of stormwater (Deletic and Maksimovic, 1998), with a more sustained impact on pathogen concentrations beyond the first flush (Roser and Ashbolt, 2007); similar associations with the microbial contamination of drinking water through piped water supplies (Setty et al., 2018) have been demonstrated. Similarly to the health impacts described above, the influence of weather on microbial water quality is mediated by management: decisions

to protect and treat the water. Where access to the water on-premises is not available, drinking water quality at the point of use (PoU) can deteriorate significantly from the point of collection (PoC), highlighting the importance of household practices around hygiene, storage and treatment (Levy et al., 2008; Wright et al., 2004). Here, management behaviours can also be impacted by weather and seasons, such as due to changes in perceived risk, changes in availability or organoleptic properties of the water.

The impact of changes in water quality on health are well established, but there is limited literature that considers the role of weather on health outcomes. A randomized control trial (RCT) of handwashing and household water treatment in Pakistan reported increased diarrhoea during very heavy rainfall and flooding, with none of the interventions effective in preventing diarrhoea during this event (Luby et al., 2006). An RCT of household water treatment in Guatemala reported that their observed peak in diarrhoea rates was shortly after the onset of seasonal rains (Reller et al., 2003). Interruptions in access to safe water can have health impacts: short-term interruptions to water supplies have been associated with significant increases in disease (Hunter et al., 2009). Notably, based on a systematic review, water, sanitation and hygiene (WASH) effectiveness has been reported to be higher in shorter RCTs that don't cover all seasons (Waddington and Snilstveit, 2009), which may indicate they are missing the evidence on WASH performance during these high-risk periods during heavy rainfall. While the role of weather on water quality is increasing being recognised (Charles and Greggio, 2021), the subsequent impact on health is still poorly evidenced.

It is essential to understand how to design and manage drinking water supply systems to ensure the best outcomes for health in a changing climate. In this paper we report on a novel observational research study in three countries in Africa and Asia to analyse the influence of the environment, infrastructure and management on the level of service of water supplies, and in particular on drinking water quality at the PoC and PoU. We use the framework in Fig. 1 to explore the interactions between the environment, infrastructure and management on drinking water quality outcomes. For the environment, while the broader hydrogeology, hydrological, and land use will influence water quality, the analysis is focused on the role of weather in water supply outcomes, such as water shortages, heavy rain and temperature extremes. For infrastructure, the focus is on how drinking water is accessed, such as by piped water system, protected wells or shallow wells dug into riverbeds; the design of this infrastructure and the level of maintenance is also critical. For management, the analysis considers the behaviours and the decisions that are made about collection, treatment, storage and the management of hygiene from the individual level (e.g. handwashing) to localised source protection decisions (e.g. location of sanitation). Significantly, this analysis is the first to address the interactions between weather, water source and management, and the impacts that these have on drinking water safety.

2. Material and methods

2.1. Site selection

A three-country observational field study was designed to assess how the performance of drinking water supply services vary with weather, primarily changes in temperature and precipitation, considering the relative contribution of environment, infrastructure and management. Country teams reviewed the evidence for the impact of climate change related to

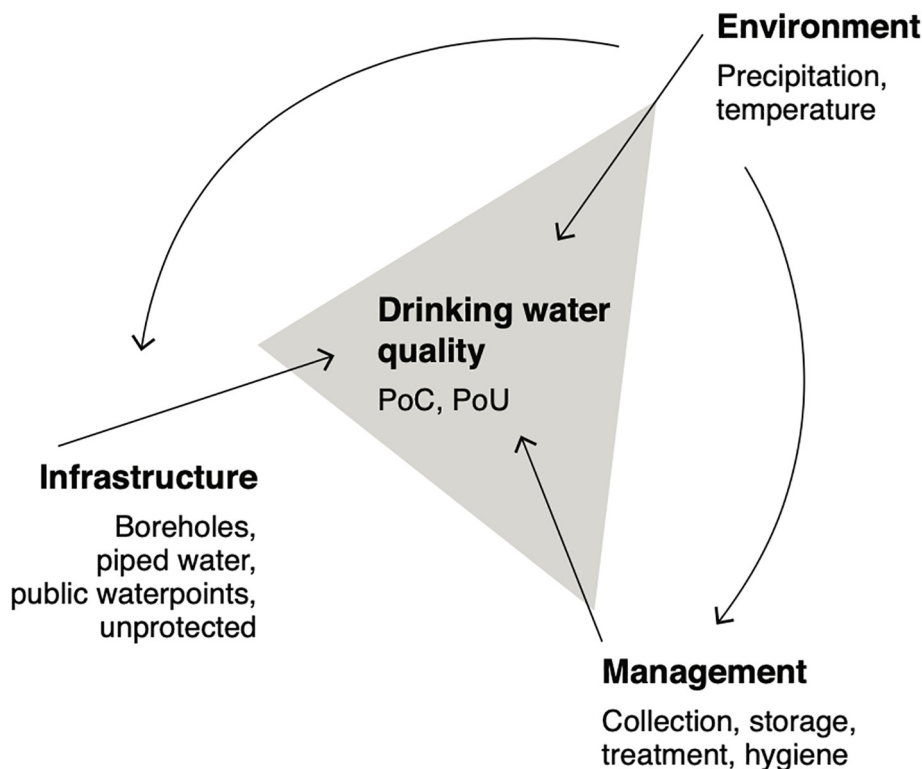


Fig. 1. Drinking water quality framework for analysis: Environment includes natural contamination sources and weather. Infrastructure is how drinking water is accessed, including its design and maintenance. Management is the decisions made about collection, treatment, storage and managing hygiene at and around the infrastructure.

WASH and health in their country, and used that to identify research sites that would represent different types of risks. Availability of meteorological information (daily precipitation and temperature) was also a criterion, using national meteorological information or local equipment. In Bangladesh, two sites were selected that represented a flood prone and a drought prone area, with a mix of urban and rural areas included. In Nepal, one area was chosen, that was split into two sites based on northerly or southerly aspect as the northern aspect was expected to have lower evaporation and higher water availability. In Tanzania, three sites were selected encompassing a coastal urban site (which experienced a cholera outbreak early in the research), and two rural sites comprising rural and village communities in the south-eastern highland region and the northern dry region. A fourth country (Ethiopia) was included in the research but, due to limitations in the meteorological data, was excluded from this analysis.

2.2. Sampling design

The experimental design was based on a common protocol, adapted to local conditions; as a result, there was some variability between countries. Sampling was clustered around focal improved water supplies in the selected geographies and are not representative of national conditions, but provide case studies of the role of weather in areas vulnerable to climate change impacts. Households were targeted who had access to the focal water supply and had used it at least once in the past year, with the actual PoC used verified during each sampling round (household visit). Systematic random sampling was used to identify a cluster of households for each PoC, from 5 in Bangladesh to 20 in Tanzania. Country teams calculated the appropriate sample size based on a primary outcome of microbial quality (*Escherichia coli*) of household drinking water (Supplementary Data 1).

2.3. Data collection

Data collection was designed to be frequent and responsive to changes in metrological and environmental conditions. In practice, this was

challenging for research teams, and more routine sampling rounds were implemented. Frequent visits over 14 months ensured a range of meteorological and environmental conditions were experienced. A total of 2353 households and 685 water sources across 7 sites in 3 countries are included in the analysis (Table 1). Water sources were classified in four categories: improved sources included piped water, public taps and protected wells, with unimproved including unprotected sources; tankers were additionally reported to be used in the first sampling round at one site only. The sampling periods are presented against meteorological data in Supplementary Data Fig. S1. Field researchers were trained in the different aspects of interviewing, data recording, water quality analysis and sanitary inspections each guided by a multicounty protocol adapted to country specific contexts. Initial site visits were undertaken to study sites to engage the support of community leaders. Community discussions were used to develop an understanding of seasonal patterns within the community that may influence the study design or outcomes and the areas using focal water supplies. Households were identified via systematic random sampling. Households were included if an appropriate respondent was present who provided informed consent, and the household has used the focal water supply in the past year. Ethical permissions were gained from WHO and relevant national and institutional bodies. A longitudinal design was used in each country: each sampling round enumerators returned to the same households enrolled during baseline to collect data via standardized survey instruments at the household and community level (e.g. water source conditions). Standardized water sampling protocols were used at the household to identify and sample household drinking water and to collect water samples from PoC.

2.3.1. Water quality analyses

Water samples were collected at the PoC and the PoU following country standard operating protocols. At the PoC, where possible, the tap or spout was flamed to sterilise it before sampling. For PoU samples, respondents were asked to provide water sample as if s/he was serving water to a family member; this water was then transferred to a sterile container for transport.

Table 1

Key characteristics of study sites. Data on water sources, treatment and sanitation from the first data collection round. Types: Pi = piped; PT = public taps, PW = protected wells, U = unimproved, T = tanker. nd = no data.

Site	Household		Urban/rural	Sources sampled		Rounds	Treat water (main method)	Sanitation improved ^a /shared	Climate data source	Precipitation Av annual (n wet days)	Daily max temperature	Daily min temperature	
	n	Size (mean, st dev)		n	Types								n
Bangladesh	1	445	4.5 (1.8)	Mixed	135	Pi 49% PW 51%	14	9.2 (filtering)	64/46	Local meteorological stations 1987-2017	1758 (113)	17.5–41.2	6.3–28.7
	2	467	4.0 (1.4)	Mixed	135	Pi 32% PW 68%	15	7.3 (filtering)	62/49		1415 (94)	12.9–38.9	7.1–28.6
Nepal	1	386	3.5 (1.6)	Mixed	82	Pi 72% PT 18% U 10%	8	59 (boiling)	45/nd	CHIRPS and ERA-Interim 1984-2017	1809 (62)**	0.5–20.1**	–12.2–14.0
	2	610	3.5 (1.5)	Mixed	117	Pi 90% PT 7% U 3%	8	35 (boiling)	62/nd		1131 (61)	23.9–33.2	17.8–25.3
Tanzania	1	125	5.8 (4.8)	Urban	78	Pi 96% PT 3% U 1%	8	7.8 (boiling)	33/97	CHIRPS and ERA-Interim 1985-2017	1373 (88)	19.3–32.0	9.3–19.6
	2	172	4.4 (2.1)	Rural	84	PT 26% PW 64% U 10%	9	4.4% (boiling)	25/70		748 (49)	19.3–32.3	9.8–19.6
	3	148	4.8 (2.4)	Rural	54	PT 47% PW 10% U 39% T 4%	9	17% (boiling)	4.1				

^a Sanitation is based on various indicators of suitable toilets, but does not conform directly to JMP questions. * indicates round 1 data only. ** As the Nepal sites are adjacent, the rainfall and temperature data are the same.

Portable pH, temperature and turbidity meters were used to measure samples at the point of sampling. After transport to the laboratory, maintaining a cold chain, 100 mL samples were analysed for *E. coli* using membrane filtration. While not a pathogen itself, there is evidence that the presence of *E. coli* in drinking water is associated gastrointestinal illness (Charles et al., 2020; Gruber et al., 2014), and is recommended as a faecal indicator to assess the microbial safety of drinking water in the absence of direct pathogen testing (Dufour, 2003; WHO, 2011). For this analysis, safe water was defined as water without detectable *E. coli*, and risk classification was based on WHO guidance (WHO, 1997): low risk <1 cfu per 100 mL; intermediate risk is 1–10 cfu per 100 mL; high risk is 11–100 cfu per 100 mL; and very high risk >100 cfu per 100 mL.

2.3.2. Household surveys

Surveys collected information from respondents on socio-demographic information, self-reported diarrhoea and other health outcomes, WASH access and behaviours. Questions were adapted to local conditions, such as management behaviours that household respondents would be expected to perform or have knowledge of, and were not directly comparable in all countries, so analysis focused on the countries separately. An additional one-off survey was added to review comparability of data.

2.3.3. Water source surveys

Water sources were evaluated with sanitary inspections, based on WHO guidelines (WHO, 1997), to identify potential sources of contamination or problems in their design or maintenance. Additionally, the flow rate at the source was measured and water source managers were surveyed to ascertain information on usage.

2.3.4. Meteorological data

National meteorological agency data was the preferred source of daily precipitation and temperature from local stations, for the duration of the study and thirty years historical data. However, reliability was poor, requiring use of other datasets in some cases. In Bangladesh, local meteorological stations were used. In Nepal and Tanzania, due to gaps in the data, and accessibility issues respectively, temperature data was obtained from ERA-Interim (Dee et al., 2011) and Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) (Funk et al., 2015) data for precipitation. Historical data was used to calculate extreme events for daily precipitation and maximum temperature at the 90th, 95th and 99th percentiles, and for minimum temperature at the 10th, 5th and 1st percentile. Weather across the

sampling periods were characterised in the following ways: average daily precipitation, maximum of daily maximum temperature, minimum of daily minimum temperatures, length in days of antecedent dry periods for each sampling round, wet and dry spells (period of unusually wet/dry of at least five consecutive days with daily precipitation exceeding/less than 1 mm during the wet season (WMO, 2015)), and cold and warm spells (at least 6 consecutive days when temperature is >90th/<10th percentile). Rainfall was categorised into drier (<1 mm average daily rainfall), intermediate and wetter periods, based on local conditions, to allow differentiation of intermediate and higher rainfall periods. Heavy rainfall was rainfall above the 90th percentile.

2.4. Statistical analysis

Data was analysed using IBM SPSS Statistics software (v26, IBM). Data was cleaned to remove households with incomplete water quality data across three local categories of rainfall (wetter, intermediate, drier). Samples with no *E. coli* detected were coded as 0.1 cfu/100 mL; *E. coli* data was then log₁₀ transformed for analysis.

Multiple weather-related factors influence water quality outcomes from different source types. Various studies have identified a lagged relationship between rainfall and changes in water quality at the source (Howard et al., 2003). In a separate analysis of the Tanzania data from this study, lag periods of two weeks (Guo et al., 2021) and one day (Guo et al., 2019) have been used. However, the relationship varies depending on the transport pathway for the contamination (e.g. direct infiltration from cracked infrastructure, vs contamination of the aquifer), and the relevant local conditions, making a single lag period inappropriate across the diverse contexts in this study. While coliform concentrations are associated with temperature (Ramteke et al., 1992), less is reported about the rate of change and associated lag. Additionally, there are likely to be many impacts on water quality via management decisions that will have complex links to weather that may be lagged over different periods. Due to these complexities, water quality was analysed in relation to the weather for that round, not the individual day or to a specific preceding period.

Two-tailed Pearson correlation, and analysis of variance (ANOVA) were used to compare water quality across sources and sites ($p < 0.01$), and if weather (daily precipitation and maximum and minimum temperatures) was correlated with water quality at PoC and PoU. Generalised Estimating Equations (GEE) were used to model the log₁₀ *E. coli* concentrations at PoC and PoU water by country to account for the potential correlation between

rounds for an individual household or source. GEE models were built to assess the contribution of weather-related variables and source type on PoC water quality, as well as the contribution of management and socioeconomic variables on PoU water quality. Households and sites were subject variables, with rounds representing within subject variables. Improvement of the model was based on the goodness-of-fit statistic Quasi-likelihood under Independence Model Criterion (QIC). In Bangladesh and Nepal, water quality at PoU was linked to a specific PoC, enabling analysis to include the impact of PoC water quality on PoU water quality. For Tanzania, source type was used as a proxy for PoC water quality.

There were strong similarities between system types within sites, due to climatic and geological conditions. However, due to differences between countries, and sometimes between sites, analysis is reported at a site level.

3. Results

3.1. Water quality at PoC

Faecal contamination in water increased with rainfall, and varied by type of source (Fig. 2). Improved sources had better water quality than unimproved sources. *E. coli* concentrations were generally significantly ($p < 0.01$) positively-correlated with rainfall and temperature for improved sources at the PoC (Supplementary data Table S1). However, there was variability, with water quality from piped water sources in Bangladesh notably not related to meteorological variables, or protected wells in two sites in Tanzania. Rainfall reduced access to safe water; for example, in Bangladesh, at site 1, 85% of protected wells were low risk (no *E. coli* detected) in one round in the dry season compared to 62% in one round during the monsoon. Water quality between PoC types varied by country, due to different construction of infrastructure and local conditions; for example, in Nepal, piped to premises was from springs, which demonstrated strong correlations with weather variables, whereas in Bangladesh, piped networks were more likely to be from

deeper, better protected boreholes. Unimproved sources had poorer water quality in all conditions, and did not exhibit such as strong relationship to rainfall (Fig. 2); reductions in faecal contamination in open wells were measured with dilution from rainfall, however, these shallow wells were more commonly dried up during the dry periods than deeper, protected wells. In Tanzania, one site enabled comparisons of protected boreholes and protected dug wells; protected boreholes provided higher quality water, and were more protected from the impacts of wet weather than protected dug wells (Fig. 3).

Analysis with GEE models demonstrated the interactions between different aspects of the weather, and highlighted the differences in the impact of local climate on water quality. Weather is not the primary explainer for water quality, but it does have a significant effect. While we have categorised graphs by rainfall, temperature also had a strong impact on PoC water quality (and is correlated to rainfall). In Bangladesh, where rainfall was associated with higher minimum and maximum temperatures (see supplementary data Fig. S1), water quality was most strongly influenced by rainfall over the sampling period, including by extreme rainfall (days with precipitation above the 90th and 95th percentile). In Nepal, where rainfall was also associated with higher minimum and maximum temperatures (see supplementary data Fig. S1), in addition to precipitation and minimum and maximum temperature, the length of the precipitation (interaction term: length of wet spell*average daily precipitation for round) or dry (antecedent dry period*average daily precipitation for round) were significant predictors. In Tanzania, where the climate is drier and rainfall was associated with higher minimum, but lower maximum temperatures (see supplementary data Fig. S1), precipitation explained little of the variability, with maximum temperature the main predictor for PoC water quality.

3.2. Water quality at the PoU

Water quality at the PoU was worse than at the PoC (Supplementary Table S2). Water quality at the PoU (Fig. 4) deteriorated with precipitation,

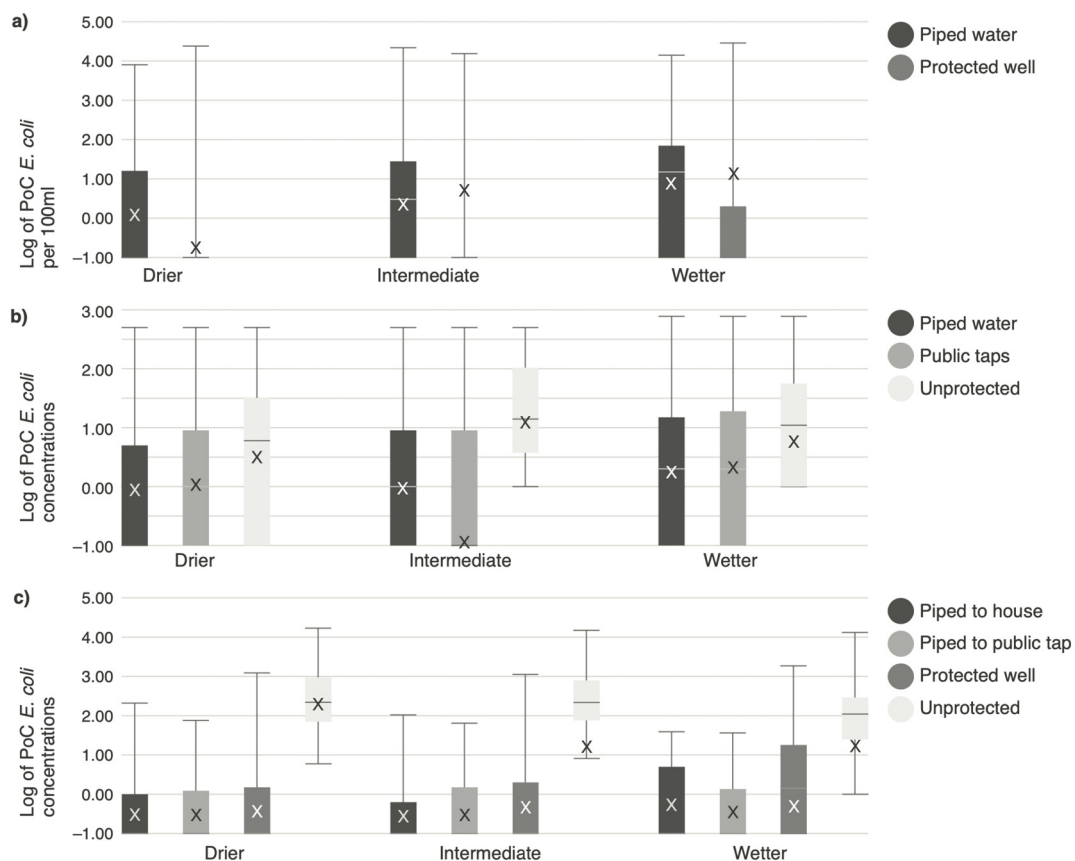


Fig. 2. PoC water quality in (a) Bangladesh, (b) Nepal and (c) Tanzania for drier, intermediate and wetter conditions.

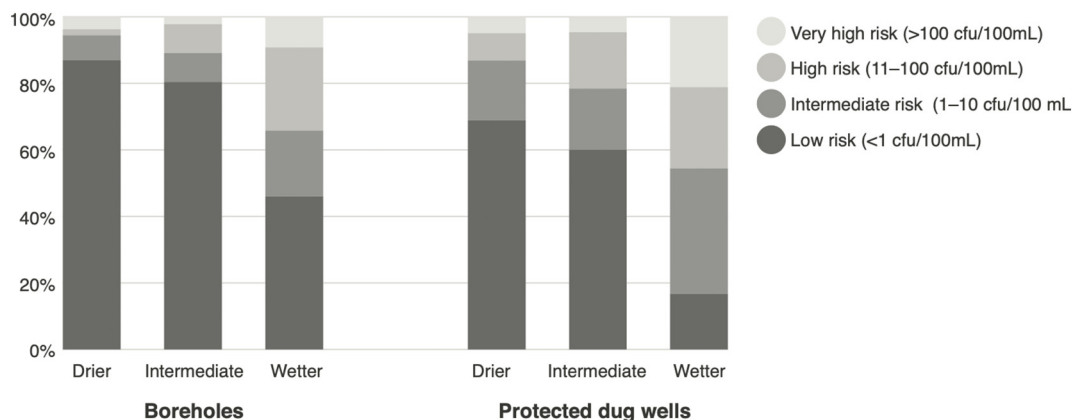


Fig. 3. Comparison of PoC water quality at boreholes ($n = 30$) and protected dug wells ($n = 41$) highlights that, while water quality in boreholes does deteriorate in wet weather, boreholes have a higher level of water quality in all weathers than protected dug wells. (Tanzania, site 2 only).

but not always as dramatically as for PoC water quality. Mechanisms for the impact of weather on PoU water quality are more complex than for PoC water, being influenced by PoC water quality, hygiene and storage. Statistical relationships are presented in Supplementary Table S1. In Bangladesh and Nepal, there were significant positive correlations between precipitation and PoU water quality for all improved source types at each site, and between maximum and minimum temperature and PoU water quality, indicating similar vulnerabilities to weather changes. In Nepal, PoU water quality from unprotected sources did not vary significantly with precipitation

but had high levels of contamination under all conditions. In Tanzania, relationships were not consistent across sites; there were significant positive correlations for PoC and PoU water quality for piped to household with precipitation at site 1, and with minimum temperature. In contrast to the other countries, all significant correlations between water quality and maximum temperature were negative in Tanzania, across all water types (but not all sites). At site 2, only protected well PoC water quality was significantly associated ($p < 0.01$) with weather variables, while PoU water quality was more influenced by weather with correlations for public taps and

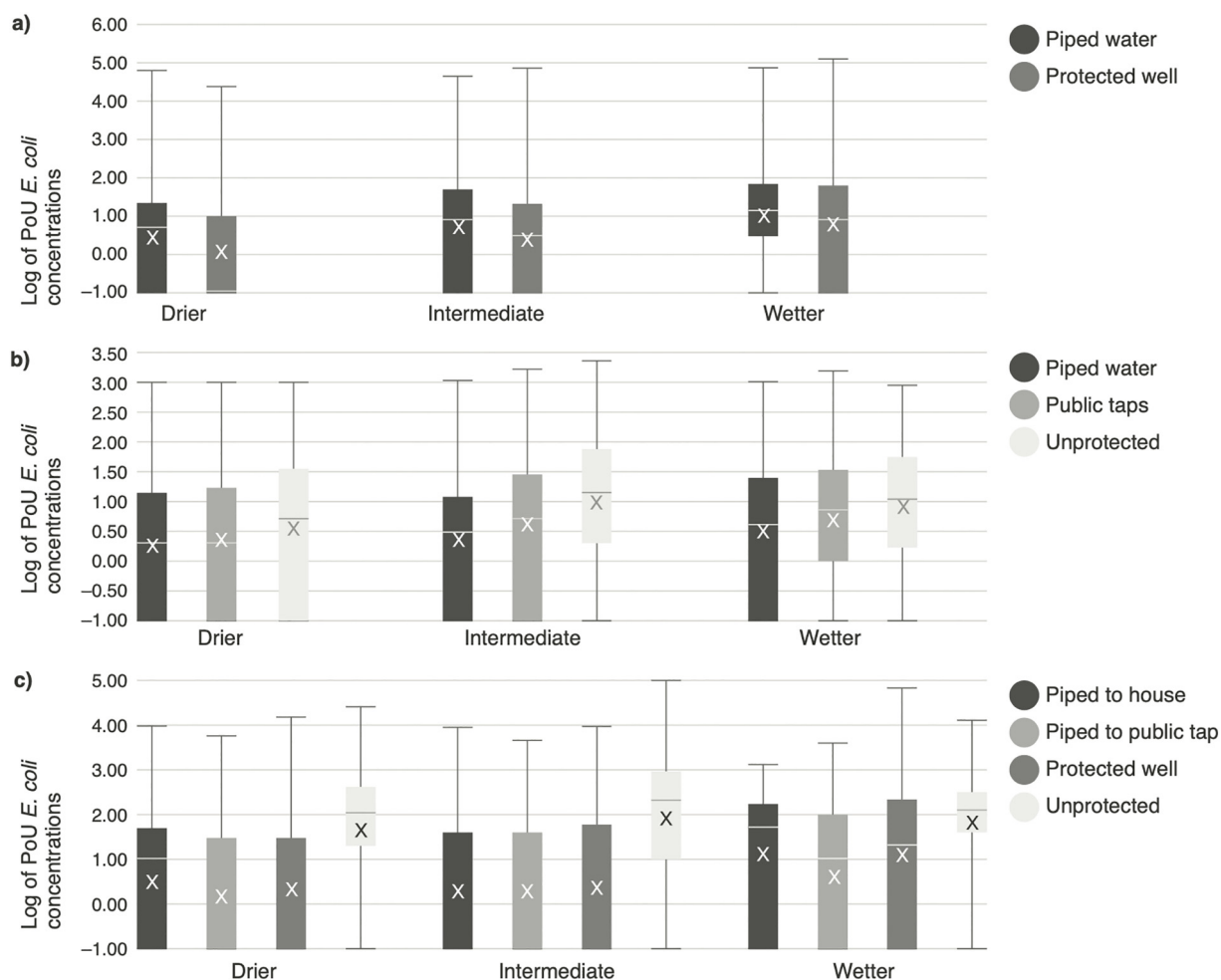


Fig. 4. PoU water quality in (a) Bangladesh, (b) Nepal and (c) Tanzania for drier, intermediate and wetter periods.

unprotected sources as well. At site 3, there were more correlations with temperature than with precipitation, and negative correlations with minimum temperature as well as maximum temperatures.

For Bangladesh and Nepal, where direct comparisons could be drawn between PoC and PoU water quality, PoC water quality was an important predictor of PoU water quality. In Bangladesh, a strongly significant correlation between PoC and PoU water quality was observed (0.425, $p < 0.001$) that remained consistent across sites, rounds and source types. In Nepal, a strongly significant correlation was also observed, but PoC water quality explained less of the variability in PoU water quality (0.137, $p < 0.001$); piped on-premises water sources had a closer relationship to PoU water quality than public water points, while unprotected sources did not have a significant relationship to PoU water quality.

In Bangladesh and Nepal, where PoC water quality could be included in GEE models, it was again an important predictor of PoU water quality. In Bangladesh, in contrast to the PoC water quality, the PoU water quality was most strongly influenced by the minimum temperature. In Nepal, key variables were precipitation and interactions of precipitation with minimum temperature and antecedent dry period. In Tanzania, where source water quality was not included in the model only source type, interactions terms between rainfall, minimum temperature and maximum temperature influenced PoU water quality, as well as periods of heavy rainfall and dry spells, suggesting that rainfall in the hotter period impacted water quality differently to rainfall in a cooler period.

While PoU water quality was worse than PoC water quality overall, this was not the case on all rounds at all sites. The proportion of PoU and PoC samples with no *E. coli* detected were compared by site and round

(Fig. 5). The difference between PoU and PoC water quality ranged between an average of 4% and 39% at different sites, while the seasonal variability was higher, ranging from 14% to 47% for PoC and 14% to 21% for PoU. It is notable that at some sites in Nepal and Tanzania, for some rounds, PoU water quality was comparable to or better than PoC water quality. Overall, the difference in risk was higher between rounds, than between PoC to PoU.

3.3. Sanitary inspections

Sanitary inspections were carried out in Bangladesh on a regular basis, with scores varying between visits. Overall, risk ratings based on sanitary inspection were correlated with piped water quality, such that an increase in the risk was significantly positively correlated with an increase in the \log_{10} *E. coli* concentration at PoC ($p < 0.001$) and PoU water quality ($p < 0.001$). However, for protected wells, there was a significant negative correlation ($p < 0.001$) at PoC, such that an increase in sanitary inspection risk was associated with a decrease in \log_{10} *E. coli* concentration. For protected wells, at site 2 which was drought prone, sanitary risk scores did improve the fit of the GEE model (based on QIC) with rainfall included (the relationship didn't hold at site 1 which was flood prone). Sanitary inspections scores indicated greater hazard in wet weather.

3.4. Extreme weather events

Extreme weather events occurred during the sampling visits, and were frequently associated with deterioration of water quality at PoC and PoU

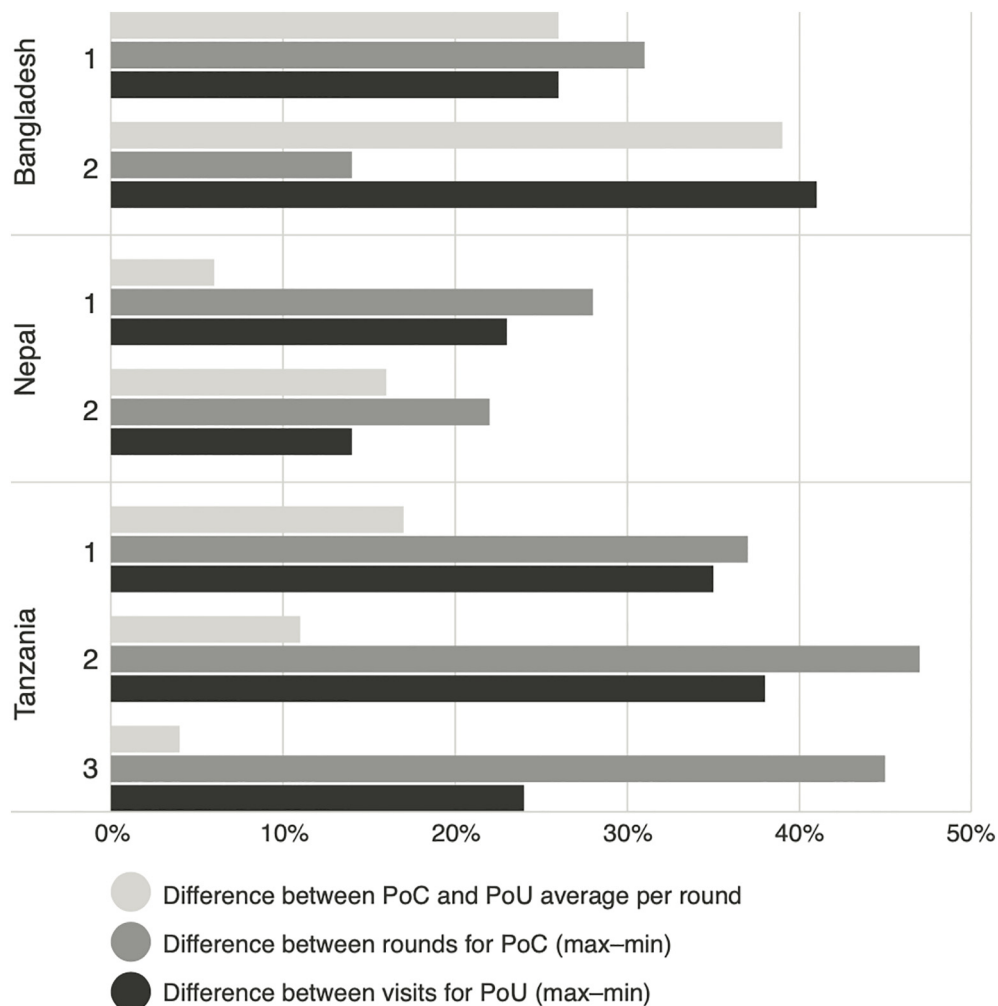


Fig. 5. Absolute difference in the percent of PoC or PoU samples with safe drinking water (no *E. coli* detected in 100 mL) between PoC and PoU, and between visits for each.

Table 2

Occurrence of extreme events over the sampling periods, including daily precipitation and maximum temperature above the 90th, 95th and 99th percentiles, and minimum temperature under the 10th, 5th and 1st percentiles. Number of rounds with extreme events occurring during the sampling periods. A continuous variable of number of days of an extreme event over the sampling period was included in the GEE models for water quality at source and PoU, which improved model fits for water at the PoC (*) water quality at the PoU (+).

Country	Site	Rounds	Maximum temperatures			Minimum temperatures			Daily precipitation		
			90 th	95 th	99 th	10 th	5 th	1 st	90 th	95 th	99 th
Bangladesh	1	14	6 ⁺	3	0	4* ⁺	2* ⁺	1* ⁺	10* ⁺	7* ⁺	4* ⁺
	2	15	6	1	0	3 ⁺	1 ⁺	1 ⁺	10* ⁺	8* ⁺	3 ⁺
Nepal	1	8	0	0	0	4*	2*	1*	3* ⁺	3* ⁺	2* ⁺
	2	8	2*	2*	0	2*	1*	1*	3*	1* ⁺	0
Tanzania	1	8	2 ⁺	0	0	1	1	0	6	3* ⁺	3 ⁺
	2	9	4 ⁺	3 ⁺	2 ⁺	1 ⁺	0	0	5	2	3
	3	9	0	0	0	1 ⁺	0	0	3*	1*	2*

(Table 2). Heavy rainfall was associated with increases in *E. coli* contamination across all sites, but temperature extremes influenced water quality in different ways. In Bangladesh, in the flood prone site 1, minimum temperatures and rainfall improved the GEE models for PoC and PoU (accounting for changes in PoC water quality); higher minimum temperatures and higher rainfall were associated with poorer water quality. In contrast, in the drought prone site 2, there was a similar relationship for PoC but only minimum temperatures affected PoU water quality. In Nepal, where minimum temperatures drop below freezing, minimum temperatures improved the GEE model at the PoC, but not the PoU, with higher minimum temperatures associated with poorer water quality; weather extremes had more impact on PoC than PoU water quality. In Tanzania, at site 2, maximum temperature extremes were associated with better water quality. While the sampling design aimed to capture variability, some weather events made it impossible to sample, restricting the representativeness of the dataset, for example, flooding limiting access to sampling sites in Bangladesh and some water sources were unavailable in the drier periods in Tanzania.

3.5. Management

Weather does not just impact microbial water quality directly, but is mediated through how water is managed. In this research, management included actions and behaviours as reported by respondents. These included management at a local level, such as source protection for local

Table 3

Correlations of management variables with weather (average precipitation, maximum temperature and minimum temperature) and water quality at PoU. All variables improved the GEE model while those with a + were significant in GEE model including source type, PoC water quality and weather variables. Two-tailed correlations * significant at $p < 0.05$, ** significant at $p < 0.01$.

Country	Category	Variable	Average precipitation	Maximum temperature	Minimum temperature	Log ₁₀ <i>E. coli</i> at POU
Bangladesh	Storage	Use of storage ⁺	-0.056**	0.026**	-0.163**	0.010
		Clean container before collecting water	0.096**	0.101**	0.106**	0.015
	Treatment	Treat their drinking water ⁺	-0.101**	-0.118**	-0.074**	-0.031**
		Monthly spend on safe water	-0.151**	-0.120**	-0.101**	0.22*
	Hygiene	Cleanliness of surrounding environment ⁺	0.041**	-0.017	0.028**	0.058**
		Observed handwashing	-0.071**	-0.01	-0.099**	-0.033**
Nepal	Collection	Source cleaned in past week	0.109**	-0.045**	0.103**	-0.048**
		Leakage in pipeline in past week	0.088**	-0.060**	0.099**	0.045**
	Storage	Storage is uncovered ⁺	0.081**	-0.044**	0.089**	0.088**
		Storage is cleaned	0.059**	-0.086**	-0.017	0.033**
	Treatment	Water is treated	0.028*	-0.195**	-0.014	-0.028*
	Hygiene	Observed clean hands ⁺	0.001	-0.007	-0.043**	0.063**
Tanzania	Collection	Source has enough water	0.046**	-0.051**	-0.172**	-0.002
	Storage	Covered storage	0.176**	-0.010	0.278**	0.046**
	Treatment	Water is treated	-0.025	0.004	-0.031	-0.0002

water sources, to decisions by the individual that would indirectly or directly influence water quality, such as decisions to practice household treatment or to wash their hands. The water quality outcomes can be in part attributed to decisions made about sources, treatment, and storage (Table 3). For Bangladesh, in wetter weather, people were more likely to clean the container before collection and the local environment was observed to be cleaner, while in drier weather people were more likely to store water, treat their drinking water, spend money on water, and have been observed washing their hands properly. While all management variables improved the PoU water quality model (in addition to source, PoC water quality and weather) the strongest were the cleanliness of surrounding environment (cleaner environment associated with cleaner water), and the interaction between storage and treatment. Where treatment was reported to be practiced, it was associated with better water quality, while storage (>95% in a covered container) was associated with a deterioration in water quality. When these parameters were included in the model, the minimum temperature was still significant, highlighting a separate impact from weather on water quality outcomes.

In Nepal, during wetter periods respondents were more likely to report having had their source cleaned, and report leakage in the pipeline, use uncovered storage and clean their storage. In cold weather, respondents' hands were observed to be dirtier by the enumerators. In the GEE model, management variables further improved the model for PoU water quality that included source type, PoC water quality and weather variables. Observed cleanliness of hands (dirty hands associated with worse water quality) and covered drinking water vessel (covered associated with better water quality) had a significant impact on PoU water quality within the model. Reported treating of water did not have a significant impact on PoU water quality.

In Tanzania, fewer management variables were collected. Respondents reported that the source had enough water more commonly with increased with rainfall, and use of covered storage (in contrast to Nepal) was reported to increase with rainfall. None of the management variables improved the GEE model for PoU water quality.

One cause of changes in water quality at the POU is from use of multiple sources of varying quality. Source switching was identified across all sites (Supplementary data Table S3), and was recognised in the structure of the data collection and analysis such that a household's water source could vary. Weather-related drivers for switching were observed in some cases, such as drying of unprotected wells in Tanzania site 3, however it was not possible to include them in the analysis fully. The majority of respondents used a variety of water sources, which can result in additional contamination in water containers if sources have varying quality, as well as potentially representing an increased health risk.

4. Discussion

The results demonstrate that weather, both rainfall and temperature, significantly influences microbial water quality outcomes at the PoC and at the PoU by multiple complex mechanisms. Extreme events such as heavy rainfall and cold and hot temperatures affected water quality, however the mechanisms varied, with differences in impacts by system type, context and by management behaviours. Previous analysis of the Tanzanian dataset had demonstrated the strong relationship between rainfall and faecal contamination (Guo et al., 2021). These extreme events are becoming more common with climate change (Masson-Delmotte et al., 2021). Hence, it is important to consider how climate change will affect drinking water quality and the transmission of waterborne and water-related diseases.

There are various established mechanisms by which temperature changes could have influenced water quality. Temperatures affect the growth and survival of pathogens and bacterial indicators, such as *E. coli*. In colder temperatures, *E. coli* would be expected to survive for longer periods (Pedley et al., 2006). Conversely, in warmer weather, survival rates would decrease, however *E. coli* growth in soils are reservoirs has been observed at higher temperatures (Ashbolt et al., 1997). Temperature can also affect behaviour: handwashing decreases in colder weather, potentially increasing contamination at POU; in Nepal, a preference for drinking boiled water in cold weather was identified; and heatwaves increase water consumption which could increase ingestion of pathogens and reduce storage times. In Tanzania, hotter weather (maximum temperature) was associated with more frequent water collection in rural areas (data not shown).

Similarly, there are different mechanisms by which rainfall influences water quality. The direct processes have been outlined earlier, but changes to management were also reported. In Bangladesh, water treatment was more frequently used in the dry season, and the use of household storage was more common. The amount of money spent on water also varied with weather, decreasing in the monsoon; this may be related to source switching which has been identified elsewhere in Bangladesh (Hoque and Hope, 2019; Huhmann et al., 2019). The use of multiple water sources to ensure water needs are met, or to meet different needs for quality and quantity, is common in many low- and middle-income communities (Daly et al., 2021), meaning household water quality can be expected to vary substantially. In Nepal, cleaning of sources and storage vessels was associated with higher rainfall. To achieve safe, reliable water supply services, resilience needs to consider both infrastructure and management at the household and community level.

4.1. Environment*infrastructure

The integrity of infrastructure is important because if this is inadequate to protect against contamination during extreme events or is at risk of damage, then maintaining safe water supply becomes increasingly difficult. Whilst household water treatment has been shown to be effective in reducing water contamination and associated with reductions in disease (Clasen et al., 2015), it has proven difficult in many low and middle income countries to ensure sustained use (Waddington and Snilstveit, 2009). It is therefore risky to assume that poor resilience of infrastructure can be off-set solely through household action to treat water.

Overall, water from boreholes was generally of better quality in this study and least prone to change in relation to weather events. This is expected. By their design, boreholes are likely to provide better microbial water quality because intakes are at depth, provided rising mains are properly joined there is limited potential for contamination at shallower depths, and the headworks are relatively small and easy to maintain. Previous studies have shown that overall, boreholes are likely to be more resilient than many alternatives (Howard et al., 2010). However, this resilience will only be realised if the infrastructure is well managed, the source is protected and if there is effective groundwater management. In a critical review, Kelly et al. (2020) found that microbial contamination of boreholes

was most commonly associated with damage to well-head infrastructure. Furthermore, a number of studies have shown that widespread contamination of aquifers may occur during inundation events and this, rather than specific failures at the wellhead leads to contamination (Luby et al., 2006). Without wider management of the environment and sources of faecal pollution, such infrastructure will not therefore be resilient. In many parts of the world, the low-cost of drilling and cheap pumping is increasing groundwater abstraction. Groundwater levels are dropping leading to increasing failure in pumping. Unrestricted abstraction of this type cannot be considered resilient and urgent action is needed to invest in groundwater management.

Other types of infrastructure included in this study (dug-wells and springs) tend to use shallower groundwater and less sophisticated construction. As a consequence, they demonstrate problems with contamination that have been found with dug wells and springs in other studies, where failures in sanitary integrity have been identified as a key cause of failure (Godfrey et al., 2006; Howard et al., 2003). These types of system tend to react more rapidly to rainfall and with more limited infiltration, there is limited potential for the attenuation of contamination. The resilience of such supplies can be improved through improved designs, particularly the use of better filter packs around intakes, but as noted by Howard et al. (2010) they remain vulnerable to the effects of climate.

The poor water quality from piped systems reflects the literature more broadly (Bangladesh Bureau of Statistics and UNICEF Bangladesh, 2021; Payment and Robertson, 2004). The sources of contamination could include poor source water quality, ingress into pipes, associated with breakages or illegal connections, or sloughing of biofilms within the pipes. Piped water systems have to adapt to ensure resilience, as evidenced recent droughts in Cape Town and Sao Paulo (Muller, 2018), and numerous out-breaks associated with heavy rainfall events (Hrudey and Hrudey, 2019). New design standards will be required as average recurrence intervals decrease. Maintaining pipe systems is relatively straightforward, but demands skilled plumbers, regular inspection and adequate finance. Source protection can be more complex to maintain due to the increasing sources of pollution from development with low rates of wastewater treatment. While this paper has focused on faecal contamination, chemical water quality will also vary with climate. For large piped systems using surface water, longer periods with less rainfall to dilute chemical contamination, such as from industrial effluents, may create challenges for existing treatment systems.

4.2. Environment*management

In all water supplies, management is critical for both the infrastructure and in households to maintain safe and resilient supplies (Howard et al., 2016; Howard et al., 2010). The strong association of PoU contamination with climate variables in this study suggests that at present such resilience is not being built. This in part can be due to a lack of awareness of the mechanisms whereby weather impacts on water safety, such as through impacts on source water quality and on management behaviours. This study demonstrates a number of different modes by which weather influences management of water supplies, with impacts on water quality. The deterioration of water quality from the source to the household is argued to not increase exposure pathways (VanDerslice and Briscoe, 1993), although health impacts have been demonstrated (Ercumen et al., 2015). The use of water treatment and, as importantly, safe storage by households may be an important way to build resilience to manage short-term disruptions to water quality, supporting households to manage the risks from extreme events. However, the nature of extreme events may impact the availability of time, labour, parts and money required to sustain safe water treatment and storage. The evidence from Bangladesh, with increased treatment in the dry season, suggests that people may practice water treatment in response to perceived risks that may not coincide with increased water quality risks. Whilst it is clear relying solely on household action to reduce contamination is unlikely to result in greater resilience, there is little doubt that there needs to be ongoing investment to support households

take action until such time as they receive safe piped water delivered to their homes by well-resourced and managed utilities.

Understanding these interactions between the environment, infrastructure and management can help to inform development of more climate resilient water services and inform how to measure climate resilience and water security in drinking water supplies (Howard et al., 2021).

4.3. Limitations

This study is the first multi-country study to track the impact of weather variables on performance of water systems. This deeper understanding of the seasonal variability and impact of extreme events on water quality has helped to inform analysis of the Bangladesh national water quality data, highlighting the lack of climate resilience in water systems at a national scale (Charles and Greggio, 2021), and is informing on-going development and implementation of climate-resilience water safety plans. It is imperative that weather events are considered in studies of WASH performance. However, there were limitations and challenges in this study that future studies could address.

Aligning weather information to data collected on WASH is difficult. Local weather data was not always sufficient; weather stations should be embedded in national meteorological offices to ensure reliability and maintenance however this is not always possible on research timescales creating unreliable data. In this study, where local data was not sufficient, international databases such as CHIRPS were used, which are known to underrepresent local extremes. The difficulty accessing weather data highlights the challenge of building climate resilience in the water sector (Murgatroyd et al., 2021). Furthermore, it is critical to recognise the variability in source use so that water sources aren't excluded based on baseline conditions. However, weather events will still prevent data collection at times such as flooding reducing physical access.

Studies that include multiple contexts, including internationally, offer a richer understanding of vulnerability and resilience to future climate change as the impact of weather events on WASH is relative to the local climate. However, they also present challenges for comparisons. In this study, research teams adapted the surveys for their own contexts, increasing validity locally but decreasing the opportunity for direct comparisons. Core questions help to address this, but even well-established questions from SDG monitoring methodologies pose problems, for example the differences in 'piped water' systems between countries and contexts, from small unmanaged piped systems to large utility systems.

While this study has focused on *E. coli* as the measure of water safety, future studies should consider analysis of pathogens to allow an assessment of variation in public health risks with weather events. Future studies should also consider including electrical conductivity as a proxy for salinity based on fluctuation with rainfall and from extreme events such as coastal storm surges, and variability in contaminants (chloride, nitrate, arsenic, fluoride, and more) between water sources where people rely on more marginal water sources during the drier periods.

5. Conclusion

Climate change threatens the Sustainable Development Goal (SDG 6.1) of achieving universal access to safe drinking water. Climate resilient water supplies are needed that provide access to drinking water, that is sustained through seasons and through extreme events, and where the safety of water quality is also sustained. The novel sampling design, based on observational field studies in seven sites across three countries, enabled a focus on water quality outcomes, triangulating the impact of weather and environmental factors with infrastructure and management. This research highlighted a diverse range of mechanisms by which weather impacts on water quality, and the potential ways in which climate change will affect water quality. However, there were limitations in implementing the study design and accessing required data across the study sites which affected the comparability of analyses.

The results demonstrate that, to ensure climate resilience for water supplies, consideration of infrastructure and management decisions, at both community and household level, are essential. The role of the lay water managers in small and community water supplies, including managers within the household, who make decisions about sourcing water, payments for water and maintenance, cleaning sources and storage equipment, and treating water, needs to be considered and better understood to improve resilience. The impacts of weather on water quality vary by local climate and context, highlighting the complexity of understanding the impact of climate change on water quality and health. This analysis demonstrates the importance of including weather variables in analysis of water quality and WASH studies more broadly to adequately understand variability in efficiency of interventions.

CRedit authorship contribution statement

Katrina J. Charles: Methodology, Formal analysis, Writing – original draft. **Guy Howard:** Conceptualization, Writing – review & editing. **Elena Villalobos Prats:** Project administration, Writing – review & editing. **Joshua Gruber:** Supervision, Writing – review & editing. **Sadekul Alam:** Investigation. **A.S.M. Alamgir:** Investigation. **Manish Baidya:** Resources, Supervision. **Meerjady Sabrina Flora:** Supervision. **Farhana Haque:** Investigation. **S.M. Quamrul Hassan:** Resources. **Saiful Islam:** Investigation. **Alfred Lazaro:** Investigation. **Dickson Wilson Lwetoijera:** Investigation. **S.G. Mahmud:** Resources, Supervision. **Zahid Hayat Mahmud:** Investigation. **Fatuma Matwewe:** Investigation. **Kamal Pasa:** Investigation. **Mahmudur Rahman:** Investigation. **Ashok Ahammed Shahid Reza:** Investigation. **M. Selimuzzaman:** Supervision. **Ahmed Raihan Sharif:** Investigation. **Subodh Sharma:** Supervision. **Jacqueline Marie Thomas:** Investigation. **Diarmid Campbell-Lendrum:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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