Journal of Water & Health

IWA PUBLISHING

Journal of Water and Health Vol 20 No 4, 589 doi: 10.2166/wh.2022.199

Climate variability, water supply, sanitation and diarrhea among children under five in Sub-Saharan Africa: a multilevel analysis

Donald Njatang Kemajou

University of Yaounde II-IFORD, Yaounde, Cameroon
E-mail: njatangkemajou@yahoo.fr

DNK, 0000-0002-5792-1826

ABSTRACT

Climate variability is expected to increase the risk of diarrhea diseases, a leading cause of child mortality and morbidity in Sub-Saharan Africa (SSA). The risk of diarrhea is more acute when populations have poor access to improved water and sanitation. This study seeks to determine individual and joint effects of climate variation, water supply and sanitation on the occurrence of diarrhea among children under five in SSA using multilevel mixed-effect Poisson regression including cross-level interaction. We merged 57 Demographic and Health Surveys (DHS) from 25 SSA countries covering the period 2000–2019 with climatic data from the DHS geolocation databases. The results of the research indicate that 77.7% of the variation in the occurrence of diarrhea in Sub-Saharan households is due to climatic differences between clusters. Also, a household residing in a cluster with a high incidence of diarrhea is 1.567 times more likely to have diarrhea cases than a household from a cluster with a low incidence. In addition, when average temperature and rainfall increase, households using unimproved sanitation or unimproved water have more cases of diarrhea. For SSA, the results of the multilevel analysis suggest the adoption at both levels; macro (national) and micro (household), of climate change adaption measures in the water sector to reduce the prevalence of diarrhea.

Key words: climate variability, diarrhea, multilevel model, sanitation, water supply

HIGHLIGHTS

- Diarrhea remains the second driving causes of under-five years old children's mortality in developing countries.
- 77% of the variation in the occurrence of diarrhea is due to climatic differences in SSA countries.
- Increases in average rainfall and average temperatures lead to an increase in the occurrence of diarrhea in households using unimproved sanitation facilities or unimproved water.

1. INTRODUCTION

Sub-Saharan Africa (SSA) has been identified as the region of the world most vulnerable to the effects of climate change (Ramin 2009; IPCC 2014). According to the Intergovernmental Panel on Climate Change (2014), climate variability in recent decades has already led to profound changes in natural systems, including increased droughts and floods. Also, variations in temperature and precipitation influence the breeding cycle of vectors of arboviruses and waterborne diseases that cause diarrhea in children (Ramin 2009; Mordecai *et al.* 2020; WHO 2020). Stanke *et al.* (2013), Nataro & Guerrant (2017) and Kotloff *et al.* (2019) report that diarrhea has negative consequences on children's growth, cognitive development and metabolism. Diarrhea remains the second driving cause of mortality for children under five in developing countries (Khan & Bhutta 2017). It is responsible for the death of approximately 525,000 children every year with most of them occurring in African countries (Reiner *et al.* 2018).

Children are more exposed than adults to extreme weather events around the world (Xu *et al.* 2012; Akresh 2016; Larr & Neidell 2016). Moreover, compared to children in rich countries, those from poor countries are the most affected (Hanna & Oliva 2016). The consequences of extreme weather events on children's health are the critical health issues in African countries (Schulte-Uebbing *et al.* 2015; Opoku *et al.* 2021). For example, in Southern Africa following Cyclones Idai and

---

Kenneth in April 2019, Mozambique recorded an increase in cholera cases among children in Cabo Delgado, Pemba, Mecufi and Sofala; and Zimbabwe counted nearly 2.3 million people with signs of severe malnutrition (USAID 2019).

The effects of climate change on a population's health is rarely direct, but depends on a set of contextual factors that reinforce its impact on pre-existing situations of vulnerability (UNECA 2011; IPCC 2014). Among these factors, lack of access to safe water and quality sanitation facilities increases the risk of exposure to waterborne diseases (Alemayehu *et al.* 2020; Voth-Gaeddert *et al.* 2020). In 2020, although many developed regions have achieved the UN Millennium Development Goals (MDGs) related to water and sanitation, 48 less developed countries, particularly those in SSA, still fare poorly in this area with almost 113 and 108 million people, respectively, using unimproved water source and facilities (World Health Organization & UNICEF 2021). In places where people use unimproved sanitations such as flush toilets that do not drain into a sewer system, pit latrines without slabs and the practice of open defecation, surface runoff from heavy rainfall carries feces to unprotected water sources that people use (Medina *et al.* 2007; Bhavnani *et al.* 2014; Bhandari *et al.* 2020a, 2020b; Holcomb *et al.* 2020). Human feces is the primary source of diarrhea pathogens (Khan & Bhutta 2017). Drinking or using water from these sources increases the risk of diarrhea if not treated first (Carlton *et al.* 2014; Wolf *et al.* 2018).

The risk of diarrhea increases under certain temperature conditions. Changes in ambient temperature may alter the distribution, survival and virulence of diarrhea pathogens and the patterns of transmission (Carlton *et al.* 2016). During drought, people in the southern Sahara have inadequate access to drinking water (World Health Organization & UNICEF 2021). Scarcity of water increases the risk that the remaining sources usually contaminated with diarrhea pathogens (*Escherichia coli*, *Campylobacter*, *Vibrio cholera*, *Rotavirus*, *Giardia*, *Cryptosporidium*) will be used by human beings (Stanke *et al.* 2013; Asmall *et al.* 2021). Cann *et al.* (2013) and Hofstra (2011) found that bacterial pathogens that cause diarrhea are in high concentrations in drinking water when evaporation increases as a result of rising temperatures. Similarly, high temperature leads to an extension of the life expectancy of diarrhea pathogens (in particular, bacteria and protozoa) in their zoonotic host, facilitating prolonged pathogen transmission (Lal *et al.* 2012). Also, drought increases susceptibility to diarrheal diseases, due to negative effects of drought on agricultural crops, livestock and fisheries (Stanke *et al.* 2013; Levy *et al.* 2016).

Associations between climatic conditions, sanitation, water sources and diarrhea have been studied in various countries and with different methods. Bandyopadhyay *et al.* (2012) using pseudo-panel analysis found that a 1 mm increase in rainfall reduced the prevalence of diarrhea by 3% in 14 SSA countries. They also found no relation between unimproved water and diarrhea. In the same way, Mukabutera *et al.* (2016) using multivariate logistic regression show that increased runoff was protective against diarrhea (Odd Ratio (OR) = 0.54) when household use unimproved type facilities in Rwanda. In contrast to these studies, Dunn *et al.* (2020) using spatial Poisson regression found a positive association between diarrhea and rainfall on the one hand, and a negative association between diarrhea and toilet type on the other in West Africa. Bhavnani *et al.* (2014) and Carlton *et al.* (2014) show that unimproved water source and unimproved sanitation increased the risk of diarrhea (OR = 6.8; OR = 1.38) after maximum rainfall in Ecuador. Thiam *et al.* (2019) using Bayesian conditional autoregressive models show that the unit increase in rainfall and increase in the proportion of people with untreated stored drinking water was associated with an increase in diarrhea risk by 22% in Senegal. These studies use a standard regression model with assumption that health outcomes are independent or uncorrelated for all of the individuals. Diez-Roux (2000) and Leyland & Groenewegen (2020) point out that the health outcomes of individuals who share the same context (e.g. climate, health) cannot be independent. Also, Merlo *et al.* (2005) noted that individuals with similar characteristics who live in different contexts may have different health statuses. When the independence assumption is not satisfied, analysis using standard regression methods underestimates the standard errors and gives biased results (Merlo *et al.* 2005; Leyland & Groenewegen 2020).

The previous studies, by confusing the macro level in which individuals are nested and interact with the micro level, may lead to attributing either the macro relationships to relations at the individual level (ecological fallacy or ecological error) or the individual relationships to relations at the macro level (atomistic fallacy or atomistic error) which bias the results (Diez-Roux 2000; Leyland & Groenewegen 2020). In practice, whenever the macro and micro levels are confused when analyzing a phenomenon, information from one level is aggregated or disaggregated to obtain information from the other level. For example, Bandyopadhyay *et al*. (2012) aggregates individual DHS data to obtain regional characteristic such as per cent of children who have diarrhea, percentage of households with no toilet facilities, percentage of households with access to safe water. Dunn *et al.* (2020) and Mukabutera *et al.* (2016) disaggregate information of the household level (mother's education, mother's occupation, type of toilet) to the individual level.

Relaxing the assumption of independence, multilevel analysis (or hierarchical modeling) distinguishes the different levels of analysis of a phenomenon and leads to a better understanding of the cross-level interactions (Leyland & Groenewegen 2020). Moreover, compared to standard regression, it allows us to measure the climatic heterogeneities that exist between regions in terms of health. The existence of such heterogeneities justifies the need to implement climate mitigation and adaptation strategies adapted to each context (Nyiwul 2021). This study seeks to determine individual and joint effects of climate variation, water supply and sanitation on the occurrence of diarrhea among children under five in SSA using multilevel mixed-effect Poisson regression including cross-level interactions. To do this, we use Demography Health Survey (DHS) data from 25 SSA countries covering the period 2000–2019 and temperature and precipitation data from geolocated DHS databases. It contributes to the existing literature by providing the first attempt to explore the relationship between climate change, water, sanitation and diarrhea using multilevel analysis.

2. MATERIALS AND METHODS

2.1. Data sources

The data used in this research is derived from the fusion of individual country and climate data. The individual data comes from the DHS of 25 SSA countries carried out between 2000 and 2019, i.e. a total of 57 DHS. The criteria for selecting SSA countries in this study were: (i) the country must have climate data available under the DHS program; (ii) it must have a DHS dataset with standardized questions on drinking water sources and toilet type at the household level over the period 2000–2019. DHS are nationally representative household surveys that provide indicators in the areas of population, health and nutrition. This study uses file Kid's Recode (KR) of DHS data type that contains child health indicators such as recent occurrences of diarrhea, fever and cough for young children and treatment of childhood diseases. This file can be downloaded from https://dhsprogram.com/data/available-datasets.cfm. The climate data, in particular on rainfall and temperature, come from the geolocalized databases developed by the DHS program for each of these surveys. After merging these databases, our work covers a sample of 530,625 children under five. Table 1 presents the different DHS for which geolocated data are available per country and per year. The geolocated data are available on http://spatialdata.dhsprogram.com/covariates.

Data analysis was carried out in STATA version 14 (StataCorp; College Station, TX, USA).

2.2. Study variables

2.2.1. Household level variables

The household variables are of two types: household environment variables and household characteristics variables. The variables in the household environment are source of water supply (1. improved, 2. unimproved), type of sanitation (1. improved, 2. unimproved), which are collected at the household level in the DHS. We use the 'improved' or 'unimproved' classification scheme of WHO & UNICEF (2021) on page 100. In tropical regions, 80% of diseases are transmitted by germs in the water, or by vectors that thrive in it (Ntouda *et al.* 2013).

The variables that capture the household characteristics are the number of cases of diarrhea among children under five in the household who constitute our dependent variable (this variable is constructed from the variable h11 (diarrhea in the last 2 weeks) in DHS data, the standard of living (1. poor, 2. average, 3. rich), the place of residence of the household (1. urban, 2. rural), the sex of the head of the household (1. male, 2. female) and the average number of children per household.

2.2.2. Climatic level variables

The climate variables are GPS location data of surveyed DHS clusters. These are mean annual temperature data (units: Degrees Celsius) and mean annual rainfall level (units: millimeters per year) collected at the cluster level in each DHS in each country presented in Table 1.

2.3. Statistical methodology

The multilevel Poisson model is used when there is a hierarchical structure of the data, i.e. households (level 1) nested in clusters on which climate data are collected (level 2), and a count variable as the dependent variable (the number of diarrhea cases in households). The multilevel analysis consists in the estimation of five models. First, the null model or empty model (M0) which included only cluster-specific random effects. Estimation of model M0 allows us to see if the multilevel analysis is relevant. This is the case when the inter-group variance (σ^2) derived from the estimation of M0 is statistically different from

Table 1 | Distribution of DHS databases for the 25 SSA countries by year and type

Country	Years	DHS databases (GPS datasets available)	Number of observations
Angola	2015	DHS-VII	11,837
Benin	2012	DHS-VI	10,201
Burkina	2003, 2010	DHS-VI, DHS-IV	22,353
Burundi	2010, 2016	DHS-VII, DHS-VII	18,585
Cameroon	2004, 2011, 2018	DHS-VII, DHS-VI, DHS-IV	25,843
Ethiopia	2005, 2011, 2016	DHS-V, DHS-VI, DHS-VII	28,559
Gabon	2012	DHS-VI	4,600
Ghana	2003, 2008, 2014	DHS-VII, DHS-V, DHS-VII	10,822
Guinea	2012, 2018	DHS-VI, DHS-VII	11,850
Kenya	2003, 2008, 2014	DHS-V, DHS-VI, DHS-VII	28,346
Lesotho	2004, 2009, 2014	DHS-IV, DHS-V, DHS-VI	9,267
Malawi	2004, 2010, 2015	DHS-IV, DHS-VI, DHS-VII	40,297
Mali	2006, 2012	DHS-V, DHS-VI	21,573
Mozambique	2011, 2015	DHS-VI, DHS-VII	20,876
Namibia	2006, 2013	DHS-V, DHS-VI	8,634
Nigeria	2008, 2013, 2018	DHS-V, DHS-VI, DHS-VII	81,046
Dem Rep of Congo	2007, 2013	DHS-V, DHS-VI	23,108
Rwanda	2005, 2010, 2015	DHS-V, DHS-VI, DHS-VII	23,406
Senegal	2005, 2010, 2015	DHS-IV, DHS-VI, DHS-VII	26,051
Tanzania	2010, 2016	DHS-VI, DHS-VII	11,468
Chad	2014	DHS-VII	16,657
Togo	2013	DHS-VI	6,430
Uganda	2006, 2011, 2016	DHS-V, DHS-VI, DHS-VII	26,390
Zambia	2007, 2013, 2018	DHS-V, DHS-VI, DHS-VII	27,196
Zimbabwe	2005, 2010, 2015	DHS-V, DHS-VI, DHS-VII	15,230
Total	/	/	530,625

zero. The M0 model is written as follows:

$$\text{Model M0: } ln(\lambda_{ij}) = \beta_0 + u_{0j} + e_{0ij} \tag{1}$$

$$Y_{ij} \sim poisson(\lambda_{ij})$$

where λ_{ij} is the expected count for the ith household in the jth cluster, Y_{ij} is our dependent or response variable, $u_{0j} \sim N(0,\ \sigma^2)$ denotes the normally distributed random intercept with an expected value of zero and random effects variance (inter-group variance) of σ^2, and $e_{0ij}\tilde{N}(0,\ \sigma_e^2)$ denotes the normally distributed residuals with an expected value of zero and random effects variance of σ_e^2.

Then, the model of household level (M1) = M0 + household characteristics, the model of cluster level (M2) = M0 + climatic characteristics and the model of household and cluster level (M3) which correspond to model M1 + M2. These three models can be written as:

$$\text{Model M1: } ln(\lambda_{ij}) = X_1\beta_1 + u_{0j} + e_{0ij} \tag{2}$$

$$\text{Model M2: } ln(\lambda_{ij}) = X_2\beta_2 + u_{0j} + e_{0ij} \tag{3}$$

$$\text{Model M3: } ln(\lambda_{ij}) = X_1\beta_3 + X_2\beta_4 + u_{0j} + e_{0ij} \tag{4}$$

where X_1 is the matrix of independent or explanatory variables observed or measured at the household level (household variables), X_2 is the matrix of explanatory variables measured at the cluster level (climatic variables) and X represents the combination of X_1 and X_2. In Equations (2)–(4), β_i $i = 1, 2, 3, 4$ are the regression coefficient.

Finally, the model of household and cluster level with their interaction (M4):

$$\text{Model M4: } ln(\lambda_{ij}) = X_1\beta_3 + X_2\beta_4 + X_1X_2\beta_5 + u_{0j} + e_{0ij} \tag{5}$$

where β_5 is the regression coefficient of interaction term.

Through the estimation of these models, multilevel analysis can detect the context effect and the composition effect associated with the variability of a phenomenon through variations in the inter-group variance for each model. If the variance decreases from M0 to M1 ($\sigma^2(M0) < \sigma^2(M1)$), the differences in diarrhea occurrence between households are due to a compositional effect, i.e. differences are attributable to differences in group composition (i.e. in the characteristics of the household who make up the clusters). In contrast, if the variance decreases from M0 to M2 ($\sigma^2(M0) < \sigma^2(M2)$), the differences in diarrhea occurrence are due to a context effect, i.e. differences are attributable to differences in group characteristics (climatic characteristics).

The multilevel analysis is also based on the Variance Partition Coefficient (VPC) and the Median Rate Ratio (MRR), both measures of higher level residual heterogeneity. Goldstein *et al.* (2002) introduced the VPC to describe the percentage of variation in a dataset that is attributed to a particular level. In our study, VPC measures the proportion of the total variance in the occurrence of diarrhea attributable to climatic differences. Generally, this statistic is the ratio of the inter-group variance to the total variance.

VPC in the context of count data is given by the formula of Stryhn *et al.* (2006):

$$\text{ICC} = \text{VPC} = \frac{\exp(2\beta X + 2\sigma^2) - \exp(2\beta X + \sigma^2)}{\exp(2\beta X + 2\sigma^2) - \exp(2\beta X + \sigma^2) + \exp(\beta X + \sigma^2/2)} \tag{6}$$

where σ^2 is the inter-group variance.

MRR measures the change in the occurrence of diarrhea when comparing two identical individuals randomly selected from different groups classified according to the degree of the rate (high or low). Higher MRR indicates larger cross-country differences.

According to Rabe-Hesketh & Skrondal (2012), the MRR is calculated as follows:

$$\text{MRR} = \exp\left(\sqrt{2\sigma^2}\,\Phi^{-1}(0.75)\right) \tag{7}$$

where Φ^{-1} represents the inverse of the standard normal cumulative distribution function.

3. RESULTS

3.1. Context and composition effects

The use of multilevel analysis is relevant because inter-group variance is statistically different from 0 in the M0 model. Table 2 presents the inter-group variance, VPC and MRR of each model. The results show that 77.7% (VPC (M4) = 0.777) of the variation in the occurrence of diarrhea in Sub-Saharan households are due to climatic differences between clusters.[1] It also emerges from the MRR analysis that a household residing in a cluster with a high incidence of diarrhea among children under five is 1,567 times more likely to have diarrhea cases than a household from a cluster with a low incidence of diarrhea. Similarly, the decrease in inter-group variance between model M0 (0.424) and M1 (0.365) reflects the existence of a context

---

[1] The results of the VPC and the MRR are part of the final model (M4) which takes into account the climate variables (level 2), the household characteristics (level 1) and the interaction between the two levels.

Table 2 | Inter-group variance, VPC and MRR of diarrhea models

	M0	M1	M2	M3	M4
Inter-group variance	0.424	0.365	0.302	0.315	0.222
VPC	0.395	0.475	0.412	0.559	0.777
MRR	1.861	1.779	1.689	1.708	1.567

MRR, Median Rate Ratio; VPC, Variance Partitioning Coefficient.

effect. In addition, there is a composition effect (decrease in inter-group variance between model M0 and M2, $0.424 < 0.302$). Thus, the variation in the occurrence of diarrhea between cluster is due to differences in household characteristics (composition effect) but also to differences in climate (context effect).

3.2. Individual effects of climate and households variables

The results in Table 3 show that the increase in mean temperature of 1 °C results in the increase of the incidence rate (IRR) of diarrhea of 6.7% in Sub-Saharan households (IRR = 1.067, $p < 0.001$), while a 1 mm increase in rainfall results in a 0.6% increase in incidence rate (IRR = 1.006, $p < 0.001$). The results show that in model M2, the type of sanitation influences the occurrence of diarrhea in households where water supply is not significant. However, after the introduction of the climate and inter-action variables in model M4, not only does the water supply variable becomes significant but there is also an increase in the effect of the climate variables between M1 and M4. Household environment variables mediate the effect of climate variations on the occurrence of diarrhea. Table 3 shows that the incidence rate of diarrhea in poor and middle-income households is respectively 1.21 (IRR = 1.21, $p < 0.001$) and 1.12 (IRR = 1.12, $p < 0.001$) times greater than that of rich households. Similarly, the incidence rate of diarrhea in rural households is 1.049 (IRR = 1.049, $p < 0.001$) times higher than in urban households.

3.3. Interaction effect between climate variable, water and sanitation

The previous table shows that the interaction between the climatic variables (level 2) and the household level variables (level 1) is statistically significant (IRR = 1.013, 1.000, 1.001, $p < 0.001$). Since it is not easy to interpret the Incidence Rate Ratio (IRR) of these interaction variables, the analysis of the results is based on the analysis of the marginal plot from the estimation of the interaction model (Figure 1). Thus, Figure 1 shows that the combined effect of average rainfall and average temperature on the occurrence of diarrhea in children under five varies according to the type of sanitation and the source of water supply used by the household. Thus, as the average rainfall and temperature increases, households using unimproved sanitation or unimproved water have more cases of diarrhea than those using improved sanitation or improved water. Specifically, when the temperature is between 15 and 25 °C and is associated with increased rainfall, the occurrence of diarrhea in households using unimproved sanitation or unimproved water increases, while it decreases in households using improved sanitation or improved water. In contrast, an average temperature of 30 °C combined with increased rainfall results in an overall decrease in the occurrence of diarrhea in households (regardless of type of sanitation or water source).

4. DISCUSSION

The results of the multilevel Poisson regression model obtained in our study show that there are climatic heterogeneities in SSA countries. It is estimated that 77.7% of the variation in occurrence of diarrhea among children under five in households are due to climatic differences. Moreover, the results show that climatic variables have a positive effect on the occurrence of diarrhea in children, which is in line with the findings in the studies of Musengimana *et al.* (2016), Azage *et al.* (2017), Abu & Codjoe (2018) and Alemayehu *et al.* (2020) and contradicts to the work of Bandyopadhyay *et al.* (2012) and Mukabutera *et al.* (2016) which found that rainfall has a negative effect on the prevalence of diarrhea. In our study, the positive and significant effect of rainfall on the occurrence of diarrhea in Sub-Saharan African countries can be explained by the fact that, in countries in the region where a large part of the population practice open defecation (22%), use flush toilets that do not drain into a sewer system or pit latrines without slabs and use unimproved water (World Health Organization & UNICEF 2021), heavy rainfall results in surface water runoff that carries feces materials to the unprotected water sources (boreholes and wells) that people use (Wilby *et al.* 2005; Gray 2014; Bhandari *et al.* 2020a, 2020b). According to some studies, runoff water contains waterborne diseases including *Rotavirus* (Koroglu *et al.* 2011), *Cryptosporidiosis* and *Giardiasis* (Lane &

Table 3 | Incidence Rate Ratio estimates of multilevel Poisson mixed-effects models including interaction between levels

Diarrhea cases	**M0**	**M1**	**M2**	**M3**	**M4**
Climate level variables					
Mean temperature		1.027***		1.025***	1.067***
Mean rainfall		0.999***		0.999***	1.006***
Household level variables					
Type of sanitation					
Unimproved			1.131***	1.147***	0.689***
Improved			Ref	Ref	Ref
Water supply					
Unimproved			1.007^{ns}	0.982^{ns}	0.932**
Improved			Ref	Ref	Ref
Standard living					
Poor			1.230***	1.209***	1.213***
Middle			1.128***	1.121***	1.120***
Rich			Ref	Ref	Ref
Sex of household head					
Male			1.075***	1.050***	1.049***
Female			Ref	Ref	Ref
Type place of residence					
Rural			1.024^{ns}	1.053***	1.049***
Urban			Ref	Ref	Ref
Total children ever born			1.017***	1.014***	1.013***
Variable interactions					
Mean prep # mean temperature					1.000***
Safe water # mean rainfall					Ref
Unsafe water # mean rainfall					1.001**
Improved # mean rainfall					Ref
Unimproved # mean rainfall					1.006***
Observations	530,625	530,625	530,625	530,625	530,625
AIC	749,467.0	747,475.4	746,898.1	745,350.8	744,520.0
Log lik.	−374,731.5	−373,732.7	−373,440.0	−372,663.4	−372,245.0
Chi-squared		309.5	514.2	716.3	885.9

Exponentiated coefficients $^{ns}p < 1$, $*p < 0.10$, $**p < 0.05$, $***p < 0.01$.

Lloyd 2002; Baldursson & Karanis 2011) *Campylobacter* and *Escherichia coli* (Strauch 2011); all of which are responsible for episodes of diarrhea in children. Drinking unimproved water is one of the factors responsible for diarrhea in children.

Another finding in this study is the significant and positive impact of temperature (between 15 and 25 °C) on the occurrence of diarrhea in households using unimproved water or unimproved sanitation. This is also in line with the studies of Bandyopadhyay *et al.* (2012), Chou *et al.* (2010), Mukabutera *et al.* (2016) and Azage *et al.* (2017). This can be explained by the fact that high temperature is associated with rapid multiplication and survival of diarrhea pathogens for longer periods (Lal *et al.* 2012; Carlton *et al.* 2016). Hoque *et al.* (2006) and Levy *et al.* (2016) note that warm climatic conditions lead to temporal changes in human behavior, such as higher water consumption, use of unimproved drinking water and less hygienic practices due to water scarcity. Moreover in SSA, the most severe cases of diarrhea in children are caused by the *Rotavirus*, *Campylobacter*, *Cryptosporidium* spp., *Escherichia coli* and *Shigella* spp. (Galloway & Cohen 2021). *Campylobacter* in unimproved water proliferates at ambient temperatures between 5 and 28 °C (Oberheim *et al.* 2020) while *Rotavirus* is present in high

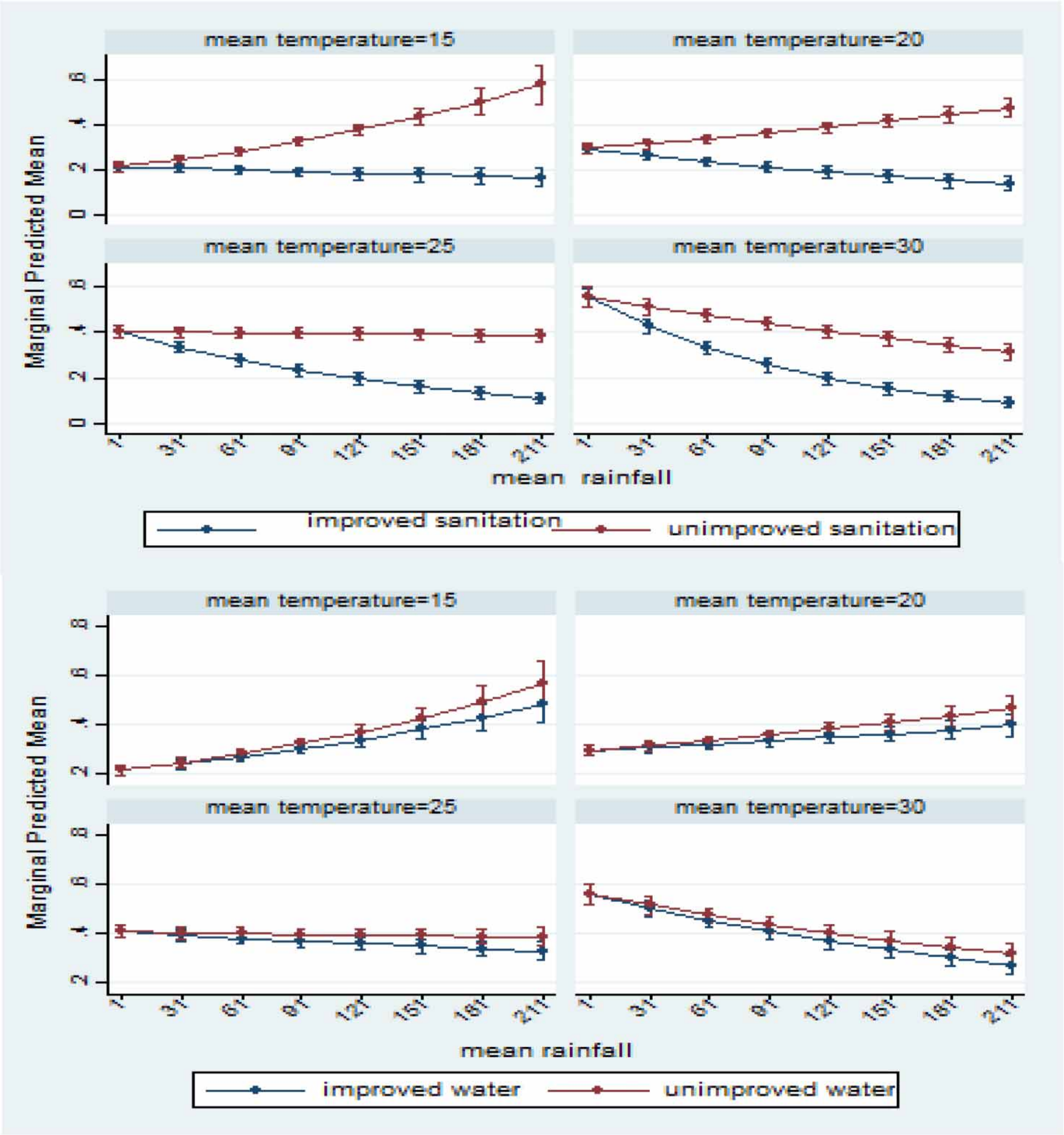

Figure 1 | Differential effects of the interaction between climate variables, water and sanitation on the occurrence of diarrhea in households. *Source*: Author.

concentrations at 18 °C (Barril *et al.* 2015) which explains why at these temperature conditions, the prevalence and incidence of diarrhea increases. On an additional note, our findings on the decrease in the occurrence of diarrhea in children in SSA for a temperature of 30 °C is in line with the results obtained by Rice & Johnson (2000), Obiri-Danso *et al.* (2001), van Gaalen *et al.* (2017) and Bhandari *et al.* (2020a, 2020b). The latter shows that bacteria (*Campylobacter*, *E. coli*, *Shigella*), protozoa (*Gardia*, *Cryptosporidium*) and viruses (*Rotavirus*) that cause diarrheal diseases are inactive at higher temperatures (more than 30 °C), resulting in fewer cases of diarrhea. This suggests that higher temperatures play an important role in regulating diarrhea cases through less viral transmission.

People's vulnerability to climate change depends on their standard of living. In this study, household poverty is a factor that increases the incidence ratio of diarrhea in children under five. Fagbamigbe *et al.* (2021), Novignon & Nonvignon (2012) and Yusuf *et al.* (2010) reveal that in low- and middle-income countries the prevalence of diarrhea is higher among children from poor households than among those from non-poor households. Moreover, Shiras *et al.* (2018) and Simiyu *et al.* (2017) show that in many low-income countries, poor households often share sanitation facilities, circumstances that increase the risk of diarrhea.

Our results suggest that efforts must be made at the macro and micro levels to achieve Sustainable Development Goal (SDG) 6 which specifies that access to safe drinking water and sanitation must be guaranteed for all within 10 years, in order to mitigate the effects of climate change on health in SSA. Indeed, we have shown that fluctuations in temperature and rainfall in an unsanitary environment contribute to a more rapid increase in diarrhea cases in households. This implies that adaptation to climate change in the water sector will be an appropriate response to control the occurrence of diarrheal diseases. In Africa, the water sector is the second most vulnerable sector to the effects of climate change, behind the agricultural sector (Nyiwul 2019). The most common adaptation strategies can be summarized as follows: storage (groundwater recharge dams or reservoirs and subsurface dams, conservation ponds and reservoirs), reutilization and community-based water resource management (IPCC 2014; Nyiwul 2019). In addition, investment in flood protection technologies is another aspect on which SSA must focus on in order to adapt to climate change (Calzadilla *et al.* 2013).

5. LIMITATIONS AND PERSPECTIVES

Certain limitations regarding data analysis should be mentioned. The study reveals a selection bias problem due to the constitution of our country's sample which is conditioned by the availability of DHS data over the period 2000–2019. It is difficult to overcome such a bias in the statistical analysis of survey data collected at the regional or sub-regional level. The main way to reduce this bias would be to have panel data on a large sample of SSA countries, although in practice such data are difficult to obtain. Also, our estimates do not include random effects such as the influence of water quality on diarrhea occurrence which may vary from one context to another. These influences could be caused by the presence of unobservable heterogeneity such as household knowledge of water purification methods. Thus, future studies could opt for an estimation method that captures such effects in order to better appreciate the relationship between climate change and diarrhea occurrence. These studies could also incorporate into their model variables on climate change adaptation strategies in the water sector.

6. CONCLUSION

Water supply and sanitation mediate the effect of climatic variations on the prevalence of diarrhea. This study highlights the need for a multilevel analysis of the diarrhea phenomenon in SSA by splitting the micro level (or individual level) and the macro level (or contextual level) to avoid atomistic fallacy, ecological fallacy that biases the results. We found that variations in the occurrence of diarrhea are due to climatic differences (context effect). Furthermore, we found that there was a positive association between temperature, rainfall and occurrence of diarrhea when households used unimproved water and unimproved sanitation. These results highlight the need to adopt climate change adaptation strategies in the water sector both at the macro (national policies) and micro (household) levels in order to reduce the occurrence of diarrheal diseases within households. At the macro level, this means protecting water sources from flooding or surface water, increasing people's access to water and improved sanitation facilities. At the micro (household) level, this involves training individuals in non-potable water treatment methods such as chlorination and filtration and in hygiene practices.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories (https://dhsprogram.com/data/available-datasets.cfm and https://spatialdata.dhsprogram.com/covariates/).

REFERENCES

Abu, M. & Codjoe, S. N. A. 2018 Experience and future perceived risk of floods and diarrheal disease in urban poor communities in Accra, Ghana. *International Journal of Environmental Research and Public Health* **15** (12), 2830. https://doi.org/10.3390/ijerph15122830.

Akresh, R. 2016 Climate change, conflict, and children. *The Future of Children* **26** (1), 51–71.

Alemayehu, B., Ayele, B. T., Melak, F. & Ambelu, A. 2020 Exploring the association between childhood diarrhea and meteorological factors in Southwestern Ethiopia. *Science of The Total Environment* **741**, 140189.

Asmall, T., Abrams, A., Röösli, M., Cissé, G., Carden, K. & Dalvie, M. A. 2021 The adverse health effects associated with drought in Africa. *Science of The Total Environment* **793**, 148500.

Azage, M., Kumie, A., Worku, A. C., Bagtzoglou, A. & Anagnostou, E. 2017 Effect of climatic variability on childhood diarrhea and its high risk periods in northwestern parts of Ethiopia. *PloS One* **12** (10), e0186933. https://doi.org/10.1371/journal.pone.0186933.

Baldursson, S. & Karanis, P. 2011 Waterborne transmission of protozoan parasites: review of worldwide outbreaks – an update 2004–2010. *Water Research* **45** (20), 6603–6614.

Bandyopadhyay, S., Kanji, S. & Wang, L. 2012 The impact of rainfall and temperature variation on diarrheal prevalence in Sub-Saharan Africa. *Applied Geography* **33**, 63–72.

Barril, P. A., Fumian, T. M., Prez, V. E., Gil, P. I., Martínez, L. C., Giordano, M. O., Masachessi, G., Isa, M. B., Ferreyra, L. J., Ré, V. E., Miagostovich, M., Pavan, J. V. & Nates, S. V. 2015 Rotavirus seasonality in urban sewage from Argentina: effect of meteorological variables on the viral load and the genetic diversity. *Environmental Research* **138**, 409–415.

Bhandari, D., Bi, P., Dhimal, M., Sherchand, J. B. & Hanson-Easey, S. 2020a Non-linear effect of temperature variation on childhood rotavirus infection: a time series study from Kathmandu, Nepal. *Science of The Total Environment* **748**, 141376.

Bhandari, D., Bi, P., Sherchand, J. B., Dhimal, M. & Hanson-Easey, S. 2020b Assessing the effect of climate factors on childhood diarrhoea burden in Kathmandu, Nepal. *International Journal of Hygiene and Environmental Health* **223** (1), 199–206.

Bhavnani, D., Goldstick, J. E., Cevallos, W., Trueba, G. & Eisenberg, J. N. S. 2014 Impact of rainfall on diarrheal disease risk associated with unimproved water and sanitation. *The American Journal of Tropical Medicine and Hygiene* **90** (4), 705–711.

Calzadilla, A., Zhu, T., Rehdanz, K., Tol, R. S. J. & Ringler, C. 2013 Economywide impacts of climate change on agriculture in Sub-Saharan Africa. *Ecological Economics* **93**, 150–165.

Cann, K. F., Thomas, D. R., Salmon, R. L., Wyn-Jones, A. P. & Kay, D. 2013 Extreme water-related weather events and waterborne disease. *Epidemiology and Infection* **141** (4), 671–686.

Carlton, E. J., Eisenberg, J. N. S., Goldstick, J., Cevallos, W., Trostle, J. & Levy, K. 2014 Heavy rainfall events and diarrhea incidence: the role of social and environmental factors. *American Journal of Epidemiology* **179** (3), 344–352.

Carlton, E. J., Woster, A. P., DeWitt, P., Goldstein, R. S. & Levy, K. 2016 A systematic review and meta-analysis of ambient temperature and diarrhoeal diseases. *International Journal of Epidemiology* **45** (1), 117–130.

Chou, W.-C., Wu, J.-L., Wang, Y.-C., Huang, H., Sung, F.-C. & Chuang, C.-Y. 2010 Modeling the impact of climate variability on diarrhea-associated diseases in Taiwan (1996–2007). *Science of The Total Environment* **409** (1), 43–51.

Diez-Roux, A. V. 2000 Multilevel analysis in public health research. *Annual Review of Public Health* **21**, 171–192. https://doi.org/10.1146/annurev.publhealth.21.1.171.

Dunn, G., Johnson, G. D., Balk, D. L. & Sembajwe, G. 2020 Spatially varying relationships between risk factors and child diarrhea in West Africa, 2008–2013. *Mathematical Population Studies* **27** (1), 8–33.

Fagbamigbe, A. F., Ologunwa, O. P., Afolabi, E. K., Fagbamigbe, O. S. & Uthman, A. O. 2021 Decomposition analysis of the compositional and contextual factors associated with poor-non-poor inequality in diarrhoea among under-five children in low- and middle-income countries. *Public Health* **193**, 83–93.

Galloway, D. & Cohen, M. B. 2021 38 – Infectious diarrhea. In: *Pediatric Gastrointestinal and Liver Disease*, 6th edn. (R. Wyllie, J. S. Hyams & M. Kay, eds.) Elsevier, Philadelphia, pp. 398–415.e5.

Goldstein, H., Browne, W. & Rasbash, J. 2002 Partitioning variation in multilevel models. *Understanding Statistics* **1** (4), 223–231. https://doi.org/10.1207/S15328031US0104_02.

Gray, N. F. 2014 Chapter 36: The implications of global warming and climate change on waterborne diseases. In: *Microbiology of Waterborne Diseases*, 2nd edn. (S. L. Percival, M. V. Yates, D. W. Williams, R. M. Chalmers & N. F. Gray, eds). Academic Press, London, pp. 653-666.

Hanna, R. & Oliva, P. 2016 Implications of climate change for children in developing countries. *The Future of Children* **26** (1), 115–132.

Hofstra, N. 2011 Quantifying the impact of climate change on enteric waterborne pathogen concentrations in surface water. *Current Opinion in Environmental Sustainability* **3** (6), 471–479.

Holcomb, D. A., Knee, J., Sumner, T., Adriano, Z., de Bruijn, E., Nalá, R., Cumming, O., Brown, J. & Stewart, J. R. 2020 Human fecal contamination of water, soil, and surfaces in households sharing poor-quality sanitation facilities in Maputo, Mozambique. *International Journal of Hygiene and Environmental Health* **226**, 113496.

Hoque, B. A., Hallman, K., Levy, J., Bouis, H., Ali, N., Khan, F., Khanam, S., Kabir, M., Hossain, S. & Shah Alam, M. 2006 Rural drinking water at supply and household levels: quality and management. *International Journal of Hygiene and Environmental Health* **209** (5), 451–460.

Intergovernmental Panel on Climate Change 2014 *Climate Change 2014 – Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects: Working Group II Contribution to the IPCC Fifth Assessment Report: Volume 1: Global and Sectoral Aspects*, Vol. 1. Cambridge University Press, Cambridge.

Khan, A. M. & Bhutta, Z. A. 2017 Childhood infectious diseases: overview. In: *International Encyclopedia of Public Health*, 2nd edn. (S. R. Quah, ed). Academic Press, Oxford, pp. 517-538.

Koroglu, M., Yakupogullari, Y., Otlu, B., Ozturk, S., Ozden, M., Ozer, A., Sener, K. & Durmaz, R. 2011 A waterborne outbreak of epidemic diarrhea due to group A rotavirus in Malatya, Turkey. *The New Microbiologica* **34** (1), 17–24.

Kotloff, K. L., Nasrin, D., Blackwelder, W. C., Wu, Y., Farag, T., Panchalingham, S., Sow, S. O., Sur, D., Zaidi, A. K. M., Faruque, A. S. G., Saha, D., Alonso, P. L., Tamboura, B., Sanogo, D., Onwuchekwa, U., Manna, B., Ramamurthy, T., Kanungo, S., Ahmed, S., Qureshi, S., Quadri, F., Hossain, A., Das, S. K., Antonio, M., Hossain, M. J., Mandomando, I., Acácio, S., Biswas, K., Tennant, S. M., Verweij, J. J., Sommerfelt, H., Nataro, J. P., Robins-Browne, R. M. & Levine, M. M. 2019 The incidence, aetiology, and adverse clinical consequences of less severe diarrhoeal episodes among infants and children residing in low-income and middle-income countries: a 12-month case-control study as a follow-on to the Global Enteric Multicenter Study (GEMS). *The Lancet Global Health* **7** (5), e568–e584.

Lal, A., Hales, S., French, N. & Baker, M. G. 2012 Seasonality in human zoonotic enteric diseases: a systematic review. *PLoS ONE* **7** (4), e31883.

Lane, S. & Lloyd, D. 2002 Current trends in research into the waterborne parasite Giardia. *Critical Reviews in Microbiology* **28** (2), 123–147. https://doi.org/10.1080/1040-840291046713.

Larr, A. S. & Neidell, M. 2016 Pollution and climate change. *The Future of Children* **26** (1), 93–113.

Levy, K., Woster, A. P., Goldstein, R. S. & Carlton, E. J. 2016 Untangling the impacts of climate change on waterborne diseases: a systematic review of relationships between diarrheal diseases and temperature, rainfall, flooding, and drought. *Environmental Science & Technology* **50** (10), 4905–4922.

Leyland, A. H. & Groenewegen, P. P. 2020 *Multilevel Modelling for Public Health and Health Services Research: Health in Context*. Springer International Publishing, Cham, pp. 13–27.

Medina, D. C., Findley, S. E., Guindo, B. & Doumbia, S. 2007 Forecasting non-stationary diarrhea, acute respiratory infection, and malaria time-series in Niono, Mali. *PLoS ONE* **2** (11), e1181.

Merlo, J., Chaix, B., Yang, M., Lynch, J. & Råstam, L. 2005 A brief conceptual tutorial on multilevel analysis in social epidemiology: interpreting neighbourhood differences and the effect of neighbourhood characteristics on individual health. *Journal of Epidemiology & Community Health* **59** (12), 1022–1029.

Mordecai, E. A., Ryan, S. J., Caldwell, J. M., Shah, M. M. & LaBeaud, A. D. 2020 Climate change could shift disease burden from malaria to arboviruses in Africa. *The Lancet Planetary Health* **4** (9), e416–e423.

Mukabutera, A., Thomson, D., Murray, M., Basinga, P., Nyirazinyoye, L., Atwood, S., Savage, K. P., Ngirimana, A. & Hedt-Gauthier, B. L. 2016 Rainfall variation and child health: effect of rainfall on diarrhea among under 5 children in Rwanda, 2010. *BMC Public Health* **16** (1), 731.

Musengimana, G., Mukinda, F. K., Machekano, R. & Mahomed, H. 2016 Temperature variability and occurrence of diarrhoea in children under five-years-old in Cape Town Metropolitan Sub-Districts. *International Journal of Environmental Research and Public Health* **13** (9), 859.

Nataro, J. P. & Guerrant, R. L. 2017 Chronic consequences on human health induced by microbial pathogens: growth faltering among children in developing countries. *Vaccine* **35** (49, Part A), 6807–6812.

Novignon, J. & Nonvignon, J. 2012 Socioeconomic status and the prevalence of fever in children under age five: evidence from four sub-Saharan African countries. *BMC Research Notes* **5**, 380.

Ntouda, J., Sikodf, F., Ibrahim, M. & Abba, I. 2013 Access to drinking water and health of populations in Sub-Saharan Africa. *Comptes Rendus Biologies* **336** (5), 305–309.

Nyiwul, L. M. 2019 Climate change mitigation and adaptation in Africa: strategies, synergies, and constraints. In: *Climate Change and Global Development: Market, Global Players and Empirical Evidence*(T. Sequeira & L. Reis, eds.). Springer International Publishing, Cham, pp. 219–241.

Nyiwul, L. 2021 Climate change adaptation and inequality in Africa: case of water, energy and food insecurity. *Journal of Cleaner Production* **278**, 123393.

Oberheim, J., Höser, C., Lüchters, G. & Kistemann, T. 2020 Small-scaled association between ambient temperature and campylobacteriosis incidence in Germany. *Scientific Reports* **10** (1), 17191.

Obiri-Danso, K., Paul, N. & Jones, K. 2001 The effects of UVB and temperature on the survival of natural populations and pure cultures of *Campylobacter jejuni, Camp. coli, Camp. lari* and urease-positive thermophilic campylobacters (UPTC) in surface waters. *Journal of Applied Microbiology* **90** (2), 256–267.

Opoku, S. K., Leal Filho, W., Hubert, F. & Adejumo, O. 2021 Climate change and health preparedness in Africa: analysing trends in Six African countries. *International Journal of Environmental Research and Public Health* **18** (9), 4672.

Rabe-Hesketh, S. & Skrondal, A. 2012 *Multilevel and Longitudinal Modeling Using STATA, Volume II: Categorical Responses, Counts, and Survival*, 3rd edn. Stata Press, College Station, pp. 1–484.

Ramin, B. 2009 Slums, climate change and human health in sub-Saharan Africa. *Bulletin of the World Health Organization* **87** (12), 886.

Reiner, R. C., Graetz, N., Casey, D. C., Troeger, C., Garcia, G. M., Mosser, J. F., Deshpande, A., Swartz, S. J., Ray, S. E., Blacker, B. F., Rao, P. C., Osgood-Zimmerman, A., Burstein, R., Pigott, D. M., Davis, I. M., Letourneau, I. D., Earl, L., Ross, J. M., Khalil, I. A., Farag, T. H., Brady, O. J., Kraemer, M. U. G., Smith, D. L., Bhatt, S., Weiss, D. J., Gething, P. W., Kassebaum, N. J., Mokdad, A. H., Murray, C. J. L. & Hay, S. I. 2018 Variation in childhood diarrheal morbidity and mortality in Africa, 2000–2015. *New England Journal of Medicine* **379** (12), 1128–1138.

Rice, E. W. & Johnson, C. H. 2000 Short Communication: Survival of *Escherichia coli* O157:H7 in.dairy cattle drinking water. *Journal of Dairy Science* **83** (9), 2021–2023. https://doi.org/10.3168/jds.S0022-0302(00)75081-8.

Schulte-Uebbing, L., Hansen, G., Hernández, A. M. & Winter, M. 2015 Chapter scientists in the IPCC AR5–Experience and lessons learned. *Current Opinion in Environmental Sustainability* **14**, 250–256.

Shiras, T., Cumming, O., Brown, J., Muneme, B., Nala, R. & Dreibelbis, R. 2018 Shared sanitation management and the role of social capital: findings from an urban sanitation intervention in Maputo, Mozambique. *International Journal of Environmental Research and Public Health* **15** (10), E2222.

Simiyu, S., Swilling, M., Cairncross, S. & Rheingans, R. 2017 Determinants of quality of shared sanitation facilities in informal settlements: case study of Kisumu, Kenya. *BMC Public Health* **17**, 68.

Stanke, C., Kerac, M., Prudhomme, C., Medlock, J. & Murray, V. 2013 Health effects of drought: a systematic review of the evidence. *PLoS Currents* **5**.

Strauch, A. M. 2011 Seasonal variability in faecal bacteria of semiarid rivers in the Serengeti National Park, Tanzania. *Marine and Freshwater Research* **62** (10), 1191–1200.

Stryhn, H., Sanchez, J., Morley, P., Booker, C. & Dohoo, I. 2006 T4-1.2.3–Interpretation of variance parameters in multilevel Poisson regression models. In: *International Symposia on Veterinary Epidemiology and Economics Proceedings, ISVEE 11: Proceedings of the 11th Symposium of the International Society for Veterinary Epidemiology and Economics, Cairns, Australia (Theme 4-Tools & Training for Epidemiologists: Statistical Modelling Session)*. p. 702.

Thiam, S., Cissé, G., Stensgaard, A.-S., Niang-Diène, A., Utzinger, J. & Vounatsou, P. 2019 Bayesian conditional autoregressive models to assess spatial patterns of diarrhoea risk among children under the age of 5 years in Mbour, Senegal. *Geospatial Health* **14** (2), 321–328.

UNECA 2011 *Climate Change and Health Across Africa: Issues and Options* (Working Paper No 20).

USAID 2019 *Southern Africa - Tropical Cyclones Fact Sheet#14 FY2019*. USAID.

van Gaalen, R. D., van de Kassteele, J., Hahné, S. J. M., Bruijning-Verhagen, P. & Wallinga, J. 2017 Determinants of rotavirus transmission: a lag nonlinear time series analysis. *Epidemiology (Cambridge, Mass.)* **28** (4), 503–513.

Voth-Gaeddert, L. E., Jonah, C., Momberg, D., Ngandu, B., Said-Mohamed, R., Oerther, D. B. & May, J. 2020 Assessment of environmental exposure factors on child diarrhea and systemic inflammation in the Eastern Cape. *Water Research* **169**, 115244.

WHO 2020 *World Malaria Report 2020: 20 Years of Global Progress and Challenges*.

Wilby, R. L., Hedger, M. & Orr, H. 2005 Climate change impacts and adaptation: a science agenda for the Environment Agency of England and Wales. *Weather* **60** (7), 206–211.

Wolf, J., Hunter, P. R., Freeman, M. C., Cumming, O., Clasen, T., Bartram, J., Higgins, J. P. T., Johnston, R., Medlicott, K., Boisson, S. & Prüss-Ustün, A. 2018 Impact of drinking water, sanitation and handwashing with soap on childhood diarrhoeal disease: updated meta-analysis and meta-regression. *Tropical Medicine & International Health: TM & IH* **23** (5), 508–525.

World Health Organization & UNICEF 2021 *Progress on Household Drinking Water, Sanitation and Hygiene 2000–2020: Five Years Into the SDGs*. World Health Organization; UNICEF.

Xu, Z., Etzel, R. A., Su, H., Huang, C., Guo, Y. & Tong, S. 2012 Impact of ambient temperature on children's health: a systematic review. *Environmental Research* **117**, 120–131.

Yusuf, O. B., Adeoye, B. W., Oladepo, O. O., Peters, D. H. & Bishai, D. 2010 Poverty and fever vulnerability in Nigeria: a multilevel analysis. *Malaria Journal* **9** (1), 235.

First received 11 August 2021; accepted in revised form 25 March 2022. Available online 6 April 2022