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Recent and future exposure of water, sanitation, and hygiene systems to climate-related hazards in Zambia

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ABSTRACT

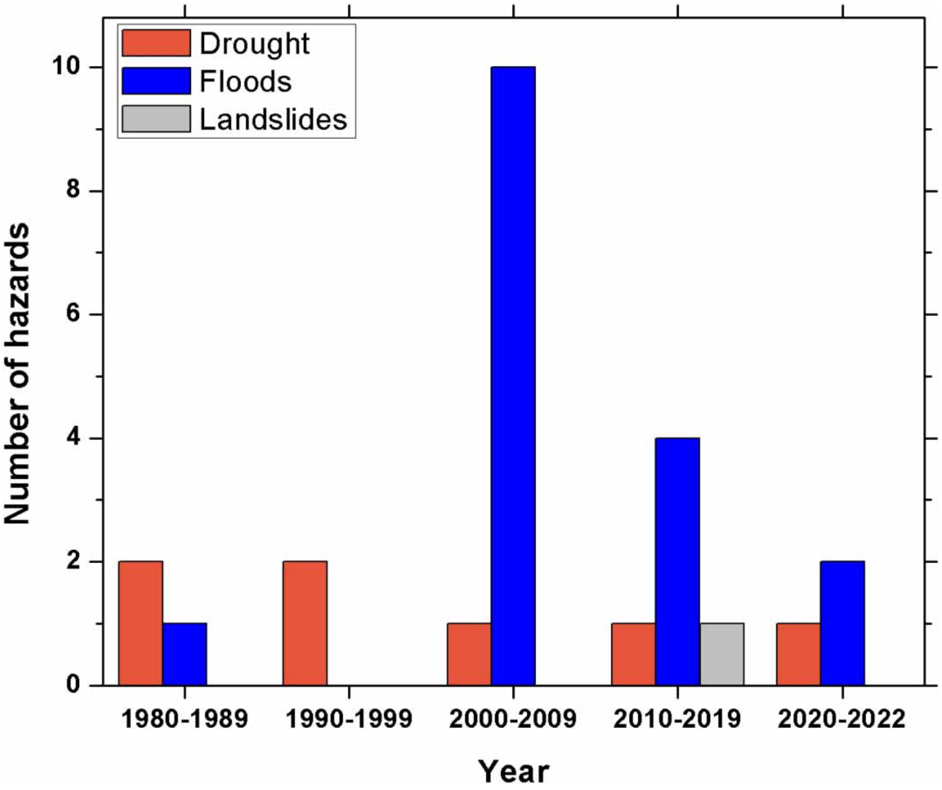
Climate change-driven water scarcity will lead to inequitable water, sanitation, and hygiene (WASH) access. However, current research in Zambia has ignored linking climate science dimensions to WASH access programs, thus limiting WASH-related climate action across the country. Here, we combine analyses of *in situ* datasets, modeling techniques, and systematic literature reviews to provide a solid climate science basis for WASH–climate action in Zambia. We find that in a warm near future climate, the stretch along the Copperbelt–Livingstone railroad from the north to the south of the country is expected to record an increase in heavy rainfall single-day events ranging between 50 and $\geq$150 mm. As such, bacterial diseases, such as cholera outbreaks, are expected to increase, especially in the Copperbelt, Central, Lusaka, Southern, and the Eastern Provinces. Models further predict a drier Zambia in the near and far future of up to 12 days year^{-1}, suggesting a higher risk of increased aridity which will compound challenges to the provision of safe drinking water. The projected rapid population growth in these regions will also heighten the challenges of accessing safe drinking water. Strategic investments in enhancing WASH access in these areas should be considered a matter of urgency.

Key words: bacterial diseases, climate change, CMIP6, WASH access, Zambia

HIGHLIGHTS

- This study provides the first comprehensive assessment of WASH–climate interactions in Zambia.
- Areas along the Copperbelt–Livingstone railroad are expected to record an increase in heavy rainfall events.
- Models further suggest a high risk of increased aridity.
- Drilling and mechanization of boreholes are likely to be more expensive.
- Strategic investments in enhancing WASH access should be considered a matter of urgency.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Efforts to safely manage water occupy center stage in global dialogues about water, sanitation, and hygiene (WASH; UN 2020). However, billions of people still lack access to reliable WASH (Rahut *et al.* 2022). In total, over 2 billion people lack access to safe drinking water, over 4 billion do not have access to safe sanitation, and basic handwashing facilities remain elusive for ~3 billion people (WHO 2019). Curtis & Cairncross (2003) contend that reliable access to WASH services has the potential to cut diarrhea-related mortality by 45%. In addition, access to WASH services can significantly reduce time spent on water fetching, thus potentially enhancing school attendance (Belay *et al.* 2020), food production (Gomez-Zavaglia *et al.* 2020), and overall quality of livelihoods (Uddin *et al.* 2020). Global estimates indicate that 500 million menstruating persons lack access to adequate water and facilities for menstrual hygiene management (MHM; World Bank 2022). The availability of WASH, MHM services has also been found to significantly impact school attendance (Chinyama *et al.* 2019). This is concerning especially considering that millions of girls and women still lack access to MHM in schools across the globe (UNICEF 2022a, 2022b).

Challenges related to WASH access are especially apparent in developing regions such as Sub-Saharan Africa where water resources are increasingly threatened by the increase in demand vis-à-vis rapid population growth, agricultural expansion, and civil unrest (Msangi 2014; Momberg *et al.* 2020). For example, in the Central African Republic (CAR), WASH developmental pursuits have been hampered by civil unrest, and the country's access to drinking water is at just 37% (UNICEF 2022a, 2022b). As a major consumer of water in Sub-Saharan Africa, agricultural expansion has also hindered progress toward achieving sustainable development goal number 6: water and sanitation for all. For example, in Mozambique, the cultivation of sugar cane consumes 600% more water per ton compared to the global standard. This ineffective use of water can strain the availability of drinking water (Water Footprint Network 2020).

Perhaps one of the most common hindrances to WASH access relates to climate change-induced hazards that are affecting Sub-Saharan Africa in increasingly severe ways. We use 'hazards' to mean the occurrence of climate-related physical events that may cause damage and/or loss depending on the level of exposure, i.e., 'the presence of assets, services, resources, &

infrastructure that could be adversely affected if a hazard occurred' and vulnerability, i.e., a general lack of capacity to cope and adapt (IPCC 2014). Sub-Saharan Africa is one of the most vulnerable regions to climate change and one of the least ready to respond to the impacts of climate-related hazards (Davis & Vincent 2017). The region's vulnerability undermines WASH developmental pursuits by reducing the availability of critical natural resources such as freshwater (Kusangaya *et al.* 2014). During the 2015/2016 season, climate change-induced drought exacerbated by one of the strongest El Niño events characterized by an unusual warming of the eastern equatorial Pacific Ocean (ECMWF 2017) triggered high-intensity droughts that led to freshwater shortages across much of southern Africa (Action Aid 2020). Similarly, floods have become frequent across the region (Schatz 2008; Dube *et al.* 2021), damaging WASH and other critical infrastructure (WaterAid 2022). The most recent devastating flood occurrence across the region was triggered by Tropical Cyclone Freddy (TC Freddy; UN 2023) which made landfall in Mozambique, undoing some WASH progress, and taking a toll on healthcare systems by the destruction of critical infrastructure and leaving over 200 people dead in neighboring Malawi (AP 2023). Tropical Cyclone Freddy left thousands of people across southern Africa cut off from shelter, basic food, and clean water.

All these climatic shocks highlight the need for WASH sustainability mechanisms across southern Africa where estimates of WASH access remain fraught with uncertainty. However, empirical research evaluating the impact of climate hazards on WASH systems has been mostly anecdotal. Much research focuses on WASH access (e.g., Bresee *et al.* 2016; Morgan *et al.* 2017). The research often aims to narrow the gap between policy and practice. There is very little WASH research that uses cutting-edge climate models to understand climate–WASH interactions. To our knowledge, no peer-reviewed research work exists that links high-resolution climate modeling and WASH systems in countries like Zambia. As such, there is a general lack of understanding of the extent of the impacts of climate-induced hazards on WASH access. Perhaps more concerning, research focusing on future climate hazards and their likely impacts on WASH has mainly been ignored. This gap, if filled, would facilitate practice and pinpoint useful areas that need to be addressed to sustain WASH systems in countries like Zambia.

The overarching goal of the present study is to examine the current and future impacts of climate hazards on WASH access and services in southern Africa, focusing on Zambia. In Zambia, previous research has mainly focused on the success or failure, in hindsight, of WASH programs but has largely ignored linking climate science dimensions to WASH access programs. In this study, we aim to provide a novel overview of climate change-induced hazards on WASH access in Zambia for the past, present, and future. We argue that doing so will provide the much-needed climate science basis for WASH–climate action in Zambia. To achieve this aim, we discuss two independent research questions:

(i) What are the past and present impacts of climate variability on WASH access and services in Zambia?
(ii) What are the projected climate trends in Zambia and how will they likely impact WASH provisioning?

2. DATA SOURCES AND METHODOLOGY

2.1. Data sources

2.1.1. WASH access data

We retrieved household and national WASH access data from the WHO/UNICEF Joint Monitoring Programme on Water supply, Sanitation and Hygiene (JMP; https://washdata.org/ accessed 1 February 2023) for the period 2000–2021. The JMP is internationally recognized for providing up-to-date global estimates of WASH based on data from partners at the country level. The 2022 progress update covering the period 2000–2021 is the most recent version of the dataset. Therefore, the analysis embodied in this study represents the most recent WASH coverage across Zambia. The JMP dataset is widely used in environmental and public health research due to its high-quality data control measures. For example, it has previously been used successfully to analyze the risk of diarrheal diseases and urbanization in Sub-Saharan Africa (Zerbo *et al.* 2021), and most recently, it was used to examine WASH inequalities in Nigerian Schools (Wada *et al.* 2022).

2.1.2. *In situ* climate reference data

While a lot of progress has been made to expand Zambia's climate observations network, access to long-term historical climate data remains difficult and contested which limits the ability to assess satellite precipitation information across the country. To bridge this information gap, previous studies, including the IPCC's latest sixth assessment report (hereafter AR6; Gutiérrez *et al.* 2021) relied on Global Precipitation Climatology Centre (GPCC) monthly precipitation data from the Physical Science Division of the Earth System Research Laboratory (https://www.esrl.noaa.gov/psd/data/gridded;

accessed 28 February 2023). The present study also relied on GPCC data to understand historical variations of precipitation across the country (Sian *et al.* 2021). GPCC data has a spatial resolution of $0.5° \times 0.5°$ and covers the period 1891–2016.

2.1.3. CMIP6 model data

Simulations from the latest state-of-the-art Coupled Model Intercomparison Project Phase 6 (CMIP6), as used in AR6, were employed to deepen the understanding of extreme precipitation events and the risk they pose to WASH systems across Zambia in the future. Before projections, a rigorous skill assessment of 23 CMIP6 general circulation models (GCMs; Table 1, Sian *et al.* 2021) was done. For compatibility, only the first-member variations (rli1p1f1 r1: realization index, i1: initialization index, p1: physics index, and f1: forcing index) of each model were used in the assessment. Furthermore, the assessment was done using only the intermediate scenario (SSP2-4.5) which was chosen because it offers the closest representation of current global efforts being implemented to keep emissions of greenhouse gases from escalating (Riahi *et al.* 2017).

2.2. Methodological approach

We used descriptive statistics to analyze WASH access across Zambia. Key metrics used include the distribution of WASH coverage at rural, urban, and national levels. Central tendency and variability of the full dataset were also considered.

To quantify future extreme rainfall events across Zambia, we employed a set of internationally recognized core climate indices as proposed by the Climate and Ocean Variability, Predictability, and Change (CLIVAR), the Global Climate Observing System (GCOS), and the United Nations World Meteorological Organization (WMO). While there are 27 core indices (Karl *et al.* 1999), in this study, we focused on 2 key indices that describe the frequency and intensity of heavy rainfall events and that invariably affect the WASH sector. These indices include (i) heavy rainfall, i.e., R95p – Annual total precipitation when daily rainfall (RR) $>$ 95th percentile and (ii) consecutive dry days (CDDs).

Before examining the potential impact of extreme rainfall events on WASH access in the future, the Taylor Skill Score (TSS; Taylor 2001) was used to identify well-performing models among the 23 CMIP6 GCMs relative to GPCC data (Sian *et al.* 2021). The TSS is a convenient statistical performance measure that summarizes three different metrics into one. These metrics include correlation coefficient *(R),* root mean square difference (RMSD), and standard deviation (STD). Given its robustness, the TSS is widely used in climate modeling studies (Babaousmail *et al.* 2021; Ngoma *et al.* 2021). Mathematically, the Taylor Skill Score can be expressed as given in Equation (1):

$$\mathrm{TSS} = \frac{4(1+R)^2}{((\sigma_m/\sigma_r)+(\sigma_r/\sigma_m))^2(1+R_0)^2} \tag{1}$$

where R is the correlation coefficient between GPCC and CMIP6 GCMs, σ_m is the GPCC standard deviation, σ_r is the CMIP6 standard deviation, and R_0 is the highest achievable correlation coefficient at the threshold of 0.999. 1 represents the ideal TSS score.

For projections, we divided the future into two time slices herein referred to as 'the near future' (2025–2054) and 'the far future' (2071–2100). Regarding emission scenarios, this study mainly relies on Shared Socioeconomic Pathways (SSPs) and in particular, the SSP2-4.5 which we repeatedly refer to as 'the middle road scenario' throughout the present study. Although we did not examine other scenarios per se, we make a few references to the SSP5-8.5 scenario which we refer to as the 'business-as-usual scenario' or the 'high-end scenario'. A detailed description of all the scenarios is given by the United Nations Economic Commission for Europe: https://unece.org/fileadmin/DAM/energy/se/pdfs/CSE/PATHWAYS/2019/ws_Consult_14_15.May.2019/supp_doc/SSP2_Overview.pdf [Accessed: 25 December 2022].

Regarding trends, we used the non-parametric Mann–Kendall trend test (MK test) and its modified version. The MK test compares each value to all subsequent ordered data samples (Mann 1945; Kendall 1948). The MK statistic *(S)* is thus calculated as shown in Equation (2):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{2}$$

Based on the work done by Mann (1945) and Kendall (1948), the application of a trend test is done to a time series x_i which is ranked from $i = 1,2,\ldots\ldots\ldots n-1$ and x_j, which is ranked from $j = i+1,2,\ldots\ldots\ldots n$. Each of the data points x_i is taken as a point of

Table 1 | CMIP6 models used in this study

	Model	Modeling institution	Horizontal resolution
1	ACCESS–CM2	Commonwealth Scientific and Industrial Research Organization/Australia	1.25° × 1.875°
2	ACCESS–ESM1–5	Commonwealth Scientific and Industrial Research Organization/Australia	1.25° × 1.875°
3	BCC–CSM2–MR	Beijing Climate Center China Meteorological Administration/China	1.125° × 1.125°
4	CanESM5	Canadian Centre for Climate Modeling and Analysis/Canada	2.8° × 2.8°
5	CNRM–CM6–1	Centre National de Recherches Météorologiques–Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique/France	1.4° × 1.4°
6	CNRM–ESM2–1	Centre National de Recherches Météorologiques–Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique/France	1.4° × 1.4°
7	EC–Earth3–Veg	EC–EARTH consortium/Europe	0.7° × 0.7°
8	FGOALS–g3	Chinese Academy of Sciences/China	2.25° × 2°
9	GFDL–CM4	NOAA Geophysical Fluid Dynamics Laboratory/USA	1° × 1.25°
10	GFDL–ESM4	NOAA Geophysical Fluid Dynamics Laboratory/USA	1° × 1.25°
11	HadGEM3–GC31–LL	Met Office Hadley Centre/UK	1.25° × 1.875°
12	INM–CM4–8	Institute for Numerical Mathematics, Russian Academy of Science/Russia	1.5° × 2°
13	INM–CM5–0	Institute for Numerical Mathematics, Russian Academy of Science/Russia	1.5° × 2°
14	IPSL–CM6A–LR	L'Institut Pierre–Simon Laplace/France	1.26° × 2.5°
15	MIROC6	Japan Agency for Marine–Earth Science and Technology, Atmosphere and Ocean Research	1.4° × 1.4°
16	MIROC–ES2L	Institute, The University of Tokyo, National Institute for Environmental Studies, and RIKEN Center for Computational Science/Japan	2.8° × 2.8°
17	MPI–ESM–1–2–HR	Max Planck Institute for Meteorology/Germany	0.9375° × 0.9375°
18	MPI–ESM–1–2–LR	Max Planck Institute for Meteorology/Germany	1.875° × 1.875°
19	MRI–ESM2–0	Meteorological Research Institute/Japan	1.125° × 1.125°
20	NESM3	Nanjing University of Information Science and Technology/China	1.875° × 1.875°
21	NorESM2–LM	Norwegian Climate Centre/Norway	1.875° × 2.5°
22	NorESM2–MM	Norwegian Climate Centre/Norway	0.9375° × 1.25°
23	UKESM1–0–LL	Met Office Hadley Centre/UK	1.25° × 1.875°

reference which is compared with the rest of the data points x_j so that,

$$Sgn(x_j - x_i) = \begin{cases} +1, & > (x_j - x_i) \\ 0, & = (x_j - x_i) \\ -1, & < (x_j - x_i) \end{cases} \tag{3}$$

when n in Equation (3) is ≥ 8, the statistic S is approximately normally distributed with the mean.

$$E(S) = 0$$

The variance statistic Var*(S)* is then calculated as given in Equation (4):

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i)(i-1)(2_i+5)}{18} \tag{4}$$

where t_i is the number of ties up to sample i. n is the number of data points, m is the number of tied groups. A tied group is a set of sample data having the same value. The probability associated with S and the sample size, n, is then calculated to statistically quantify the significance of the trend using the normalized test statistic Z_c as shown in Equation (5):

$$Z_c \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}} \\ 0, S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}}, S < 0 \end{cases} \tag{5}$$

A positive or negative value of Z_c indicates an upward or downward trend. At the 95% significance level, the null hypothesis of no trend is rejected if $Z_c > 1.96$; and at the 90% significance level, the null hypothesis of no trend is rejected if $Z_c > 1.645$ (Mann 1945; Kendall 1948).

In the present study, we employed the modified MK test to quantify the evolution of rainfall trends. To do this, we used the 'modifiedmk' Package (Patakamuri & O'Brien 2021) in R Programming Language (R Core Team 2020). In modified MK tests, the equivalent normal variants of the rank of the detrended series are obtained using Equation (6):

$$Z_i = \varphi^{-1}\left(\frac{R_1}{n+1}\right) for \quad i = 1{:}n \tag{6}$$

where R_i refers to the rank of the detrended time series, n refers to the length of the time series, and φ^{-1} is the inverse standard normal distribution function with a mean of 0 and a standard deviation of 1 (Hamed & Rao 1998).

Preliminary findings of the climate risk analysis were shared with the government and other stakeholders during a 2-day discussion at Asmara Hotel in Lusaka, Zambia from 18 to 19 April 2023. The goal of the discussion was to first, peer review the climate risk analysis and second, to solicit climate-resilient WASH ideas. Seventeen participants were drawn from the Ministry of Water Development and Sanitation, the National Water Supply and Sanitation Council, the Ministry of Green Economy and Environment, The University of Zambia, The World Bank, UNICEF, and International Non-Governmental Organizations.

Care was taken to ensure that all participants are Water–Energy–Food Ecosystem (WEFE) Nexus experts. We hypothesized that avoiding limiting participants to WASH only and including those from the WEFE Nexus would ensure that the results include as many different ideas and perspectives as possible. While there is no scientific consensus on the exact number of participants required for an effective focus group discussion, 5–50 participants are generally considered adequate (Dworkin 2012). Therefore, 17 participants were considered enough to satisfy the goal of this study.

The discussions were held in the hotel conference room, providing a conducive environment with all participants seated in an oval conference setting. Consent was obtained to record the discussion anonymously for analyses afterward. Participants were first asked to describe the WASH facilities and services their institutions provide or support. We then followed up with open-ended questions while taking every effort to avoid dichotomous ones. Therefore, the specific questions that were asked are as follows: (i) From an institutional perspective, what are the current and projected climate risks to your ability to provide or support the WASH sector in Zambia? (ii) What recommendations can you give to ensure that your institution continues to provide or support the WASH sector in Zambia? (iii) What project ideas can you suggest that support climate resilience and strengthen the provision of WASH services for the identified high-risk areas and their surroundings?

3. RESULTS AND DISCUSSION

3.1. WASH access

In the first set of analyses, we explored recent WASH access patterns across the country. We found that 50% of urban populations have access to safely managed drinking water. This suggests that safely managed drinking water remains a preserve of urban dwellers across much of the country. Slightly under half of the rural population has access to basic drinking water services while 32% still rely on unimproved services. At 12%, the population of rural dwellers depending on surface water is still large compared to the 2% of urban dwellers (Figure 1). It is notable, however, that the quality of surface water in rural areas is likely better since they are removed from urban contamination and other forms of waste from industrial residues which lead to the degradation of surface water and trigger bacterial diseases (APEC 2022). However, there are exceptions to this sweeping statement. It cannot be generalized that all rural areas have higher-quality water, especially those that practice intensive agricultural activities and mining (Gyamfi *et al.* 2019; Tsoraeva *et al.* 2020). The impact of mining and agricultural activities on rural water supplies can be severe (Tokatli & Varol 2021). It is further notable that regardless of the source, drinking water is susceptible to contamination by microorganisms and other forms of organic matter (Mukhopadhyay *et al.* 2022), especially during transport and storage. Also, the prevalence of contamination is higher in surface water than in other sources (Bell *et al.* 2021).

Results further indicate that at the national level, 65% of the population have access to basic drinking water services, 32% remain reliant on unimproved water services, 6% depend on limited service and the remaining 7% depend on surface water (Figure 1).

Results of the sanitation access analysis reveal that, unlike water, safely managed sanitation is accessible to a bigger part of the rural than the urban population. Specifically, 24% of rural dwellers have access to safely managed sanitation while it remains elusive to the urban dwelling populace. Unplanned urban settlements which constitute 70% of urban dwellers are especially characterized by substandard or complete absence of sanitation facilities (Nkonde 2019). Notwithstanding the number of people with access to safely managed sanitation in rural areas, 49% still use unimproved sanitation with 19% being reliant on open defecation (OD). Without the industries that characterize urban areas, OD is the leading cause of

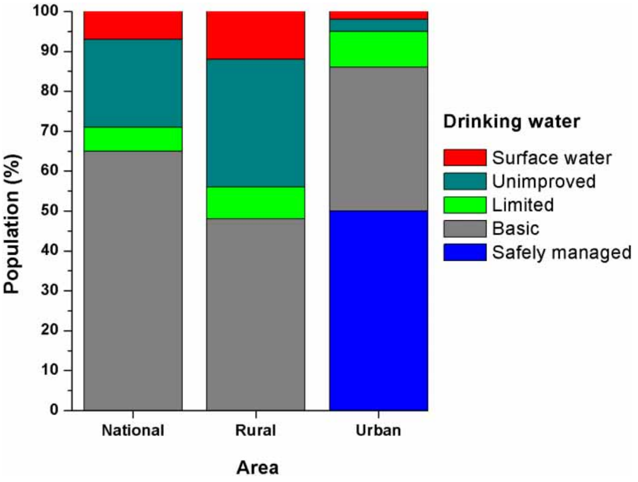


Figure 1 | Drinking water accessibility across Zambia for the period 2000–2021 based on the data from the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation, and Hygiene (JMP; https://washdata.org/; accessed 6 March 2023).

environmental contamination in rural areas and its devastating consequences can include bacterial diseases, stunting, morbidity, and mortality (UNICEF 2018).

The observation that more rural dwellers have access to safely managed sanitation than urban dwellers is counterintuitive and challenges the conventional understanding of sanitation access in Zambia. These discrepancies can be attributed to a general lack of data across much of Zambia. Furthermore, even where data are available, sources and methods used to collect it together with the areas covered tend to differ. Overall, the country's population consists of 32% with access to basic sanitation, 20% have limited sanitation, 11% depend on OD, and the largest number, – 37%, use unimproved sanitation.

Regarding hygiene access, results indicate that 62% of rural and 36% of the urban population have no hygiene services. Estimates reveal that 35% of urban and 29% of the rural population has limited service, 29% of the urban population has access to basic services while only 9% of rural dwellers have access to basic hygiene services. Taken together, over half of the population in Zambia remains without access to hygiene services and only 18% have access to basic services. The remainder of the population has access to limited hygiene services, meaning they have a handwashing facility, but lack water or soap.

3.2. Impacts of climate variability on WASH access and services

Having assessed current patterns of WASH access across Zambia, we interrogated the interwoven relationship of climate variability and WASH access by first, looking in hindsight, at the occurrence of climate hazards across Zambia. From 1980 to the present, 23 high-impact natural hazards have been reported in Zambia (Figure 2). We use 'high impact' in this study to mean a natural hazard that affects a minimum of 100 people. Therefore, floods, droughts, and landslides that affected less than 100 people are not considered in this study. For easy comparative analysis with contemporary literature, when the same hazard is reported in different parts of the country in the same year, we counted it only once. Results indicate that floods are the most recurring high-impact hazard, and they constitute 68% of the total hazards. After floods, droughts are the most recurring high-impact accounting for 28% of high-impact hazards. The last major recurring high-impact hazard is landslide which account for 4% of all high-impact hazards reported. Results further show that from 1980 to 1999, the dominant high-impact hazard was drought, but recently, floods have become more dominant (Figure 2).

Assessing the number of casualties and the total number of people affected by natural hazards between 1980 and the near present revealed that the highest number of casualties was during the recent past (2010–2019) when 4,500 people were reported to have died (Figure 3). Overall, 1.5 million people were reported to have been affected directly or indirectly by the floods, droughts, and landslides that occurred in the recent past. The two decades from 1990–2009 had the highest impact in terms of the total number of people affected which was more than 8 million people. In December 2006 and January 2007, for example, the country suffered devastating floods in Mpulungu in Northern Province and Solwezi in Northwestern Province. The torrential rains and concomitant floods that turned streets into high-current streams washed away WASH and

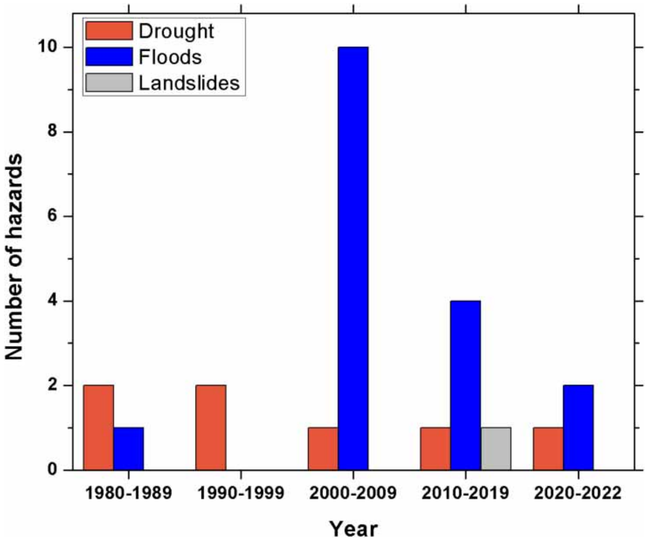


Figure 2 | Number of high-impact hazards across Zambia from 1980 to near present, based on data from the International Disaster Database.

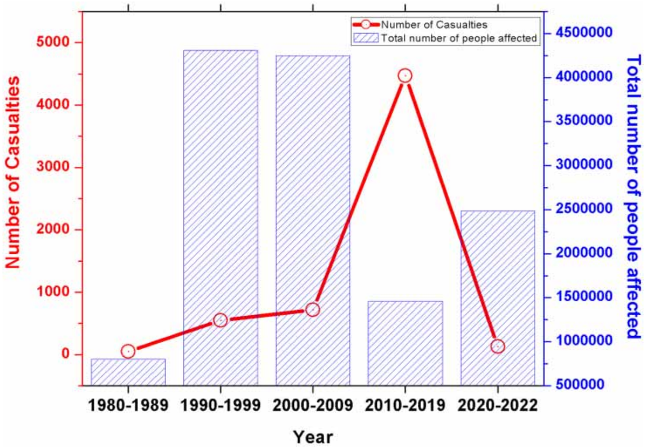


Figure 3 | Number of casualties and people affected by high-impact hazards across Zambia from 1980 to near present, based on data from the International Disaster Database.

other critical infrastructures in Luapula, Copperbelt, Central, Eastern, Lusaka, and parts of the usually dry Southern Province. The floods were reported to have severely battered rural communities that live in mud houses and rely on shallow unsafe wells. Several latrines collapsed, contaminating drinking water sources, and leaving over 5,000 households without access to safe WASH (Red Cross 2007).

Given the interlinkages between climate hazards, epidemics, bacterial, and viral diseases, we explored the relational matrix of the occurrence of hazards and the latter. We found that 50% of bacterial diseases across Zambia occur during flood years. The two viral diseases that were classified as disasters occurred in 1982 and 1990 but they did not coincide with the occurrence of any climate hazard. Only one landslide that occurred during the anomalous 2010 flood year was classified as a disaster. Lastly, the one epidemic that was graded as a disaster in the database occurred in 2000 and this coincided with the occurrence of floods and bacterial diseases.

Further analysis revealed that covering 93% of all cases, cholera is the predominant bacterial disease affecting Zambia. Only one case of dengue was reported in Petauke district of Eastern Province in 2001 (Table 2). As expected, being a water-borne disease, the majority (71%) of cholera cases were observed to have started during the rainy season covering the months of October–April/May. 50% of all cholera cases started during the core of the rainy season (December–February; DJF), three cases – equivalent to 21% of all cases started at the onset of the rainy season in October while only one case (7%) was reported to have started toward the end of the rainy season (April/May). These results are consistent with those of Fernández *et al.* (2009) who studied the influence of temperature and rainfall on the evolution of cholera epidemics in Lusaka and found that all epidemics are seasonal and coincided with the rainy season across Zambia.

It was observed that cholera is linked to only 50% of flood occurrences but is associated with rainy season start dates for over 70% of all cases. This suggests that while rainstorms and floods facilitate and accelerate the transmission of cholera to new areas (Adetoro *et al.* 2022), these can be reduced through comprehensive water, sanitation, and hygiene development planning ahead of the rainy season (Baltazar *et al.* 2022). It is important to note that, in addition to addressing climate risk, social systems are indispensable to reducing or eradicating cholera occurrences (Elimian *et al.* 2020; Gupta & Gupta 2020; Charnley *et al.* 2022). We use the term 'social systems' here to refer to the conditions in which people live and how they influence health disparities. A social system as a determinant of health, therefore, covers behaviors, socioeconomic factors such as income, education, etc., and environmental or physical drivers such as climate and water quality.

3.3. Future extreme rainfall events and their potential impacts on WASH access

Turning to projections, we picked two top-performing models, i.e., the Max Planck Institute Earth System Model (MPI-ESM-2-HR; Müller *et al.* 2018) and the Flexible Global Ocean–Atmosphere–Land System model (FGOAL-g3; Li *et al.* 2020) and developed an ensemble following a rigorous skill assessment of 23 CMIP6 general circulation models (GCMs; Table 1; Sian *et al.* 2021). We then used the ensemble to study future extreme rainfall events. Results indicate that while there are wide spatial variations, extreme dryness across Zambia is projected to increase (Figure 4). Under the middle road scenario of

Table 2 | Timing of bacterial disasters in Zambia for the period 1980–near present, based on data from the International Disaster Database

Disaster type	Start year	Start month	Event name	Affected provinces	Affected districts
Bacterial disease	1991	2	Cholera	*No data*	*No data*
Bacterial disease	1992	1	Cholera	Northern and Lusaka	*No data*
Bacterial disease	1999	5	Cholera	*No data*	Kaputa and Chiengi
Bacterial disease	1999	1	Cholera	Lusaka and Copperbelt	Lusaka and Ndola
Bacterial disease	1999	10	Cholera	Luapula	Kaputa
Bacterial disease	2000	1	Cholera	*No data*	*No data*
Bacterial disease	2001	3	Plague	Eastern	Petauke
Bacterial disease	2003	12	Cholera	Lusaka, Southern, Copperbelt, Northern and Central	*No data*
Bacterial disease	2005	8	Cholera	Lusaka, Central, Copperbelt, Southern, Luapula, Eastern, and Western	Lusaka, Kabwe, Chibombo, Kapiri Mposhi, Mufulira, and Kasempa. No data for other provinces
Bacterial disease	2006	10	Cholera	Lusaka, Central, Copperbelt, Eastern, Luapula, NorthWestern, and Southern provinces	*No data*
Bacterial disease	2007	2	Cholera	Lusaka	Lusaka
Bacterial disease	2008	9	Cholera	Northern, Lusaka, Southern, and Copperbelt	Mpulungu, Mazabuka, Livingstone, and Lusaka
Bacterial disease	2009	10	Cholera	Lusaka, Southern, Copperbelt, Northern, Luapula	*No data*
Bacterial disease	2012	8	Cholera	Northern Province	Mpulungu
Bacterial disease	2017	9	Cholera	Lusaka	Lusaka, i.e., Matero, Chipata, Kanyama
Bacterial disease	2023	1	Cholera	Eastern, Luapula, Lusaka, Southern	*No data*

Shared Socioeconomic Pathways (SSP2-4.5), models predict positive anomalies of CDDs by the middle of the century across the whole country apart from the Lake Bangweulu wetland region and parts of the Copperbelt covering Ndola (Figure 4(a)).

In the far future (Figure 4(b)), CDDs are expected to intensify, and negative anomalies are projected to be non-existent. Areas such as Livingstone in the Southern Province, the Chipata region in the Eastern Province, and the Solwezi region in Northwestern Province will experience the largest dryness of up to 12 days per year in both the near and the far future (Figure 4), thus suggesting that dry parts of the country during the middle of the century will get drier toward the end of the century. It should, however, be noted that although these identified areas will experience more CDDs than other parts of the country, the intensity of dryness is expected more over southwestern Zambia due to already generally low rainfall patterns in that part of the country (Laudien *et al.* 2022).

Drought causes temporal to chronic water shortages that affect the WASH sector. Already, given increased drought conditions, much of the southern African region has in recent years experienced increased incidences of cholera (Tærup *et al.* 2011; Cambaza *et al.* 2019). Drought-driven water shortages lead to the use of often poorer quality alternative water sources. If these locations already often have poor hygiene and sanitation services or OD, water-borne diseases can spread rapidly (Joubert 2023). Projected drought-driven disruptions in water access will likely jeopardize the already fragile water and sanitation systems and further weaken generally poor hygiene practices, especially in populated areas (Howard *et al.* 2016).

Findings from the analysis of the temporal evolution of CDDs (Figure 5) are consistent with the results of the spatial analysis (Figure 5). Overall, the MK-trend test shows that the trend of CDDs ranges between 0.002 and 3.0 days per year and averages 1.4 days per year on the Sen's slope estimator of trend. Models further show that the upward trend is projected to continue up to the end of the century (Figure 5). Interannual variabilities will also increase especially from 2040 to 2050 suggesting the need for water planning amidst larger uncertainty brackets. CDDs lead to dry spells which develop into droughts. Therefore, droughts will become more pronounced, and this will exert a strain on freshwater access, especially

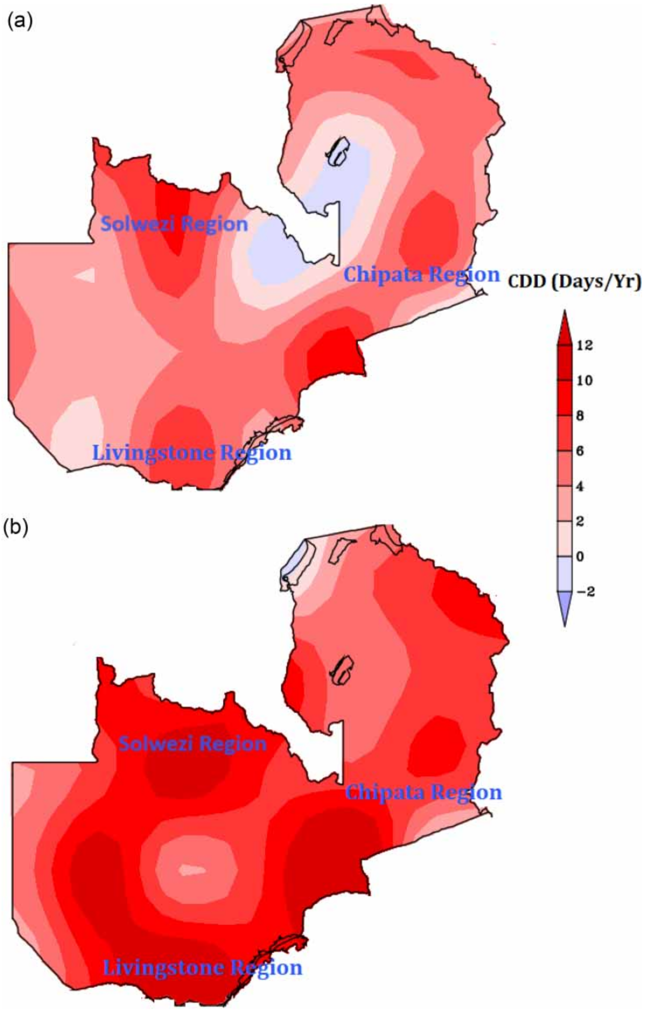


Figure 4 | Anomalies of consecutive dry days (CDDs: days/year) under the SSP2-4.5 scenario with respect to the 1980–2009 baseline period across Zambia for (a) the near future, i.e., 2025–2054 and (b) the far future, i.e., 2071–2100, averaged over longitudes 21.8°E–34°E and latitudes 18°S–8°S, based on CMIP6 multi-model ensemble projections.

by the middle of the century. Conclusively, this finding can be summarized in one salient point: *models predict a drier Zambia in the near and far future, and this will strain the WASH sector by compounding challenges to the provision of safe drinking water*.

Anomalies of heavy rainfall events (R95p mm/year, i.e., total rainfall per year from days with rainfall above the 95th percentile of daily rainfall total) indicate wide spatial variability (Figure 6). What stands out however is that the stretch along the Copperbelt–Livingstone railroad from the north to the south of the country is expected to record an increase in heavy rainfall events ranging between 50 and $\geq$150 mm, especially in the near future. Furthermore, apart from small parts of Luapula and Western Provinces, the whole country is expected to experience an increase in single-day heavy rainfall events. The number of days with heavy downpours is equally projected to increase (Laudien *et al.* 2022).

A comparative analysis of CDDs and heavy rainfall events shows that the areas that are expected to experience an increase in CDDs will also be characterized by increases in heavy rainfall events. This finding, therefore, points toward the dominance of single-day extreme precipitation events. These single-day extreme precipitation events will likely be enhanced by the projected increases in intensity of tropical cyclones (TCs) making landfall over central and northern Mozambique (Fitchett 2018; Seneviratne *et al.* 2021). In a nutshell, TCs making landfall in Mozambique often modulate the climate of Zambia by introducing rainstorms and damaging winds.

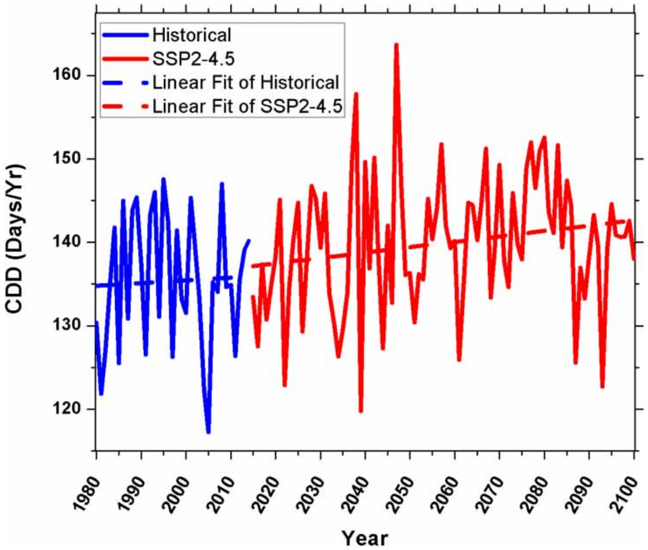


Figure 5 | Interannual variability of consecutive dry days (CDDs; days/year) over the 21st century from the historical period (1980–2009) under the SSP2-4.5 scenario across Zambia, averaged over longitudes 21.8°E–34°E and latitudes 18°S–8°S, based on CMIP6 multi-model ensemble projections.

3.3.1. Future single-day extreme wetness and WASH access

The observation that single-day extreme wet events will increase in the near future across much of Zambia suggests a higher risk of rainstorms and floods facilitating and accelerating the transmission of water-borne diseases such as cholera to new locations. There is overwhelming evidence from cholera transmission mechanistic models that rainfall is a statistically significant driver of cholera outbreaks through several transmission pathways but mainly by increasing people's exposure to contaminated water, especially when coupled with deteriorating sanitary conditions during extreme rainfall events (Lemaitre *et al.* 2019; Elimian *et al.* 2020; Kruger *et al.* 2022; Wheeler *et al.* 2023).

Based on these projections, cholera outbreaks are expected to take their toll along the Copperbelt–Livingstone railroad from the north to the south of the country where record-breaking heavy rainfall events are expected (Figure 6(a)). Climate change will create hostile consequences for humanity and other systems such as WASH (IPCC 2020), with higher risks of climate change-induced outbreaks of cholera expected across areas along the line of rail that are also projected to experience rapid population expansion in the near future (Figure 7). At the current annual average population growth of 3.4% (ZAMSTATS 2022), Zambia is projected to experience increases of up to 60 million by the end of the century (see: https://ourworldindata.org/future-population-growth accessed 10 March 2023), rapid increases are especially projected in the Kitwe and Ndola regions on the Copperbelt, the Kabwe region in Central Province, all of Lusaka Province, the Livingstone region in the Southern Province, and the Chipata region in Eastern Province (Figure 7). Parts of Northwestern Province are also projected to experience an increase in single-day extreme rainfall events (see Figure 6), but these areas are unlikely to experience rapid population growth which, therefore, minimizes the hazard risk.

A closer look at the future climate risk of the Kitwe and Ndola regions on the Copperbelt, the Kabwe region in Central Province, all of Lusaka Province, the Livingstone region in the Southern Province, and the Chipata region in Eastern Province reveals that by the middle of the century, an increase in water runoff ranging between 50–100% with respect to the 1981–2010 baseline period should be expected (see climateinformation.org; accessed 16 March 2023). Water runoff is a major source of pollutants because as the water runs on any given surface, it carries bacteria and other pollutants to surface water bodies. Poorly built or managed sanitation facilities can also encourage pathogens, bacteria, and other waste to seep into groundwater (EPA 2015). As such the Kitwe and Ndola regions on the Copperbelt, the Kabwe region in Central Province, all of Lusaka Province, the Livingstone region in the Southern Province, and the Chipata region in Eastern Province will be at a higher risk of bacterial diseases, especially cholera in the near future. With 11 out of 18 models agreeing on the potential increase of runoff across the Kitwe and Ndola regions on the Copperbelt, the Kabwe region in Central Province, all of Lusaka Province, the Livingstone region in the Southern Province, and the Chipata region in Eastern Province, the confidence in the

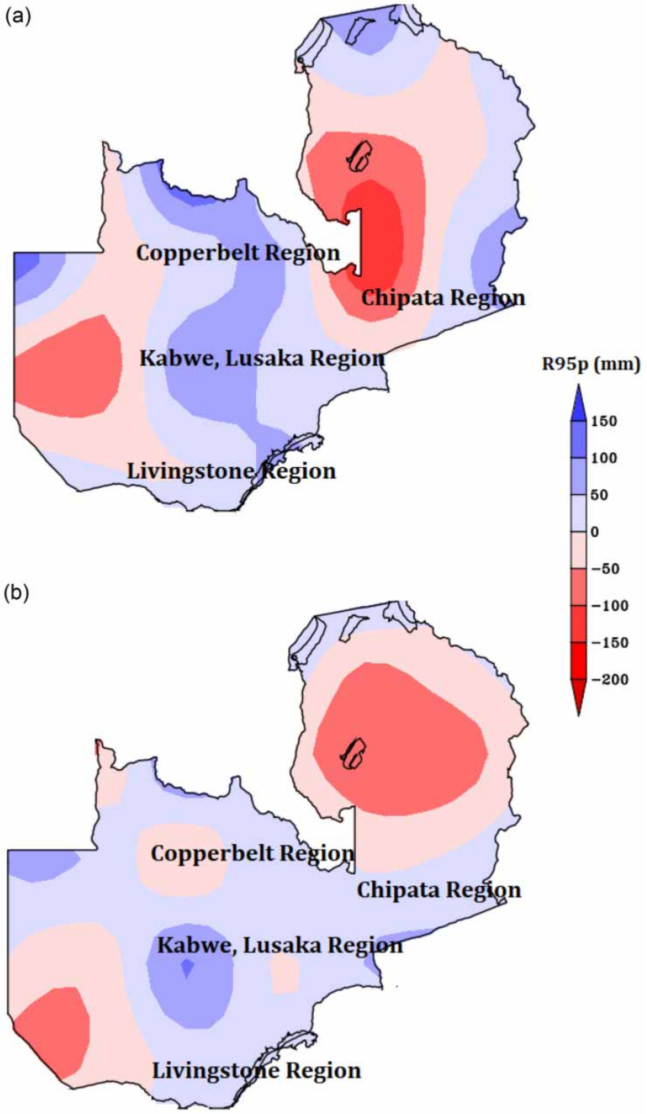


Figure 6 | Anomalies of heavy rainfall events (R95p mm/year) under the SSP2-4.5 scenario with respect to the 1980–2009 baseline period across Zambia for (a) the near future, i.e., 2025–2054 and (b) the far future, i.e., 2071–2100, averaged over longitudes 21.8°E–34°E and latitudes 18°S–8°S, based on CMIP6 multi-model ensemble projections.

projections is high. Similar to the statement made above regarding heavy rainfall events and population, areas with lower populations will have less risk. While several other parts of the country are expected to experience an increase in runoff, the projected population growth across these areas is not as high as in the Kitwe and Ndola regions on the Copperbelt, the Kabwe region in Central Province, all of Lusaka Province, the Livingstone region in the Southern Province, and the Chipata region in Eastern Province, thus minimizing the hazard risk.

3.3.2. Future single-day extreme dryness and WASH access

The observation that areas such as Livingstone in Southern Province, the Chipata region in Eastern Province, and greater Solwezi in Northwestern Province will experience the largest dryness in both the near and the far future (Figure 4) suggests a higher risk of increased aridity across these areas. Considering that these areas are also projected to experience rapid population growth in the near future (Figure 7), the concentration of the population in these areas, especially the Livingstone region in Southern Province and the Chipata region in Eastern Province will likely lead to an ecosystem imbalance which will create a new challenge of accessing safe drinking water and this will likely trigger conflicts. In a nutshell, population

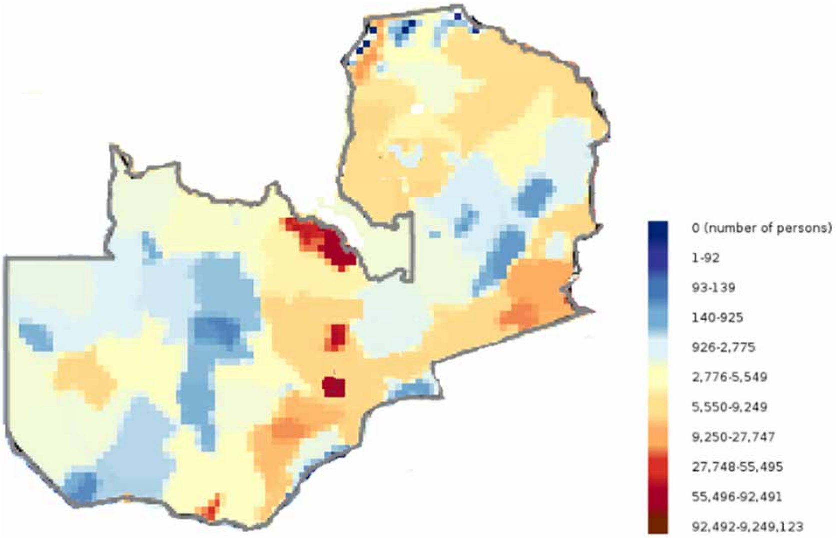


Figure 7 | Projections of population across Zambia in the near future (i.e., until 2050), based on the data from the United Nations Population Division (https://population.un.org/wpp/Download/; accessed 10 March 2023) also available at: https://ourworldindata.org/future-population-growth accessed 10 March 2023.

growth has been known to intensely aggravate water demand and strain water supplies which usually leads to community conflicts, e.g., in the middle east where limited freshwater has been plaguing the region for years (Gadain & Libanda 2023). Limited freshwater access is, therefore, widely regarded as a security challenge (UPI 2009).

In the near future, therefore, areas around the Livingstone region in Southern Province and the Chipata region in Eastern Province are projected to be affected by both water scarcity and an increased spread of bacterial diseases such as cholera. This is especially true considering that under limited freshwater availability, food storage is usually associated with degraded hygiene (Kanamaru 2009). Findings embodied herein have high confidence and complement those of the IPCC's latest assessment which documents that the region is expected to suffer from critical dryness beginning at the 1.5 °C global warming level and high temperatures are expected to enhance evapotranspiration from the region's mega-water bodies which will exacerbate aridification (Hoegh-Guldberg *et al.* 2018).

4. FGD-RECOMMENDED WASH–CLIMATE ACTION

4.1. Flood-resilient WASH action

Results from the focus group discussions (FGDs) show that due to the projected increase in single-day heavy rainfall events in some areas, the development and monitoring of local-scale precipitation thresholds to trigger flood prevention strategies is indispensable. These locations include: Kitwe and Ndola regions on the Copperbelt, the Kabwe region in Central Province, all of Lusaka Province, the Livingstone region in the Southern Province, and the Chipata region in Eastern Province. While it is known that floods invariably damage WASH infrastructure such as sewers and latrines (Milupi *et al.* 2022) and cause them to overflow, thereby introducing the Vibrio cholerae bacteria into otherwise clean water sources (Jutla *et al.* 2013; Erickson *et al.* 2019), no monitoring of precipitation thresholds exists for the identified areas. Hydrographic datasets combining past precipitation amounts, duration, and flood occurrences can aid the development of thresholds and flood return intervals for the identified areas. Thresholds can then be used in tandem with weather and El Niño forecasts to issue WASH-specific early warning information for early action. This is especially important considering that El Niño events increase cholera incidence by 300% in El Niño-sensitive regions such as Zambia (Moore *et al.* 2017). By extension, improved national and subnational technical capacity to adequately monitor, collect, and forecast the weather and climate at both short- and long-term timescales is crucial as such information can support decision-makers and aid workers to focus cholera prevention efforts on areas forecasted to experience heavy downpours and floods.

Recent evidence shows that the uptake and ownership of climate information by end users can be enhanced if indigenous climate knowledge is blended with contemporary scientific knowledge (Mushimbei & Libanda 2022). For effective cholera prevention and preparation mechanisms, FGD participants recommended renewed interest in dialogues among WASH-related sectors, end users, indigenous climate knowledge experts, and the national weather service. In turn, these dialogues can strengthen institutional arrangements and create a conducive multi-stakeholder environment for data exchange which will in turn improve access to weather-informed health advisories. Furthermore, multi-stakeholder collaboration can enhance access to data required to support project proposals aimed at improving access to climate finance for effective implementation of WASH–climate change policies. This would also help with championing private sector engagement by straightening the misalignment of policies at all levels including legal and regulatory frameworks. Project proposals can include investment in sanitation improvements, especially for highly populated areas with inadequate sanitation and thus at risk of cholera, such as informal settlements of the Kitwe and Ndola regions on the Copperbelt, the Kabwe region in Central Province, all of Lusaka Province, the Livingstone region in the Southern Province, and the Chipata region in Eastern Province. By extension, multi-sectoral approaches can be used to mitigate risks resulting from increased single-day rainfall events and a drier Zambia in the near and far future.

Results further show that poor drainage networks in Zambia's urban areas exacerbate flooding which then triggers the spread of water-borne diseases. A focus on building urban resilience against floods is therefore recommended. As a first step, drainage mapping for every city, especially Lusaka, is strongly recommended. FGD participants highlighted that all drainages need to be interconnected to ensure the effective direction of flood waters to lowlands. Social norms also need to be addressed if the clogging of drains is to be averted. Regarding rural interventions, project ideas should be gender and culturally sensitive. For instance, it is considered taboo for in-laws to use the same toilet in certain cultures; as such, if projects are not gender and culturally sensitive, OD may not be eradicated, and the spread of cholera outbreaks may not be curbed. This finding agrees with that of Bhatt *et al.* (2019) who documented that OD is usually by compulsion rather than choice.

4.2. Drought-resilient WASH action

The immediate impact of drier-than-usual climates on populations is strained access to safe drinking water (UNICEF 2022a, 2022b). The models point to a drier-than-usual Zambia in the near and far future, especially in the Livingstone region in the Southern Province and the Chipata region in the Eastern Province. This unusual dryness will result in protracted droughts leading to dire water shortages, and reduced groundwater levels compounded by increased pumping during drought. The projected enhanced droughts by the middle of the century will lower water levels to critically low levels in some regions. This will in turn make drilling of boreholes more expensive. This price increase will likely occur in the Livingstone region in Southern Province and the Chipata region in Eastern Province. To this end, strategic investment in enhancing water access should be considered a matter of urgency. Deep groundwater mapping across the Livingstone region in Southern Province and the Chipata region in Eastern Province to ascertain where groundwater is available is recommended before any climate change-resilient water resources investments.

Cholera transmission is also closely associated with limited access to reliable sanitation facilities (Wolfe *et al.* 2018). Although improved sanitation is an expensive proposition because of manifold technological challenges, rapid urbanization points to the need for safe water and improved sanitation access (Mintz *et al.* 2001; Waldman *et al.* 2013). Peri-urban unplanned settlements, refugee camps, and areas populated by internally displaced people are usually at higher risk when minimum sanitation needs are not met. Investments in sanitation improvements in the Livingstone region in Southern Province and the Chipata region in Eastern Province are, therefore, recommended. These high-risk areas can also be supported with projects that focus on enhancing artificial recharge and the control of runoff through the establishment of green areas and groundwater recharge wells.

4.3. Other considerations

For effective adaptation, FGD participants recommended that findings from this climate assessment should be incorporated into policy to inform decisions about WASH-related climate interventions. By extension, this would facilitate government-supported capacity building on climate assessments to help strengthen the climate rationale of WASH-related resilience initiatives at all levels for both personnel and mandated institutions.

5. CONCLUDING THOUGHTS

Climate change is undeniably a water, sanitation, and hygiene crisis. However, very little research work has been done to understand the interlinkages between climate change and WASH in Zambia. The present study was designed to develop a solid climate science basis for WASH–climate action in Zambia. Two key findings emerge from the analysis: first, in the near future, the stretch along the Copperbelt–Livingstone railroad from the north to the south of the country is expected to record an increase in single-day heavy rainfall events. As such, bacterial diseases such as cholera outbreaks are expected to increase. While Zambia overall will experience population increases of up to 60 million by the end of the century, rapid increases are especially projected in the Kitwe and Ndola region on the Copperbelt Province, the Kabwe region in Central Province, all of Lusaka Province, and the Livingstone region in Southern Province. These areas are therefore most at risk of cholera outbreaks. Second, models predict a drier Zambia in the near and far future, especially in the Livingstone region in Southern Province and the Chipata region in Eastern Province. This finding suggests a higher risk of increased aridity in these regions. Despite the insights embodied in the present work, there is abundant room for future research. Additional research would be helpful related to groundwater vulnerability mapping to determine available aquifers that can be exploited; storage capacities of water to survive droughts; innovative and durable sanitation facilities that can survive floods; exploration of water-reducing technologies such as low-flow handwashing and toilets that do not depend on water; and more climate-friendly menstrual health and hygiene management products. Furthermore, urgent implementation of measures to enhance national water storage is strongly recommended. These should include a mix of traditional approaches (e.g., rainwater harvesting, dam construction) and nature-based solutions (e.g., restoration of wetlands).

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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