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Article

Response of Water Supplies and Household Toilets to Climate Extremes: Evidence from Southern Malawi

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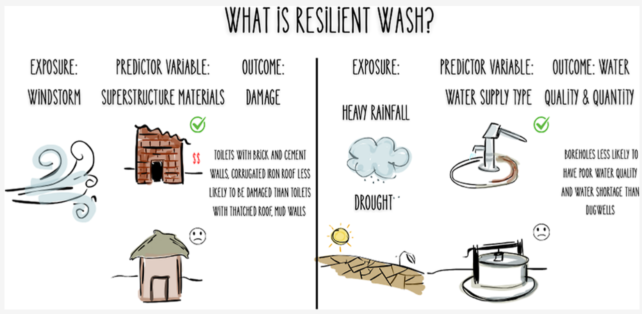
ABSTRACT: Extreme climate events damage water and sanitation infrastructure and disrupt services for millions of people globally. There is consensus that improving the response of services to climate threats will require investment in institutions, service management, and infrastructure. However, there is limited practical evidence from sub-Saharan Africa on how users and service providers can make services more resilient. The goal of this study was to collect such evidence from the southern district of Malawi, which is frequently hit by natural disasters. Our findings revealed that heavy rainfall, long dry spells, and cyclones are affecting services, but this varied by infrastructure type and factors related to management and maintenance. Boreholes with hand pumps were more resilient to changes in water quantity and quality than other water supply types; breakdown in dry seasons was affected by the group responsible for repair, whereas toilets with more robust superstructures were more resilient to cyclones and flooding.



KEYWORDS: *adaptation, climate, drought, cyclone, flood, resilience, windstorms*

INTRODUCTION

Climate extremes are a serious threat to water and sanitation services in Malawi, where frequent exposure coexists with vulnerability.[1,2] An estimated 1.5 million people are affected by drought and water scarcity annually, mainly in central and southern Malawi.[3] The 2015/2016 drought caused water supply damage and losses worth 11.8 million USD, mainly through dried up boreholes, damaged equipment caused by high turbidity, and vandalized pipes.[4] In 2024, El-Niño conditions led to long dry spells, which are projected to be followed by above-average rainfall and flooding in early 2025, putting 1.5 million people in need of water, sanitation, and hygiene (WASH)-sector assistance.[5]

These climate shocks come after three cyclones—Idai, Gombe, and Freddy—hit southern Malawi in the last six years and affected WASH services for over 1 million people.[6,7] Storms and flooding damaged toilets, contaminated boreholes, and disrupted access to soap.[7−9] This agrees with the substantial global evidence on the impacts of extreme events on WASH and has led the Government of Malawi to list drought, flooding, and tropical cyclones (which are characterized by strong winds and often bring heavy rainfall) as the top risks to the sector.[10−14]

The public health implications of this are serious. Cholera and an increase in diarrhea cases have been reported after previous tropical storms and droughts in Malawi, associated with displaced populations and disrupted access to WASH and healthcare.[4,6,7] Globally, intense rainfall and flooding often precede waterborne outbreaks in areas with poor water supply and sanitation.[15,16] Multicountry studies have shown positive associations between childhood diarrhea and exposure to flooding and drought, impacted by the level of access to water supply, soap, and feces disposal practices.[17−19]

The increase in climate extremes projected for Malawi[20,21] and the public health consequences have focused attention on the need for adaptation.[10] There is consensus that this will require stronger institutions, improved management, and robust infrastructure.[22,23] Malawi's Nationally Determined Contributions include strategies for adaptation through improved monitoring, better sanitation and hygiene, and water resource management.[24] However, there is little evidence from Malawi of the factors determining the response of services to climate extremes or the impact of adaptation actions.

Therefore, the aim of this study was to collect this evidence for rural water supplies and toilets and document adaptation actions taken by households in the southern district of Thyolo, which is regularly exposed to climate-related extremes. In particular, we wanted to answer the following research

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Table 1. Characteristics and Performance of Water Supplies

summary responses by household users		percentage of total responses (n = 398)
geographical zone	highlands	28
	midlands	63
	lowlands	9
type of water supply	borehole with hand pump	81
	unprotected dug well	9
	protected dug well	5
	piped supply with motorized borehole	3
	protected spring	1
	unprotected spring	1
negative performance outcomes reported by users	breakdown for 3+ days	41
	seasonal changes in collection time	26
	seasonal changes in taste, color, or smell	21
	cannot collect water when needed	4

summary responses by water point committees		percentage of total responses (n = 130)
technical guidelines followed during siting and construction	yes	18
	no	9
	not sure	73
community involvement in water supply management	no involvement	1
	very little involvement	78
	active involvement	21
tariff collection	monthly	82
	quarterly	2
	annually	6
	at time of breakdown	3
	no tariff paid	7
cost recovery	operating costs	84

summary responses by water point committees		percentage of total responses (n = 130)
	cost of maintenance and minor repairs	88
	cost of upgrading/building new infrastructure	30
spare parts	all parts and consumables are stored locally	5
	some parts and consumables are stored locally	83
	no parts and consumables are stored locally, but are easily available in the nearest town	11
	no parts and consumables are stored locally or easily available in the nearest town	2
perception of government support	no support	85
	inadequate support	12
	adequate support	2
monitoring	measurement of source water yield	0
	water quality testing	16
	- *E. coli* is tested once a year	1
	- turbidity	
negative performance outcomes reported by water point committee	old worn out parts	81
	broken parts	73
	leaks in pipes and reservoirs	16
	structural problems	16
	water shortage in the dry season	15
	vandalism/theft	8
	muddy water/poor water quality in the rainy season	4
	damage to pipes in the dry season	2
	source dries up	2
	damage to pipes during heavy rainfall	1

question: How do water supplies and household toilets in the southern Malawi district of Thyolo respond to climate extremes, and how do households adapt?

■ METHODS

Study Setting. Thyolo is a district in southern Malawi (Figure S1). Over half of the land area is hilly, especially in the south and southwest parts of the district. The hilly areas have historically received between 1200 and 1600 mm of annual rainfall, while the plains receive between 800 and 1200 mm.

Thyolo is divided into 27 administrative units called Traditional Authorities (TAs). According to the Thyolo District WASH survey conducted in 2021, there were 3632 water points in the district, predominantly boreholes and shallow wells equipped with Afridev hand pumps.[25] Household sanitation coverage in 2021 was 76%. The most common type of facility was a pit latrine. Only 2% of household water supplies met the criteria for safely managed service set by the WHO UNICEF Joint Monitoring Programme,[26] and none of the toilets met the criteria for safely managed sanitation.[25]

This study was carried out in 7 TAs, chosen in consultation with Self Help Africa (SHA)—an international charity working in the Malawi WASH sector since 1992—and district stakeholders. These TAs were prioritized on the basis of their exposure to natural hazards, population density, and priority program areas for SHA.

Sample Size Calculation. According to the Thyolo District Council, there are a total of 81,059 households in the 7 selected TAs. The household sample size was calculated to ensure a 95% confidence interval, 5% margin of error, and the population proportion of 76% of households with a functional toilet. This gave a sample size of 383. Assuming a nonresponse rate of 10%, the final sample size was 421 households, which were chosen randomly. Water points in the same TAs were also chosen randomly for a total of 130 water points.

Data Collection. A household survey was developed based on tools used in previous work in Ethiopia, Uganda, and Nepal,[27−30] as well as household surveys previously implemented by SHA in Malawi. The survey was designed to collect data on user experience in four key areas: exposures, or the climate hazards faced by the community; outcomes from

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hazardous events (the frequency and type of disruptions, performance of services after extreme events); household coping mechanisms; and risk factors (independent variables) at the water point and toilets that could explain whether exposure to hazards leads to negative outcomes such as environmental conditions, infrastructure type, and strength of management. Questions on exposures were developed after consultation with SHA. Questions on potential outcomes and risk factors were selected based on a review of previous work on climate resilience of water supplies and sanitation.[27−30]

Visual inspection of infrastructure was done to identify risks from poor siting and design, nondurable construction materials, or poor maintenance that could make infrastructure vulnerable to climate extremes. For drinking water supplies, enumerators inspected the source, storage tanks, and hand pumps or taps to identify the risk of river or flash flooding, significant areas of bare rock or earth uphill of any infrastructure, and evidence of animal or human feces. For sanitation, the assessment was done at the toilet only since no fecal sludge treatment plants or disposal sites exist in the study area and included questions on the proximity to flood-prone surface waters, risk of flash flooding, bare earth or risk uphill of the toilet, design and construction of the superstructure, and accessibility of the containment for emptying. Checklist design was informed by sanitary inspection forms used by the World Health Organization,[31,32] checklists used by Kohlitz et al.,[28] and parts of the water point functionality survey used by SHA in Malawi that focused on inspection of contamination risks near the water point.

Semistructured surveys were done with water point committee (WPC) members who manage the water supplies in the study area, partly informed by SHA's water point functionality survey that included questions on water supply performance and management with relevance to climate resilience. These were designed to capture the strength of management in monitoring risks from changing temperature and rainfall patterns; the ability of operators to prevent and manage disruptions to water supply, especially during and after heavy rainfall, long dry seasons, and extreme events; and their ability to undertake preventative maintenance and repairs based on their skills, available resources, and support from authorities. The survey also captured the included questions on the availability of spare parts and disruptions caused by damaged road networks after flooding, landslides, or cyclones.

Ethical approval was obtained from the University of Bristol Faculty of Engineering Research Ethics Committee (reference number: 18743, approved March 15, 2024). Surveys and checklists were uploaded to the mWater web portal.[33] Enumerators, who were recruited and trained by SHA Malawi's Monitoring and Evaluation team, collected data through the mWater mobile app.[31]

Data Analysis. Data was imported from the mWater web portal[33] and cleaned in Microsoft Excel 365 (Microsoft Corporation, 2024). Data from 398 correctly filled out surveys were analyzed using SPSS v. 24. Descriptive statistics were used to analyze characteristics of water supplies and toilets. Associations between independent variables related to environmental conditions, infrastructure type, management, and household income that could impact services and negative outcomes for users (e.g., length of water supply breakdown, water shortage, or damage to toilet) were explored through nonparametric tests that do not require a normally distributed sample. Specifically, we used Pearson's chi-square test of independence or Fisher's exact test if the sample size was too small. For statistically significant associations, posthoc analysis with Bonferroni correction was done to further explore differences between groups by calculating residuals. Additionally, odds ratios were calculated for binary variables. In all cases, a p-value of 0.05 was set as the threshold of significance.

RESULTS

Water Supply Characteristics. Of the 398 households in the study, 81% collected water primarily from a borehole with an Afridev hand pump (Table 1). The piped water supplies were sourced from springs (5%) or a borehole connected to solar panels or the grid (2%). The average distance to the water point was 207 m, and it took respondents 33 min to collect water, including queuing. The average age of the water supplies was 13 ± 9 years.

81% (n = 323) of study households paid for water, and this was statistically associated with the type of water supply (Pearson's chi-square = 25.4, $p < 0.001$). Households using piped supplies and boreholes with hand pumps were more likely to pay for water. On average, households paid 292 Malawian Kwacha, or 0.17 USD per month (MWK; 1 USD = 1735 MWK).

Management of Water Supply. Service provision followed a community management model with WPCs responsible for maintenance and tariff collection at the village level. Households reported multiple entities in charge of repairs, including WPCs (n = 220, 55%), users (n = 161, 40%), and area mechanics hired by the district (n = 28, 7%).

According to the WPC members, all but four of the 130 water points in the service provider survey had more than 50% female members. 80% of the respondents had been part of the committee between 1 and 5 years. 45% of them were involved in the siting, construction, or operation of the water supply. Other characteristics related to management are shown in Table 1.

Negative Outcomes for Water Supply. Households reported breakdown of the water point for more than 3 days (n = 164, 41%), seasonal change in the time taken to collect water (n = 105, 26%), and seasonal changes in taste, color, or smell of water (n = 82, 21%) as the main water supply issues (Table 1). The breakdown of 3+ days was unrelated to climate hazards and instead was caused by a lack of spare parts, reported by 115 households, a lack of funds to repair the water point (n = 79), and insufficient skills of the WPC (n = 34). Only five households reported a climate-related event—waiting for floodwater to subside—as a cause for long breakdown.

The other outcomes reported by households were linked to the climate. Seasonal change in collection time was caused by water shortage in the dry season (n = 69), damage or flooding of roads after heavy rainfall (n = 32), mechanical breakdown of water points in the dry season (n = 19), and flooding around the water point (n = 15). When asked to elaborate on the changes in taste, color, or smell of the water, households reported muddy water and "metallic", "moldy", or "salty" taste in the rainy season.

The three most common issues reported by WPC members were related to the condition of the infrastructure and not to any climate extremes. These were old worn-out parts (n = 105, 81%), broken parts (n = 95, 73%), leaks in pipes and reservoirs (n = 21, 16%), and structural problems and cracks (n = 21, 16%) (Table 1). Other, less frequently reported outcomes

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were linked to climate extremes. These were water shortage in the dry season (n = 19, 15%), poor water quality in the rainy season (n = 5, 4%), damage to pipes (n = 4, 3%), and source drying up in the dry season (n = 2, 2%). Water shortages occurred between 2 and 8 times a year and lasted between 2 and 10 days. The duration and frequency of downtime for other damage and disruptions from heavy rainfall and dry season (Table 1) are given in Tables S1 and S2. No damage to water supplies from landslides or cyclones was reported.

Coping Mechanisms. 249 (63%) households coped with insufficient or unavailable water supply by collecting water from an alternative source (n = 220) or reducing their nonconsumptive water use (n = 33). The odds of using an alternative supply were 4.5 times higher during heavy rainfall or flooding than in the dry season (95% CI = 1.86, 10.74, p < 0.001). The most common alternative source was a borehole with hand pump but 16% (n = 22) switched from an improved to an unimproved source like unprotected dug wells or unprotected springs. The type of alternative source was not associated with the threat to the water supply (Fisher's exact test value = 7.39, p = 0.38) or household income (Fisher's exact test value = 16.14, p = 0.32).

Households chose the alternative source based on water availability (n = 170), distance to household (n = 64), and taste, color, or smell (n = 11). Four households based their choice on cost. The average distance to an alternative source was 509 m, compared to 207 m for the primary source. The time to collect water, including queuing time, was 48 min, an increase from 33 min for the primary source. Half the households (n = 111) did not pay to use the alternative source. The rest were paid between 6 and 500 MWK per day, compared to 292 MWK per month (just under 10 MWK per day) for the primary source.

WPC members reported responding to damage or disruptions by either doing the repairs themselves or calling an area mechanic contracted by the district. Only one WPC had made an emergency response plan by keeping aside 80,000 MWK to purchase water for 5 days.

Toilet Characteristics. Out of 398 households, 95% (n = 377) reported access to a toilet. The other 21 reported defecating in a field or open drain. The most common type of toilet was a pit latrine without a slab located outside the house but within the compound (Table 1).

According to the household survey, containments were emptied for fewer than 1% (n = 3) of the 377 toilets. One person reported calling a private service with equipment, and 2 people emptied the containment themselves when they were full. One of these two people said they did not know who to call to get the containment emptied; the other used sludge as manure. 156 respondents (38%) said their containment had been full in the past, but they did not remove the sludge either because they were unsure how to remove it or the containment could not be opened. Cost was not reported as a reason for not removing waste; 221 respondents (56%) said their containment had never been full. Reports of containment being full were associated with the age of the toilet (Pearson's chi-square = 11.48, p = 0.02).

Visual inspection of toilets and their surroundings revealed several risks. 11% of the toilets were at risk of damage from falling debris or loose rocks, 6% were in a location prone to flooding from rapid runoff, and 2% were near flood-prone surface waters.

Negative Outcomes for Toilets and Coping Mechanisms. According to households, 23% (n = 88) of toilets were affected by cyclones, which caused damage, flooding, or both, and falling debris, which caused damage. Users reported that half of the toilets became unusable as a result. Other outcomes, reported by fewer than 10% of households, are shown in Table 2. Two-thirds of users (n = 62) did the repair themselves, and the rest hired a mason. The most common type of repair needed was rebuilding of the superstructure (89%), followed by rebuilding the containment (28%). The odds of users not being able to use the toilet were higher if the containment needed rebuilding [Pearson's chi-square = 7.88, p < 0.01; OR = 4.22 (95% CI = 1.49, 12.00)].

Table 2. Characteristics and Performance of Toilets

summary responses by household users		percentage of total responses (n = 398)
type of toilet	pit latrine without slab	77
	pit latrine with slab	15
	composting toilet	1
	ventilated Improved Pit (VIP) latrine	<1
	maize stalk toilet	<1
	open defecation	5
	not sure	<1
primary place of defecation	toilet outside the house but within the compound	72
	toilet outside the compound shared with other households	22
	neighbor or family member's toilet	5
	near a drain, field, or open area	5
	toilet inside the house	<1
negative performance outcomes reported by users	flooding of superstructure during cyclone	19
	damage to toilet from high winds or falling debris	18
	unable to physically access the toilet in the rainy season	9
	flooding of superstructure during flash flood	4
	blockage in dry weather	2
	flooding or damage to the containment	1
	flooding of superstructure during river flood	<1

93% (n = 38) of households reported coping with an unusable toilet by using a neighbor's toilet or another toilet in their house, while 7% (n = 3) defecated in the open, which is approximately 1% of the total study sample.

Perception of Risk and Adaptation Actions. Households perceived a threat to their water supply from drought, heavy rainfall, flooding, and landslides leading to water shortage (n = 226, 57%), damage to water points (n = 125, 31%), and changes in water quality (n = 109, 27%). However, only 12% (n = 46) have taken steps to make their water supply safer or more reliable by using household water treatment chemicals (n = 39), boiling water (n = 18), and constructing runoff diversion at the water point (n = 4).

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A comparable number of households felt that these climate extremes could damage or collapse toilet superstructures (n = 233, 56%), but fewer than 10% (n = 14) have paid to build a stronger structure. Other adaptations included a retaining wall around the toilet (5%) and an increase in the height of the toilet (3%). In all cases, the toilet was raised 1 m above the ground.

Associations between Independent Variables and Negative Outcomes. Associations between reports of negative outcomes after climate extremes and independent variables related to environmental conditions, infrastructure, management, and household income were explored to identify factors that could explain the response of water supplies and toilets when exposed to climate extremes.

Household reports of negative outcomes in water supply were statistically associated with water supply type, geographical zone, and the group responsible for repair and payment for water. Posthoc analysis showed significant variations in these outcomes between households in the highlands and midlands, between those using dug wells and boreholes with hand pumps, and between water supplies repaired by WPCs and area mechanics (Table 3).

Reports of low water availability in the dry season by WPC members were also associated with water supply type (Fisher's exact test value = 25.15, $p < 0.001$). Posthoc analysis showed that boreholes with hand pumps were less likely to have shortages (post hoc analysis adjusted residual <-1.96, adjusted p-value <0.001), and spring sources were more likely to have shortages (post hoc analysis adjusted residual >1.96, adjusted p-value <0.001). The number of WPCs reporting other types of damage was too small to explore associations with service attributes.

For households reporting exposure to cyclones, landslides, and flooding, the odds of reporting toilet damage or superstructure flooding were associated with the materials and condition of the toilet, as observed by enumerators (Table 4). The other outcomes reported by households (Table 1) could not be tested for association because of the low frequency of occurrence in the survey responses.

Household income, ranging from less than 50,000 MWK to more than 200,000 MWK per year, was associated with exposure, condition of toilets, likelihood of experiencing negative outcomes and perceived capacity to adapt. The lowest-income households were more likely to report exposure to river flooding (Pearson's chi-square = 24.40, $p < 0.001$) and landslides (Pearson's chi-square = 21.27, $p < 0.001$), but not cyclones or any other type of flooding.

Annual income was also associated with the presence of a toilet roof (Pearson's chi-square = 13.09, $p = 0.004$), roof built of corrugated iron (Pearson's chi-square = 9.29, $p = 0.03$), and the absence of urine or feces around the toilet (Pearson's chi-square = 37.09, $p < 0.001$) but not with the presence of leaks in the roof, missing or cracked containment cover, cracks in the slab, or walls built with bricks. Associations between income and negative outcomes are shown in Table 3.

Income was also associated with steps to make the water supply safer (Pearson's chi-square = 13.04, $p = 0.005$) but not with reports of payment to make toilets less susceptible to flooding or damage.

DISCUSSION

This paper presents findings on the exposure of rural water and sanitation services to climate extremes in southern Malawi, the resulting negative outcomes, consequences for users, and associated factors that impacted the exposure-outcome relationship in the study area. The damage and disruption reported by users and WPCs is in line with evidence from other parts of the country and globally[9,34,35] and contributes to emerging evidence with implications for planning and monitoring climate resilient WASH.

Water Supply. Drought and heavy rainfall were the biggest climate-related threats to households, affecting the availability, quantity, and quality of the water supply. Users were more likely to collect water from an alternative source in the rainy season and reduce water usage in the dry season, in some cases leading to increased public health risks when unimproved sources were used. The use of multiple water sources is a well-documented coping strategy in low-income households in LMICs[36] and suggests that building resilience may require improvements in secondary as well as primary water sources.

Factors affecting the choice of alternative source were similar to those reported from other parts of Malawi.[37] In community water supplies, where donation of labor may be the principal form of contribution, financial aspects are often not a driver for water source choice but have been reported as a driver in urban areas.[38,39] Perceptions of water quality and safety are often shaped by the appearance and physical properties of water in households in LMICs; thus, safety is rarely a key driver.[40,41]

The other commonly reported outcome of long breakdowns was related to management of the water supply rather than exposure to climate extremes. Weak management capacity is widely linked with lower functionality of rural supply[42] and also illustrates that these water supplies are likely to be vulnerable to climate hazards in the future.

Risk factors were identified that explain the link between climate exposures and negative outcomes in the study area. Water shortage in the dry season and water quality deterioration in the rainy season were less likely to be reported for boreholes relative to the other water supply types in the study area, which is consistent with other studies.[43−46] However, borehole performance is still sensitive to aquifer characteristics, siting, and proper construction,[47−49] all of which will be essential for safe water supply during and after extreme events.

Challenging groundwater conditions may also require a shift in the types of technologies that are promoted. A recent study in Malawi found that 15% of boreholes were sited in areas where aquifer transmissivity cannot sustain the yield for Afridev hand pumps, the most common type of hand pump used in the country.[49,50] In such areas, ensuring a resilient water supply will require selecting more appropriate technologies, including looking beyond boreholes.

Reports of negative outcomes were also based on payment of tariffs and the group responsible for repair. Our findings could imply that users were more likely to call an area mechanic if there were mechanical breakdowns in the dry season, but qualitative data are needed to confirm this. Analysis of factors associated with long breakdowns showed that a lack of funds disincentivized communities from accessing area mechanics, while a lack of knowledge of the water system within the WPC made it more likely that users called an area mechanic.

The impact of the affordability and availability of spare parts and repair services on water supply functioning has been consistently reported from across sub-Saharan Africa, including

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Table 3. Associations between Independent Variables and Negative Outcomes for Water Supply Reported by Households (Bold Indicates Statistically Significant Result Test Value Provided Is Pearson's Chi-Square Value or Fisher's Exact Test Value, If Underlined. Odds Ratios Were Only Calculated if Both Independent and Outcome Variables Were Binary)

	independent variable						
outcome	water supply type Pearson's chi-square value or Fisher's exact test value, if underlined	posthoc analysis	geographical zone (Pearson's chi-square value or Fisher's exact test value, if underlined)	posthoc analysis	responsibility for repair (Pearson's chi-square value or Fisher's exact test value, if underlined)	posthoc analysis	payment of tariff (Pearson's chi-square value or Fisher's exact test value, if underlined)
Seasonal change in collection time caused by water shortage	**10.66** (p = 0.009)	households using dug wells less likely to report outcome (adjusted residual <−1.96, adjusted p-value = 0.004); households using boreholes with hand pumps more likely (adjusted residual >1.96, adjusted p-value = 0.004). No variation in outcome for springs and motorized boreholes	**13.33** (p < 0.001)	Households in the highlands less likely to report outcome (adjusted residual <−1.96, adjusted p-value < 0.001). No significant variation in outcome for lowlands and midlands	association not explored	n/a	association not explored
seasonal change in collection time caused by mechanical breakdown in dry season	6.69 (p = 0.06)	n/a	1.91 (p = 0.38)	n/a	21.79 (p < 0.001)	outcome less likely to be reported if repair was done by WPCs only (adjusted residual < −1.96, adjusted p-value < 0.001). Outcome more likely to be reported if repair was done by area mechanics and by users (adjusted residual >1.96, adjusted p-value <0.001)	**6.51** (p = 0.011) **OR** = 0.73 **(95% CI= 0.65, 0.83)**
seasonal change in collection time caused by damage or flooding of roads	association not explored	n/a	**24.77** (p < 0.001)	households in the highlands more likely to report outcome (adjusted residual >1.96, adjusted p-value <0.001); households in the midlands less likely to report outcome (adjusted residual <−1.96, adjusted p-value <0.001). No significant variation in outcome for lowlands	association not explored	n/a	association not explored
seasonal change in collection time caused by flooding around the water point	association not explored	n/a	**9.51** (p = 0.009)	Households in the highlands more likely to report outcome (adjusted residual >1.96, adjusted p-value <0.001); No significant variation in outcome for midlands or lowlands	association not explored	n/a	association not explored
breakdown of 3+ days caused by lack of spare parts	25.19 (p < 0.001)	Households using dug wells less likely to report outcome (adjusted residual <−1.96, adjusted p-value < 0.001); households using boreholes with hand pumps more likely (adjusted residual >1.96, adjusted p-value < 0.001). No variation in outcome for springs and motorized boreholes	**6.56** (p = 0.04)	Posthoc analysis did not find significant variations between groups	11.96 (p = 0.011)	Posthoc analysis did not find significant variations between groups	**25.07** (p = 0.011) **OR** = 0.06 **(95% CI= 0.017, 0.234)**
breakdown of 3+ days caused by lack of funds	8.14 (p = 0.074)	n/a	3.09 (p = 0.21)	n/a	20.60 (p < 0.001)	Outcome less likely to be reported if repair was done by area mechanics and by users (adjusted residual < −1.96, adjusted p-value <0.001)	0.47, p = 0.49
breakdown of 3+ days because WPC does not know how to do the repair	4.73 (p = 0.17)	n/a	4.53 (p = 0.10)	n/a	61.71 (p < 0.001)	Outcome less likely to be reported if repair was done by WPCs only (adjusted residual <−1.96, adjusted p-value <0.001). Outcome more likely to be reported if repair was done by area mechanics and by users (adjusted residual >1.96, adjusted p-value <0.001)	association not explored

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Table 3. continued

	independent variable						
outcome	water supply type Pearson's chi-square value or Fisher's exact test value, if underlined	posthoc analysis	geographical zone (Pearson's chi-square value or Fisher's exact test value, if underlined)	posthoc analysis	responsibility for repair (Pearson's chi-square value or Fisher's exact test value, if underlined)	posthoc analysis	payment of tariff (Pearson's chi-square value or Fisher's exact test value, if underlined)
seasonal change in taste, color or smell	**39.85** (p < 0.001)	households using boreholes less likely to report outcome (adjusted residual <−1.96, adjusted p-value <0.001); households using dug wells more likely (adjusted residual >1.96, adjusted p-value = 0.004). No variation in outcome for springs and motorized boreholes	1.81 (p = 0.40)	n/a	association not explored		association not explored

Note: Bold indicates statistically significant result. Test value provided is Pearson's chi-square value or Fisher's exact test value, if underlined. Odds ratios were only calculated if both independent and outcome variables were binary.

Table 4. Associations between Independent Variables and Negative Outcomes for Toilets (Bold Indicates Statistically Significant Result. Test Value Provided Is Pearson's Chi-Square Value. Odds Ratios Were Only Calculated if Both Independent and Outcome Variables Were Binary)

	independent variable						
Outcome	presence of toilet roof (Pearson's chi-square value and odds ratio)	toilet roof made of corrugated iron (Pearson's chi-square value and odds ratio)	toilet walls made of burnt bricks (Pearson's chi-square value and odds ratio)	raised toilet (Pearson's chi-square value and odds ratio)	household income (Pearson's chi-square value and odds ratio)	geographical zone (Pearson's chi-square value and odds ratio)	Posthoc analysis
Flooding of superstructure during cyclone	**8.51** (p = 0.004) **OR= 0.41 (95% CI= 0.22, 0.75)**	1.86 (p = 0.17)	0.16 (p = 0.69)	0.85 (p = 0.36)	**62.51** (p < 0.001)	**18.26** (p < 0.001)	Households in the highlands more likely to report outcome (adjusted residual >1.96, adjusted p-value < 0.001). Households in the midlands less likely to report outcome (adjusted residual <−1.96, adjusted p-value < 0.001). No significant variation in outcome for lowlands
Damage to toilet from high winds or falling debris	**20.01** (p < 0.001) OR = 0.28 (95% **CI= 0.15, 0.49)**	**7.17** (p = 0.007) **OR= 0.35** (95% **CI= 0.17, 0.77)**	**8.89** (p = 0.003) **OR= 0.43** (95% **CI= 0.25, 0.76)**	1.14 (p = 0.29)	**18.93** (p < 0.001)	3.89 (p = 0.14)	n/a

Note: Bold indicates statistically significant result. Test value provided is Pearson's chi-square value. Odds ratios were only calculated if both independent and outcome variables were binary.

Malawi.[51−54] In areas with decreased rainfall, increased strain on hand pumps and falling groundwater levels during dry spells can lead to mechanical failure.[55,56] In these areas, maintenance and robust supply chains will be crucial to improving the resilience of services.[57]

Sanitation. The biggest threats to sanitation were cyclones and landslides. Toilets built with more robust materials had lower odds of being damaged or flooded. This, along with recent evidence from Malawi linking unlined pits to higher odds of collapse after rainfall,[58] strengthens the argument for the construction of more robust toilets to improve sanitation resilience.[59]

The odds of toilets becoming unusable were significantly associated with the containment needing rebuilding, causing 1% of households to defecate in the open. While this is not a significant proportion of respondents in our study area, higher rates of ODF slippage after damage to toilets in the rainy season have been reported, including from Malawi.[60−62] This could have negative public health consequences for the rural communities using groundwater sources without adequate source protection and treatment[63,64] and by increasing exposure to fecal pathogens in the environment.[65,66]

Lower-income households were less likely to have toilets made of improved materials. Previous studies from Malawi have shown that there is a demand for toilets that do not need frequent rebuilding, but this can be cost prohibitive.[60,67,68] Strengthening the sanitation market and improving access for low-income households could sustain access to toilets during and after extreme events. Interventions providing financial support to low-income households have improved uptake of more robust toilets;[69] however, the level of success also depends on user preference and nonfinancial constraints.[70−72]

Wider Risk Factors. Household income was also associated with exposure to hazards and steps taken to make the water supply safer. This points to the complexity of improving the resilience of services and supports the consideration of environmental and demographic vulnerability in resilience assessments.[73,74]

Poor condition of roads and drainage made water points and toilets inaccessible for some households, as reported in other studies.[35,74] This points to the role of public works investments in improving the resilience of water and sanitation services. Facilities on premises that can be safely accessed during heavy rainfall or flooding may also improve the experiences of users during these extreme events.

Gaps and Recommendations for Further Work. While this study provides evidence on household impacts and some associated factors, several gaps exist. Long-term groundwater data were not easily available, limiting our ability to identify areas most vulnerable to poor groundwater yield or seasonal changes in water levels. Qualitative reports of seasonal trends in water quality could not be confirmed without service provider records or long-term data collection, the latter being outside the scope of this study. Since none of the water supplies had water treatment, we could not investigate the impact of dry season or heavy rainfall on treatment efficacy.

The impact of factors related to management of the water supply could not be explored because of the low number of WPC members who reported these negative outcomes. Access to spare parts, government support, service provider training, and cost recovery affect the performance and recovery of water supplies from climate hazards and will play a crucial role in building resilience to climate change[30,54,59] and we recommend further studies to explore these associations.

Only 1% of the households reported emptying their containment in keeping with the national trend in Malawi,[58] and fecal sludge collection and treatment services did not exist in the study area. Therefore, risks along the sanitation chain and subsequent outcomes for users could not be assessed. This is an important area for future research since heavy rainfall and flooding could disrupt desludging services by making certain locations inaccessible to trucks and damage or disrupt treatment works.[12,75,76]

A similar proportion (∼1%) reported experience of flooded or damaged containments, which is in contrast to the higher rates of 7 to 66% reported elsewhere in Malawi,[77,78] but this may be attributed to differences in local soil and moisture conditions. The low frequency of these responses meant that we were unable to identify associated risk factors despite observing cracks in toilet slabs. Studies have shown that unlined pits and cracked or missing slabs can make containments more vulnerable to seepage of water,[58] and these factors should be explored in future studies.

Finally, the impact of district-level and institutional factors that can affect resilience[22,29,30] was not explored because the study was done in one district only. Larger, multiregion, or multicountry studies are needed to explore these contextual factors.

Implications for Monitoring. This study highlights the potential benefits and limitations of collecting data about climate impacts and resilience through surveys. While we identified some impacts for households and associated attributes, we could not identify the full range of environmental, infrastructure, and management attributes that impact services. In the absence of monitoring records, we could only rely on survey responses, which may suffer from differences in perception and recall bias, especially when reporting on sporadic events or times of distress, e.g., in the aftermath of a cyclone.[79−81]

Given the urgency of improving the resilience of services, it will be essential to build a database of service disruptions from seasonal and post-disaster impacts and successful adaptation measures to prioritize regional and local investment. We recommend making strengthening monitoring and reporting by community service providers the norm.

Based on our findings, we suggest the following variables for monitoring user outcomes: seasonal changes in time and money spent to collect water, occurrence of water shortage in the dry season, ability to physically access the water collection point year-round, occurrence of flooding or damage to toilet, usability of the toilet after damage, and ability to physically access the toilet year-round. Questions to collect data on these outcomes are best incorporated into routine monitoring through periodic surveys or user-reporting systems feeding into a centralized database. Suggested outcomes related to water supply functioning, which may come from regulator and service provider data, are seasonal changes in water resource availability and water quality, occurrence of damage and flooding of infrastructure, flooding or landslides at or around the water collection point, and length of disruption.

Independent variables that were risk factors for water supply were water supply type, geographical zone, payment of tariff, level of cost recovery, access to spare parts, and person(s) responsible for repair; for toilets, the materials used for construction of the superstructure, the presence of a roof,

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geographical zone, and household income were relevant. Further work is needed to identify other factors, along with aspects of user experience and service functioning, for example, related to treatment works and fecal sludge collection.

CONCLUSION

This study contributes to emerging knowledge of factors affecting the response of water supplies and sanitation to climate extremes. In areas where climate change may lead to more extreme events, robust services that are better at withstanding exposure are likely required for building resilience. According to the survey data, most households and water service providers considered that infrastructure, maintenance, and management aspects affected the ability of water supplies and household toilets to respond to extreme events. Household income affected not only the exposure of households but also their ability to cope. While this study presented evidence from rural Malawi, similar findings may well be identified in other settings and prove useful in informing WASH programs within Malawi and elsewhere in rural Africa.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestwater.5c00403.

Frequency of damage or disruption reported by WPC members; average downtime reported by WPC members; and location of Thyolo in southern Malawi (PDF)

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CRediT: **Anisha Nijhawan** conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, visualization, writing - original draft, writing - review & editing; **Joel Ndeule** data curation, methodology; **Smorden Tomoka** conceptualization, funding acquisition, project administration; **Will Tillett** conceptualization, funding acquisition, project administration; **Guy Howard** supervision, writing - review & editing.

Notes

The authors declare no competing financial interest.

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REFERENCES

(1) DoDMA *Malawi Hazards and Vulnerability Atlas*; Government of the Republic of Malawi, Department of Disaster Management Affairs: Lilongwe, 2015.

(2) Frake, A. N.; Namanya, J.; Stephen, G.; Boye, C. J.; Simuzingli, M. *Malawi − Climate and Health Vulnerability Assessment (English)*; World Bank Group: Washington D.C., 2023.

(3) World Bank Group *Disaster Risk Profile: Malawi*; World Bank: Washington, D.C., 2019.

(4) World Bank Group *Malawi Drought 2015−2016: Post-Disaster Needs Assessment (PDNA) (English)*; World Bank Group: Washington, D.C., 2016.

(5) UN OCHA *Malawi: Drought Flash Appeal July 2024−April 2025*; United Nations Office for the Coordination of Humanitarian Affairs, 2024.

(6) Government of Malawi. (**2019**). Malawi 2019 Floods post Disaster Needs Assessment (PDNA).

(7) Government of Malawi *Malawi 2023 Tropical Cyclone Freddy Post-Disaster Needs Assessment. Lilongwe*; Government of Malawi, 2023.

(8) MacLeod, C.; Sidira, G.; Kapazga, T.; Njolomole, P.; Panulo, M.; Marcella, V.; Morse, T.; Dreibelbis, R.; Chidziwisano, K. R. The impact of a climate-related disaster on sanitation coverage in rural Chiradzulu District, Malawi, pre- and post-Cyclone Freddy 2025. https://osf.io/preprints/osf/xy52m_v1.(accessed Jan 31 2025)

(9) Rivett, M. O.; Tremblay-Levesque, L. C.; Carter, R.; Thetard, R. C.; Tengatenga, M.; Phoya, A.; Mbalame, E.; Mchilikizo, E.; Kumwenda, S.; Mleta, P.; et al. Acute health risks to community hand-pumped groundwater supplies following Cyclone Idai flooding. *Sci. Total Environ.* **2022**, *806*, 150598.

(10) Government of Malawi and UNICEF *Malawi Climate Resilient WASH Financing Strategy 2022−2032*; Lilongwe, 2021.

(11) Howard, G.; Calow, R.; Macdonald, A.; Bartram, J. Climate change and water and sanitation: likely impacts and emerging trends for action. *Annu. Rev. Environ. Resour.* **2016**, *41* (1), 253−276.

(12) Hyde-Smith, L.; Zhan, Z.; Roelich, K.; Mdee, A.; Evans, B. Climate change impacts on urban sanitation: a systematic review and failure mode analysis. *Environ. Sci. Technol.* **2022**, *56* (9), 5306−5321.

(13) Khan, S. J.; Deere, D.; Leusch, F. D.; Humpage, A.; Jenkins, M.; Cunliffe, D. Extreme weather events: Should drinking water quality management systems adapt to changing risk profiles? *Water Res.* **2015**, *85*, 124−136.

(14) MacDonald, A. M.; Calow, R. C.; MacDonald, D. M.; Darling, W. G.; Dochartaigh, B. E. What impact will climate change have on rural groundwater supplies in Africa? *Hydrol. Sci. J.* **2009**, *54* (4), 690−703.

(15) Alderman, K.; Turner, L. R.; Tong, S. Floods and human health: a systematic review. *Environ. Int.* **2012**, *47*, 37−47.

(16) Cann, K. F.; Thomas, D. R.; Salmon, R. L.; Wyn-Jones, A. P.; Kay, D. Extreme water-related weather events and waterborne disease. *Epidemiol. Infect.* **2013**, *141* (4), 671−686.

(17) Dimitrova, A.; Gershunov, A.; Levy, M. C.; Benmarhnia, T. Uncovering social and environmental factors that increase the burden of climate-sensitive diarrheal infections on children. *Proc. Natl. Acad. Sci. U.S.A.* **2023**, *120* (3), No. e2119409120.

(18) Wang, P.; Asare, E.; Pitzer, V. E.; Dubrow, R.; Chen, K. Associations between long-term drought and diarrhea among children under five in low- and middle-income countries. *Nat. Commun.* **2022**, *13*, 3661.

(19) Wang, P.; Asare, E. O.; Pitzer, V. E.; Dubrow, R.; Chen, K. Floods and diarrhea risk in young children in low-and middle-income countries. *JAMA Pediatr.* **2023**, *177* (11), 1206−1214.

(20) FCFA. Country Climate Brief. Future climate projections for Malawi. Future Climate for Africa: Cape Town, 2017.

(21) McSweeney, C., New, M., Lizcano, G.. UNDP Climate change country profiles Malawi. 2014. https://www.undp.org/publications/undp-climate-change-country-profiles (accessed Nov 21 2023).

(22) Howard, G., Bartram, J. (2010). *The resilience of water supply and sanitation in the face of climate change Technical report*. WHO Vision 2030, *42*.

(23) ISF-UTS and SNV *Considering Climate Change in Urban Sanitation: Conceptual Approaches and Practical Implications*; SNV: The Hague, 2019.

(24) Government of Malawi. Updated Nationally Determined Contributions. Lilongwe, Malawi, 2021.

(25) Thyolo DSIP. *Thyolo District Council District Strategic Investment Plan for Water Sanitation and Hygiene 2023*−*2027*. Thyolo, Malawi 2023.

(26) WHO UNICEF. Joint Monitoring Program Country data for Malawi. **2022**.

(27) Nijhawan, A.; Howard, G.; Poudel, M.; Pregnolato, M.; Eunice Lo, Y. T.; Ghimire, A.; Baidya, M.; Geremew, A.; Flint, A.; Mulugeta, Y. Assessing the climate resilience of community-managed water supplies in Ethiopia and Nepal. *Water* **2022**, *14* (8), 1293.

(28) Kohlitz, J.; Geremew, A.; Okurut, K.; Poudel, P.; Ghimire, A.; Nijhawan, A.; Valenzuela, A.; Falletta, J.; Manandhar-Sherpa, A.; Willetts, J.; Howard, G. What makes household sanitation systems resilient to floods? Evidence from Ethiopia, Uganda and Nepal. *Water Res., under review* **2025**.

(29) GWP and UNICEF. Strategic Framework for WASH Climate Resilient Development. 2022. https://www.unwater.org/news/strategic-framework-wash-climate-resilient-development-2022-edition.

(30) Howard, G.; Nijhawan, A.; Flint, A.; Baidya, M.; Pregnolato, M.; Ghimire, A.; Poudel, M.; Lo, E.; Sharma, S.; Mengustu, B.; et al. The how tough is WASH framework for assessing the climate resilience of water and sanitation. *NPJ Clean Water* **2021**, *4* (1), 39.

(31) WHO. *Guidelines on Sanitation and Health*; World Health Organization: Geneva, 2018.

(32) WHO *Guidelines for drinking-water Quality: Small Water Supplies*; World Health Organization: Geneva, 2024.

(33) Feighery, J.; Smith, R.; Grassick, C.; Feighery, A. mWater: a free and open-access platform for water data sharing and collaboration. *Open Water J.* **2015**, *3* (1), 7.

(34) Braka, F.; Daniel, E. O.; Okeibunor, J.; Rusibamayila, N. K.; Conteh, I. N.; Ramadan, O. P. C.; Gueye, A. S.; Yur, C. T.; Ochien, E. M.; Kagoli, M.; et al. Effects of tropical cyclone Freddy on the social determinants of health: the narrative review of the experience in Malawi. *BMJ Public Health* **2024**, *2* (1), No. e000512.

(35) Joshua, M. D.; Tompkins, E.; Schreckenberg, K.; Ngongondo, C.; Gondwe, E.; Chiotha, S. Water policy and resilience of potable water infrastructure to climate risks in rural Malawi. *Phys. Chem. Earth. A/B/C* **2022**, *127*, 103155.

(36) Daly, S. W.; Lowe, J.; Hornsby, G. M.; Harris, A. R. Multiple water source use in low-and middle-income countries: a systematic review. *J. Water Health* **2021**, *19* (3), 370−392.

(37) Cassivi, A.; Tilley, E.; Waygood, O.; Dorea, C. Seasonal preferences and alternatives for domestic water sources: a prospective cohort study in Malawi. *ACS ES&T Water* **2021**, *1* (6), 1464−1473.

(38) Nastiti, A.; Sudradjat, A.; Geerling, G. W.; Smits, A. J. M.; Roosmini, D.; Muntalif, B. S. The effect of physical accessibility and service level of water supply on economic accessibility: a case study of Bandung City, Indonesia. *Water Int.* **2017**, *42* (7), 831−851.

(39) Tucker, J.; MacDonald, A.; Coulter, L.; Calow, R. C. Household water use, poverty and seasonality: Wealth effects, labour constraints, and minimal consumption in Ethiopia. *Water Resour. Rural Dev.* **2014**, *3*, 27−47.

(40) Foster, T.; Willetts, J. Multiple water source use in rural Vanuatu: are households choosing the safest option for drinking? *Int. J. Environ. Health Res.* **2018**, *28*, 579−589.

(41) Patrick, M.; Hennink, M.; Dasmohapatra, M.; Rout, M.; Clasen, T.; Caruso, B. A. Influences on water source selection and use among women in rural Odisha, India. *Front. Water* **2023**, *5*, 1040981.

(42) Murray, A. L.; Stone, G.; Yang, A. R.; Lawrence, N. F.; Matthews, H.; Kayser, G. L. Rural Water Point Functionality Estimates and Associations: Evidence From Nine Countries in Sub-Saharan Africa and South Asia. *Water Resour. Res.* **2024**, *60* (2), No. e2023WR034679.

(43) Bonsor, H. C.; MacDonald, A. M.; Davies, J. Evidence for extreme variations in the permeability of laterite from a detailed analysis of well behaviour in Nigeria. *Hydrol. Processes* **2014**, *28* (10), 3563−3573.

(44) MacDonald, A. M.; Bell, R. A.; Kebede, S.; Azagegn, T.; Yehualaeshet, T.; Pichon, F.; Young, M.; McKenzie, A. A.; Lapworth, D. J.; Black, E.; et al. Groundwater and resilience to drought in the Ethiopian highlands. *Environ. Res. Lett.* **2019**, *14* (9), 095003.

(45) MacAllister, D. J.; MacDonald, A. M.; Kebede, S.; Godfrey, S.; Calow, R. Comparative performance of rural water supplies during drought. *Nat. Commun.* **2020**, *11* (1), 1099.

(46) Viban, T. B.; Herman, O. N. N.; Layu, T. C.; Madi, O. P.; Nfor, E. N.; Kingsly, M. T.; Germanus, B.; Victor, N. N.; Albert, N. Risk factors contributing to microbiological contamination of boreholes and hand dug wells water in the Vina Division, Adamawa, Cameroon. *Adv. Microbiol.* **2021**, *11* (02), 90−108.

(47) Lawrence, A. R.; Macdonald, D. M. J.; Howard, A. G.; Barrett, M. H.; Pedley, S.; Ahmed, K. M.; Nalubega, M. Guidelines for assessing the risk to groundwater from on-site sanitation. *British Geological Survey CR/01/142* **2001**.

(48) MacDonald, A. M.; Davies, J.; Ó Dochartaigh, B. É. Simple methods for assessing groundwater resources in low permeability areas of Africa. *British Geological Survey CR/01/168N* **2001**.

(49) MacAllister, D. J.; Nedaw, D.; Kebede, S.; Mkandawire, T.; Makuluni, P.; Shaba, C.; Okullo, J.; Owor, M.; Carter, R.; Chilton, J.; et al. Contribution of physical factors to handpump borehole functionality in Africa. *Sci. Total Environ.* **2022**, *851*, 158343.

(50) Bianchi, M.; MacDonald, A. M.; Macdonald, D. M.; Asare, E. B. Investigating the productivity and sustainability of weathered basement aquifers in tropical Africa using numerical simulation and global sensitivity analysis. *Water Resour. Res.* **2020**, *56* (9), No. e2020WR027746.

(51) Foster, T.; McSorley, B.; Willetts, J. Comparative performance evaluation of handpump water-supply technologies in northern Kenya and The Gambia. *Hydrogeol. J.* **2019**, *27* (2), 535−551.

(52) Foster, T. Predictors of sustainability for community-managed handpumps in sub-Saharan Africa: evidence from Liberia, Sierra Leone, and Uganda. *Environ. Sci. Technol.* **2013**, *47* (21), 12037−12046.

(53) Cronk, R.; Bartram, J. Factors influencing water system functionality in Nigeria and Tanzania: a regression and Bayesian network analysis. *Environ. Sci. Technol.* **2017**, *51* (19), 11336−11345.

(54) Truslove, J. P.; Coulson, A. B.; Mbalame, E.; Kalin, R. M. Barriers to handpump serviceability in Malawi: life-cycle costing for sustainable service delivery. *Environ. Sci. Water Res. Technol.* **2020**, *6* (8), 2138−2152.

(55) Bonsor, H. C., Oates, N., Chilton, P. J., Carter, R. C., Casey, V., MacDonald, A. M., et al. (2015). *A hidden crisis: strengthening the evidence base on the sustainability of rural groundwater supplies: results from a pilot study in Uganda*.

(56) Calow, R. C.; Robins, N. S.; MacDonald, A. M.; MacDonald, D. M.; Gibbs, B. R.; Orpen, W. R.; Mtembezeka, P.; Andrews, A. J.; Appiah, S. O. Groundwater management in drought-prone areas of Africa. *Int. J. Water Resour. Dev.* **1997**, *13* (2), 241−262.

(57) Howard, G.; Charles, K.; Pond, K.; Brookshaw, A.; Hossain, R.; Bartram, J. Securing 2020 vision for 2030: climate change and ensuring resilience in water and sanitation services. *J. Water Clim. Change* **2010**, *1* (1), 2−16.

(58) Hinton, R. G. K., Kanjaye, M., MacLeod, C. J. A., Troldborg, M., Kalin, R. M.. Building Resilient Sanitation Systems in Malawi: Pit-

https://doi.org/10.1021/acsestwater.5c00403
ACS EST Water XXXX, XXX, XXX−XXX

latrine Costs, Collapse and Management. Pre-print available at EarthArxiv. Submitted: 19−10−2024. **2025**. (accessed Mar 07 2025).
(59) World Bank *Resilient Water Infrastructure Design Brief*; World Bank: Washington, DC, 2020.
(60) Cole, B.; Pinfold, J.; Ho, G.; Anda, M. Investigating the dynamic interactions between supply and demand for rural sanitation. *J. Water Sanit. Hyg. Dev.* **2012**, *2* (4), 266−278.
(61) Kouassi, H. A. A.; Andrianisa, H. A.; Traoré, M. B.; Sossou, S. K.; Momo Nguematio, R.; Ymélé, S. S. S.; Ahossouhe, M. S. Review of the slippage factors from open defecation-free (ODF) status towards open defecation (OD) after the Community-Led Total Sanitation (CLTS) approach implementation. *Int. J. Hyg. Environ. Health* **2023**, *250*, 114160.
(62) Kouassi, H. A. A.; Andrianisa, H. A.; Sossou, S. K.; Traoré, M. B.; Nguematio, R. M. Sustainability of facilities built under the Community-Led Total Sanitation (CLTS) implementation: Moving from basic to safe facilities on the sanitation ladder. *PLoS One* **2023**, *18* (11), No. e0293395.
(63) Baguma, A., Bizoza, A., Carter, R., Cavill, S., Foster, S., Foster, T., et al. (**2017**). Groundwater and poverty in sub-Saharan Africa. UPGro Working Paper.
(64) Mara, D. The elimination of open defecation and its adverse health effects: a moral imperative for governments and development professionals. *J. Water Sanit. Hyg. Dev.* **2017**, *7* (1), 1−12.
(65) Berendes, D.; Kirby, A.; Clennon, J. A.; Raj, S.; Yakubu, H.; Leon, J.; Robb, K.; Kartikeyan, A.; Hemavathy, P.; Gunasekaran, A.; et al. The influence of household-and community-level sanitation and fecal sludge management on urban fecal contamination in households and drains and enteric infection in children. *Am. J. Trop. Med. Hyg.* **2017**, *96* (6), 1404−1414.
(66) Contreras, J. D.; Islam, M.; Mertens, A.; Pickering, A. J.; Kwong, L. H.; Arnold, B. F.; Benjamin-Chung, J.; Hubbard, A. E.; Alam, M.; Sen, D.; et al. Influence of community-level sanitation coverage and population density on environmental fecal contamination and child health in a longitudinal cohort in rural Bangladesh. *Int. J. Hyg. Environ. Health* **2022**, *245*, 114031.
(67) Akpabio, E. M.; Mwathunga, E.; Rowan, J. S. Understanding the challenges governing Malawi's water, sanitation and hygiene sector. *Int. J. Water Resour. Dev.* **2022**, *38* (3), 426−446.
(68) Holm, R.; Tembo, M.; Njera, D.; Kasulo, V.; Malota, M.; Chipeta, W.; Singini, W.; Mchenga, J. Adopters and non-adopters of low-cost household latrines: a study of corbelled pit latrines in 15 districts of Malawi. *Sustainability* **2016**, *8* (10), 917.
(69) Kozole, T.; Ross, M.; Nicoletti, C.; Rogla, J.; Ives, N.; Ali, A.; Prom, R. Impact of targeted subsidies on access to resilient sanitation for climate-vulnerable households in rural Cambodia. *J. Water Sanit. Hyg. Dev.* **2023**, *13* (12), 931−940.
(70) Tribbe, J.; Zuin, V.; Delaire, C.; Khush, R.; Peletz, R. How do rural communities sustain sanitation gains? Qualitative comparative analyses of community-led approaches in Cambodia and Ghana. *Sustainability* **2021**, *13* (10), 5440.
(71) Kohlitz, J.; Lala, S.; Bartell, J.; Halcrow, G.; Foster, T.; Willetts, J. Supporting the poor to access sanitation: key lessons from targeted household consumer subsidies in Cambodia. *Dev. Pract.* **2022**, *32* (6), 812−825.
(72) Garn, J. V.; Sclar, G. D.; Freeman, M. C.; Penakalapati, G.; Alexander, K. T.; Brooks, P.; Rehfuess, E. A.; Boisson, S.; Medlicott, K. O.; Clasen, T. F. The impact of sanitation interventions on latrine coverage and latrine use: A systematic review and meta-analysis. *Int. J. Hyg. Environ. Health* **2017**, *220* (2), 329−340.
(73) Kohlitz, J.; Chong, J.; Willetts, J. Rural drinking water safety under climate change: the importance of addressing physical, social, and environmental dimensions. *Resources* **2020**, *9* (6), 77.
(74) Iyer, R.; Kohlitz, J. Climate impacts on rural sanitation: evidence from Burkina Faso, Bangladesh and Lao PDR. *Front. Water* **2024**, *6*, 1413225.
(75) Ricau, M.; Kelly, C.; Schmitt, A.; Lantagne, D. Barriers and facilitators to fecal sludge treatment in humanitarian camps: A systematic review of interventions. *PLOS Water* **2024**, *3* (11), No. e0000289.
(76) Seleman, A.; Gabrielsson, S.; Mbwette, T. S.; Kimwaga, R. Drivers of unhygienic desludging practices in unplanned settlements of Dar es Salaam, Tanzania. *J. Water Sanit. Hyg. Dev.* **2020**, *10* (3), 512−526.
(77) Hinton, R. G.; Macleod, C. J.; Troldborg, M.; Kanjaye, M. B.; Kalin, R. M. The status of sanitation in Malawi: is SDG6. 2 achievable? *Int. J. Environ. Res. Public Health* **2023**, *20* (15), 6528.
(78) Kalumbi, L. R.; Thaulo, C.; MacPherson, E. E.; Morse, T. Perspectives and practices on water, sanitation, and hygiene from a fishing community along Lake Malombe, Southern Malawi. *Int. J. Environ. Res. Public Health* **2020**, *17* (18), 6703.
(79) Bell, A.; Ward, P.; Tamal, M. E. H.; Killilea, M. Assessing recall bias and measurement error in high-frequency social data collection for human-environment research. *Popul. Environ.* **2019**, *40*, 325−345.
(80) Higuchi, Y.; Fuwa, N.; Kajisa, K.; Sato, T.; Sawada, Y. Disaster aid targeting and self-reporting bias: Natural experimental evidence from the Philippines. *Sustainability* **2019**, *11* (3), 771.
(81) Jepson, W. E.; Wutich, A.; Colllins, S. M.; Boateng, G. O.; Young, S. L. Progress in household water insecurity metrics: a cross-disciplinary approach. *Wiley Interdiscip. Rev.: Water* **2017**, *4* (3), No. e1214.