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BRIEF COMMUNICATION OPEN

Monitoring socio-climatic interactions to prioritise drinking water interventions in rural Africa

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Rainfall variability and socioeconomic shocks pose a revenue risk for drinking water services in rural Africa. We examine the year-on-year and seasonal relationship between rainfall and remotely monitored water usage from rural piped schemes in four sub-Saharan countries to identify patterns that warn of a threat to operational sustainability. Continuous monitoring of socio-climatic interactions can reveal distributions and magnitudes of risk and guide policy action to safeguard rural water services.

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Despite substantial progress over several decades, more than 500 million rural Africans still live without access to safe, affordable, and reliable drinking water services[1]. Inadequate water supply persists in part due to climate variability that compounds financial and operational risks[2]. Fluctuating availability of rainwater sources influences domestic water demand, typically leading to a reduction in the volume of water households collect from other improved water sources during higher rainfall periods[3–5]. This behaviour can reduce revenue generated from user payments in the wet season with financial implications for operational sustainability of rural waterpoints[6,7].

Rainfall dynamics are intensified by ancillary events such as disease outbreaks that stress the low and variable incomes of rural households. For example, economic and travel restrictions enacted to prevent and limit the spread of COVID-19 have affected household livelihoods and ability to pay for water and sanitation services[8]. Response measures such as providing free water to vulnerable populations and suspending service disconnections resulting from lack of payment in urban areas have led to as much as 70% reduction in revenue collection from utility customers[9].

It is difficult to anticipate when, where, and how shocks will converge to threaten viability of rural drinking water services because cost, complexity, and timeliness often prevent the measurement of direct indicators. However, analysis of the interactions between socioeconomic and climatic variables that are readily available can signal relative susceptibility while accounting for spatial heterogeneity[10]. Emerging evidence demonstrates data from in situ waterpoint sensors and from global rain gauge and satellite observation systems can be leveraged to predict drought, famine, and groundwater depletion[11–14]. It may be possible to synthesise these data to generate warning signals of revenue risk for rural water supplies.

We explore how year-on-year and seasonal changes in rainfall and metered water usage can be interpreted to anticipate a revenue risk for rural drinking water services arising from the convergence of socioeconomic and climatic shocks. We combine 29 years of geospatial, monthly total rainfall estimates with 299 months of metered, remotely transmitted water usage records between 2016 and 2020 corresponding to 25 rural piped schemes in Kenya, Malawi, Tanzania, and Uganda. April 2020 is chosen as a reference month when socioeconomic shocks from the COVID-19 pandemic were emerging in Africa. The first COVID-19 cases in Africa were reported in early March 2020[15] and by the end of the month, cases had been confirmed in more than 70% of the countries on the continent[16]. The analysis compares water usage data from January through April 2020 with April 2020, and historical periods between 2016 and 2019. We also examine operational and environmental factors that may explain observed changes in water usage including geography, scheme type and size, whether schools or healthcare facilities are served, payment modality, and rainfall. Payment modality is of particular interest because of its direct modifying effect on rural water use and revenue collection. Two approaches were employed to collect user payments among the observed schemes: "pay-as-you-fetch" (PAYF), where cash transactions are made at the waterpoint for every 20-litre container collected, and monthly fees that place no restriction on the volume of water used when a fixed payment is made.

Our results show mean water usage rates during the first four months of 2020 did not differ from historical averages (2016–2019) across any of the observed operational factors. We also do not find notable differences in water usage rate in April 2020 across all combined records, from schemes that serve schools or healthcare facilities, or in records grouped by scheme type and size (see Supplementary Table 1). These findings suggest restrictions related to COVID-19 were not affecting water usage from the observed schemes in April 2020. However, the onset of COVID-19 in early 2020 occurred at the same time as unusually high rainfall across areas of Kenya, Tanzania, and Uganda while below average rainfall occurred further south (Fig. 1). The observed schemes straddle these two climate regimes enabling the effect of rainfall extremes on water use to be examined.

The changes in water usage rates in April 2020 appear to align with transitions between wet and dry seasons and are moderated by payment modality (Fig. 2), reflecting known patterns in rural water source choice and payment behaviour. Schemes in Malawi saw decreased rainfall in April 2020 relative to the already unusually low levels experienced earlier in the year. These schemes generally saw increased usage in April 2020 because alternative rain-fed water sources were not available to users. In contrast, schemes in Kenya, Tanzania, and Uganda experienced a transition to unusually high levels of rainfall in April 2020. Schemes utilising the PAYF approach in these areas experienced

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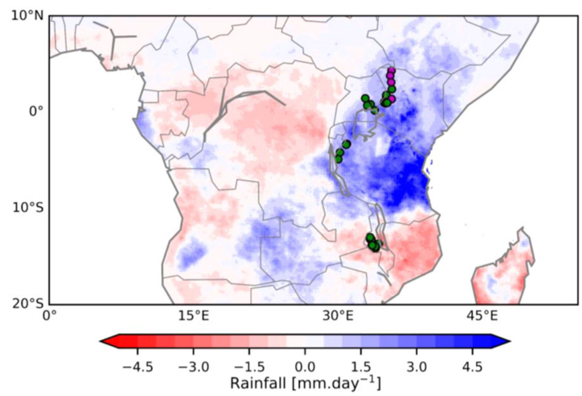

Fig. 1 Analysis of rainfall anomalies during the period from January to April 2020 against 1983–2012 climatology indicates unusually high rainfall in Kenya, Uganda, and Tanzania and low levels of rainfall in Malawi. Green dots indicate locations of piped schemes where the PAYF payment modality is employed. Magenta dots indicate locations of piped schemes where the monthly fee payment modality is employed.

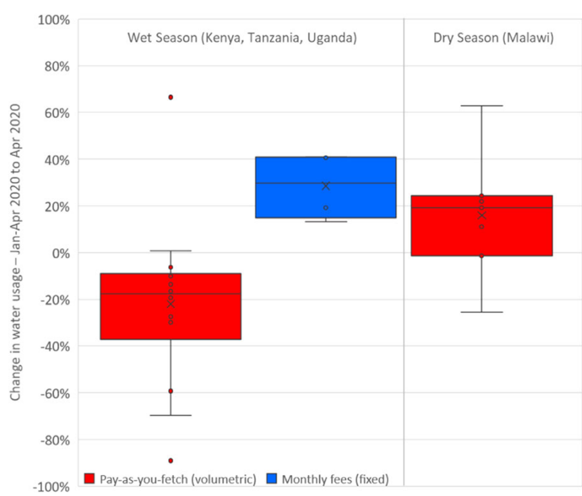

Fig. 2 Changes in water usage by payment modality and season in April 2020 compared to the period mean from January to April 2020. Where the PAYF payment modality is employed, increased rainfall and subsequent availability of alternative surface water sources during the wet season appears to buffer water demand from piped schemes. Box plot elements: mean marker, median centre line, upper and lower quartile box limits, 1.5× interquartile range whiskers, data points.

a mean 22% decrease in monthly water usage in April 2020 relative to the first four months of the year as users shifted to collecting water from alternative rain-fed sources. In Uganda and Tanzania this corresponded to an average decrease of 47 ($p = .033$) and 30 cubic metres per month ($p = .034$), respectively. Furthermore, it appears the dynamic relationship between rainfall, payment modality, and water usage in Tanzania and Uganda was amplified in 2020 compared to historical averages (see Supplementary Table 1), indicating the observed schemes in these countries are experiencing a new threat not seen in the past five years. The observed schemes that utilise monthly fees, all of which are in Kenya, experienced a reversal of this seasonal effect. These schemes saw an average increase in water usage of 90 cubic metres ($p = 0.048$) in April 2020 despite high corresponding levels of rainfall.

Our findings indicate monthly fees facilitate revenue collection from rural waterpoints during wet periods when demand would otherwise decrease. Monthly fees have been associated with greater social inclusion but lower rates of revenue generation compared to other payment modalities[7]. An analysis of detailed financial records from over 2800 rural waterpoints in four African countries reports similar revenue dynamics[17]. However, temporarily shifting from PAYF to monthly fees during periods when domestic water demand falls or rural incomes are reduced may foster affordable access while maintaining a lifeline of revenue to protect local service providers. Such an approach is likely to be more effective at achieving social and political goals of non-discriminatory access to reliable services than providing free access to water.

Rural water service providers may struggle to sustain operations with fluctuating or chronically reduced revenues, particularly under emergency conditions when operational costs are likely to increase. Performance-based subsidies that can mitigate short-term revenue risk for rural schemes require verifiable information. However, high quality financial and operational records of rural water services are rare. Our findings suggest sentinel sites in Africa that routinely monitor metered water usage and rainfall could be networked to generate spatial and temporal signals of revenue risk.

In conclusion, we highlight two implications for policy and practice. First, the nature and timing of the transition between wet and dry seasons in sub-Saharan Africa will compound the impacts of socioeconomic shocks on rural water supplies. Emerging approaches for forecasting the onset of rainfall[18] coupled with reliable and timely dissemination of information on water service delivery can generate warning signals in regions susceptible to public health, economic, and climate shocks. These signals can aid in prioritising and targeting response measures. Second, financial support to local, professional service providers through affordable tariff design and performance-based subsidies can keep water flowing through crises, as exemplified in Central African Republic[17]. We acknowledge that reliable water service provision in much of Africa is unregulated and characterised by slow repairs, questionable water quality, and ad hoc user payments. Responses to subsidise services amid climatic and socioeconomic shocks should consider the long-term implications on sustainability and invest in monitoring systems that enhance transparency and accountability and potentially unlock new funding flows[19].

METHODS

This study utilised validated data from Water Mission, an international non-governmental organisation that supports rural water services in eleven countries. The organisation installs and maintains digital water meters fitted with data loggers and satellite-based transmitters on rural water schemes, with some schemes providing ongoing information dating back to 2016. Scheme types included kiosks with piped point-source access as well as reticulated systems with multiple communal and private connections serving households, schools, and healthcare facilities. For all schemes, payment modalities and tariff levels are formally established and are not allowed to fluctuate unless agreement is reached together with users and local authorities. For schemes where fixed monthly fees are employed, the median fee in current US dollars is $2.74 per household per month. The median constant volumetric tariff where the PAYF modality is utilised is $3.28 per cubic meter.

Mean monthly water usage from the period of January to April 2020 for each scheme was compared to usage in April alone. Historic period means from January to April were calculated for every year between 2016 and 2019 where at least three months of data were available, as well as historic means in April, to determine if changes observed in 2020 differed from what has historically occurred.

Geospatial rainfall data corresponding to each scheme for the first four months of all available historical years and 2020 were obtained from the publicly available Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset[20]. The rainfall anomaly in 2020 was calculated relative to the 1983–2012 climatology. Schemes were classified as experiencing either a wet or dry season in April 2020 based on whether rainfall in April 2020 increased or decreased, respectively, compared to mean rainfall from January to April 2020.

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Paired sample *T*-tests and Wilcoxon signed ranks tests were performed to determine statistical significance ($\alpha = 0.05$) and account for small sample sizes and the potential influence of outliers. Differences in means across several groups of schemes were also tested to explore plausible explanations for variations observed in water usage. Subpopulations examined included:

- Country (Kenya, Uganda, Malawi, Tanzania)
- Payment modality (fixed monthly fees, pay-as-you-fetch)
- Scheme type (kiosk with single access point, reticulated)
- Scheme size (small serving <500 people, medium serving 500 to 5,000, large serving >5,000)
- Institutions served (schools and healthcare facilities using and paying for water)
- Season experienced in April 2020 (wet, dry)

The study complied with ethics approval granted by the School of Geography and Environment at the University of Oxford (SOGE 1A020 – 06). No human subjects were involved other than expert interviews with Water Mission staff in the process of data collection, data cleaning, and validation.

DATA AVAILABILITY

The data analysed during this study are part of an ongoing PhD project. Rainfall data are available at https://developers.google.com/earth-engine/datasets/catalog/UCSB-CHG_CHIRPS_DAILY and water usage data are available on request from the lead author.

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AUTHOR CONTRIBUTIONS

A.A. and R.H. conceived the study. A.A. carried out the analyses. C.M. contributed to the climate analysis and discussion. A.A. and R.H. wrote the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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