npj | clean water

Article

Published in partnership with King Fahd University of Petroleum & Minerals

https://doi.org/10.1038/s41545-024-00341-6

Is volumetric pricing for drinking water an effective revenue strategy in rural Mali?

Johannes Wagner [1,2] ✉, Johanna Koehler [3], Mikael Dupuis[4] & Rob Hope [1,2]

Africa lags behind the world on operational and financial progress to maintain safe drinking water services. In rural Mali, we explore the implications of monthly flat fee contributions and volumetric (pay-as-you-fetch) payments for water use and revenue generation. By assessing 4413 months of data across 177 handpumps, we find that once payment modalities switch from volumetric payments to monthly flat fees, a waterpoint registers a more than three-times higher monthly revenue. While flat fees cover a higher share of the operational costs of providing reliable water services, a subsidy gap persists. Flat fees appear to stimulate daily water use which more than doubles compared to volumetric payments. We estimate that a 1 °C increase in average monthly temperature is associated with 180 more litres of water used every day per handpump, emphasising the importance of climate-resilient water supplies. Based on these insights, we discuss the role of professional service delivery models to support reliable drinking water services for rural communities.

The global challenge of providing safely managed services to approximately two billion people[1] is amplified in rural Africa where approximately 25–30% of rural waterpoints are non-functional at any point in time. This leaves about $1.5–2.5 billion of capital investment unused[2]. Hand- and foot pumps which are the most widely used technology in Africa for providing basic water supply experience breakdown durations lasting on average 30 days[3–5]. Despite significant investments in community-based management over several decades, progress has been largely unsatisfactory in maintaining rural water supply infrastructure[4,6–9]. Cross-country evidence from rural Africa shows that significantly higher operational performance can be achieved by professional service delivery models[5,10]. Yet, these professional service providers struggle to cover related operating costs requiring a subsidy, as is common in most urban piped systems[5,11,12].

Policy and practice generally expect that some of the costs of providing rural water services are to be covered through user payments[6,13–20]. Global assessments indicate that user payments are the largest source of WASH financing[21–23]. Yet, debate prevails on how to effectively generate sufficient local revenue from user payments and which pricing strategies are the most effective in aligning affordability goals with cost recovery targets[24–29]. As costs for maintaining existing water infrastructure are globally expected to outgrow capital investments by 2030[14], empirical insights on the effectiveness of revenue collection approaches for funding maintenance services can inform policy and practice to meet the Sustainable Development Goal for Water (SDG 6.1).

Volumetric pricing is most common in urban piped water supply to increase revenue collection and improve financial sustainability while encouraging efficient water use[30]. Volumetric pricing is becoming more common in water supply across rural Africa with the increasing development of small piped systems, water kiosks and ATMs, and cashless payment facilities[31–39]. Water policies in Africa promote different approaches to generate revenue to fund the recurrent costs of providing water services[40]. Mali, for instance, officially recognises two payment modalities for rural water supply: regular flat fee contributions or volume-based payments at the waterpoint[41,42]. Yet, the applicability and effectiveness of volumetric pricing in funding maintenance services for handpumps remains empirically unclear.

Across Africa, there has been increased interest in testing professional service delivery models to guarantee higher service levels and to promote greater financial sustainability[43,44]. For example in Mali, a professional service delivery company, UDUMA, has raised private capital for a public private partnership with the government to provide reliable rural water services from 1400 handpumps[37], subject to affordable user payments. This large-scale initiative is implemented in the region of Sikasso, located in Southern Mali. The area is characterised by an annual dry season from March to June followed by a wet season from July to October, with annual rainfall of 510 to 1400 mm and average temperatures of 24 to 32 °C[45].

At the start of the professional service in November 2019, UDUMA charged a volumetric tariff of 500 FCFA per m^3 ($0.80). Following a "pay-as-you-fetch" approach, users made direct payments at the handpump for

[1]School of Geography and the Environment, University of Oxford, Oxford, UK. [2]Smith School of Enterprise and the Environment, University of Oxford, Oxford, UK. [3]Public Administration and Policy Group, Wageningen University and Research, Wageningen, The Netherlands. [4]UDUMA, Ingré, France.
✉e-mail: johannes.wagner@ouce.ox.ac.uk

every 20-litre container collected[37]. Confronted with low revenue due to limited user payments, UDUMA gradually introduced a monthly flat fee of 15,000 FCFA ($24) per handpump, with no limit on water use. The flat fee payment approach stipulates that if the flat fee is not paid, the UDUMA service is not activated, and the pump is locked until a payment is made. Since March 2022, all waterpoints are running under a monthly flat fee model. The change in payment modalities was introduced within existing contractual arrangements with local governments and communities.

By examining longitudinal volumetric use and payment data we explore what happens if payment modalities for reliable maintenance services at handpumps are changed from volumetric payments to monthly flat fee contributions. Findings from Kenya, Ethiopia, Ghana, Rwanda, and Uganda emphasise the prevalence of seasonal water demand in rural areas and related implications on revenue generation[46–49]. Therefore, we ask how does a change in payment modalities affect (1) daily water use, (2) monthly revenue, and (3) collection efficiency at handpumps, conditional on seasonal fluctuations, and (4) what, if any subsidy, is required to sustain services across the two payment modalities?

The analytical strategy of the paper is based on observed water usage and payment data from manual pumps equipped with water meters which is uncommon in rural Africa. We model a total of 4413 months of observed payments and metered water usage before and after the change in payment modalities across 177 manual pumps, covering a period from November 2019 to April 2023. The change from volumetric to flat fee payments, gradually introduced between April 2021 to March 2022, constitutes a shift in UDUMA's revenue strategy while the infrastructure type (handpump) as well as the level of service delivery (guaranteed repairs within 72 h of breakdown and annual water quality monitoring) stay constant. Similar to other cost estimates for professional service delivery guaranteeing that any breakdowns are repaired within 72 h[50], UDUMA's recurrent local operation and maintenance costs[51] are of approximately $24 per waterpoint per month.

The analysis focuses on four performance metrics which we track over time: daily volume of water used per waterpoint, monthly revenue generated, monthly working ratio, and monthly collection efficiency. A local working ratio[5,52] is a performance metric reflecting local revenue from user payments divided by local operation and maintenance costs. Working ratios may also include indirect costs, depreciation, inflation, and other operational costs. Here, we apply the simple local metric to support understanding of pathways to improve financial sustainability. Collection efficiency provides an indication for the acceptance of the payment principle in the context of rural Mali and reflects users' willingness and commitment to pay for reliable water services[31] (further detail on the performance metrics is available in the "Methods" section). We apply a fixed effects regression model to estimate the effect of changes in payment modalities on the outcomes of interest while accounting for seasonal confounders.

Our findings from Mali reveal that monthly flat fee contributions are more effective in funding professional maintenance services than a volumetric approach, generating on average $9 more revenue per month per handpump. In addition, flat fees are associated with an increase in water use throughout the year. Results indicate that payment collections double under the flat fee approach compared to volumetric payments but experience a downward trend over time. Furthermore, the results reveal the contextual variability of performance in collection efficiency across both payment modalities, highlighting that neither volumetric tariffs nor monthly flat fees are one-size-fits-all solutions to effectively collect user payments at handpumps. Despite improvements in revenue generation following the shift to flat fee payments, a monthly funding gap of about $12 per waterpoint persists, requiring targeted subsidies to ensure reliable access to water throughout the year. Based on these empirical insights we discuss how models of reliable rural water services may be sustained at scale.

Results

This section presents results of (1) volumetric water use, (2) collection efficiency, (3) monthly revenue, and (4) working ratios when manual pumps shift from volumetric to monthly flat fee payments.

Flat fees stimulate water use which is subject to seasonal variations

Using 1885 monthly meter records under the volumetric modality and 2528 meter readings under the flat fee modality between November 2019 to April 2023, we find that the average daily water use per waterpoint more than doubles under a monthly flat fee (mean: 1.74 m^3, SD: 2.26 m^3) compared to volumetric payments (mean: 0.84 m^3, SD: 1.48 m^3). A month-on-month assessment (Fig. 1a) comparing average daily water use across payment modalities indicates that the increase in daily volumetric use aligns with the shift from volumetric to flat fee payments. Under the volumetric payment modality average daily usage per pump exceeds 1 m^3 only during April and May, the hottest months in Mali, whereas water demand under a monthly flat fee in the same period reaches up to 3 m^3 per pump and decreases to 1 m^3 only during the rainy season. Across both payment modalities, increases in volumetric water use align with Mali's hot season (March to June), whereas water usage falls during the rainy season (July to October), emphasising a seasonal pattern in water demand.

Seasonal boxplots, disaggregated per payment modality (Fig. 2), track daily volumetric use over three consecutive dry and wet seasons. This monitoring reveals the nuance and variation between months and within a month indicating different patterns for individual waterpoints. Again, daily volumetric water use levels align with Mali's hot and rainy seasons across both payment modalities, with higher average water use levels for the flat fee modality.

A fixed-effects regression model supports the descriptive insights: when controlling for climatic conditions, the flat fee modality is associated with an increase of 900 litres in daily water use per waterpoint (Table 1, Model 2). Higher temperatures are positively related to higher water use: an increase of 1 °C in monthly average temperature translates into additional daily water abstraction of 180 litres per waterpoint.

Flat fees are associated with higher payment collection

When comparing the two payment modalities regarding their performance in collection efficiency, it appears that flat fees (mean: 54%, SD: 50%) are approximately two times more likely to be paid than volumetric payments (mean: 29%, SD: 37%). Disaggregating average collection efficiency at the municipality level reveals a more nuanced pattern across the 23 municipalities where the 177 waterpoints are located (Fig. 3). While the flat fee modality registers on average a two-times higher collection efficiency than the volumetric approach, we observe well-performing municipalities in volumetric payments, such as Sido or Kebila (Fig. 3a), rank relatively lower for flat fee payments (Fig. 3b). This insight highlights the spatial variation in effectiveness of user payment approaches, emphasising that the flat fee modality is not necessarily a "one-size-fits-all" approach.

Tracking payment collections over time (Fig. 4) reveals variation across months and localities. From the outset, the compliance with the volumetric approach is low and on average never exceeds 50%, illustrating the challenge of enforcing volumetric payments when users must invest in time and physical effort for accessing water[2,15,53,54]. Collection efficiency for flat fee payments remains more stable throughout the first year, averaging around 75%. Flat fee payments, however, register a downward trend since the onset of the rainy season in July 2022. Examining the data up to April 2023 shows that the declining trend reduces. Yet, uncertainty about the future evolution prevails, requiring further monitoring. In terms of unlocking user payment, regression results suggest that the flat fee approach performs better than the volumetric modality in the period of this study (Table 1, Model 8).

Flat fees generate higher monthly revenues, lowering subsidy requirements

On average, the monthly revenue per waterpoint generated through flat fee payments is almost four-times higher than through volumetric payments. Flat fees generate an average monthly revenue of $12.85 per waterpoint (SD: $11.97), whereas the volumetric modality generates $3.42 per waterpoint (SD: $9.78) per month.

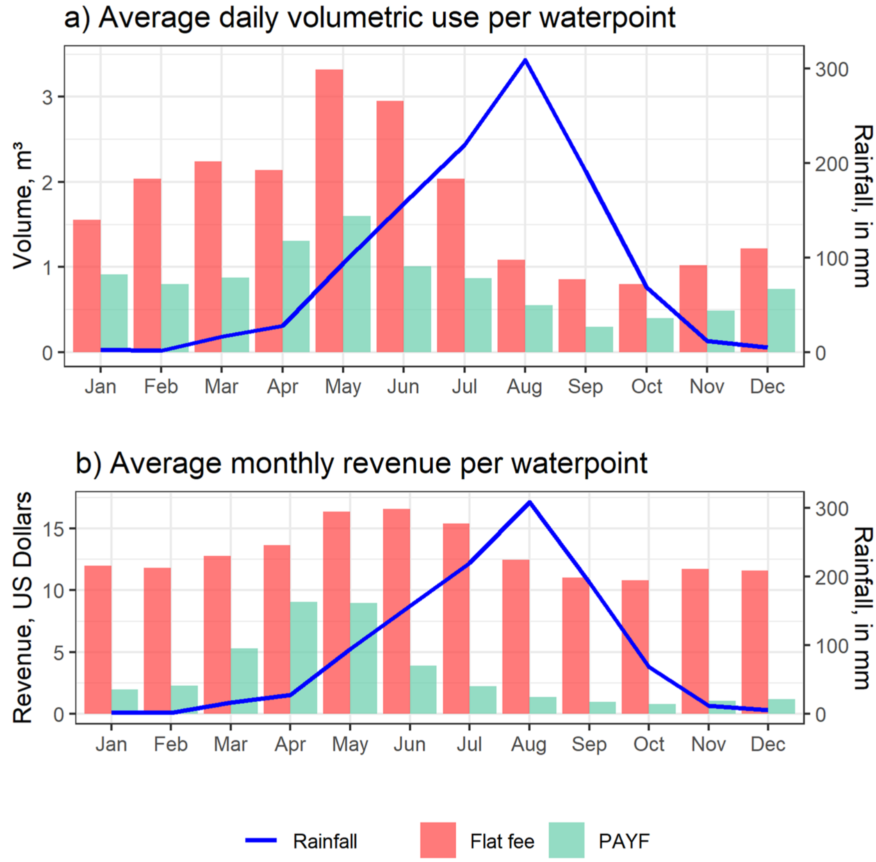

Fig. 1 | Average daily water use and monthly revenue per waterpoint. a Average daily volumetric water use (in m^3) per waterpoint. **b** Average monthly revenue generated per waterpoint (in US Dollars). Bar plots separating between payment modalities. Total of 4413 monthly observations between 2019 to 2023 across 177 waterpoints. Rainfall is total monthly average.

Month-on-month comparisons (Fig. 1b) reveal the seasonal variation in monthly revenue. When payments are based on volumetric usage, revenues reflect the seasonal variation in water demand. Under the volumetric approach, some waterpoints generate revenue peaks aligning with peaks in water demand during the annual hot seasons (the highest monthly revenue generated at an individual waterpoint under the volumetric modality was $163, registered in May 2021). However, on average, the volumetric modality registers a consistently lower revenue compared to the flat fee approach throughout the year.

Fixed-effects regression results indicate that average monthly revenue per handpump is driven by the flat fee modality (Table 1, Model 4). When controlling for seasonality, the flat fee modality is associated with an increase of $9.37 in monthly revenue per waterpoint. Furthermore, we estimate that a 1 °C rise in monthly temperature is associated with $0.82 more revenue per waterpoint.

While flat fees do not translate into single high-performing waterpoints, they provide a considerable contribution to the total revenue generated per month. The gradual shift from volumetric to flat fee payments translates into an increase in total monthly revenue for a comparable number of active waterpoints (Fig. 5). Starting operations in late 2019, UDUMA progressively deployed its service model to handpumps located in its service area throughout 2020, to achieve a scale of around 100 handpumps in early 2021. The total number of actively paying waterpoints per month (Fig. 5a) stays relatively stable between February 2021 until July 2022. Following a general downward trend in waterpoints registering payment activities, reflecting the decreasing performance in collection efficiency for flat fees (Fig. 4), the total monthly revenue is declining, too (Fig. 5b). Importantly, the total monthly revenue generated through flat fee payments since the rainy season 2022 equals the revenue registered under the volumetric modality during its best-performing period (April and May 2021), and this despite a 50% reduction in the number of actively paying waterpoints (Fig. 5a).

Similar to revenue, the average working ratio improves under the flat fee modality (mean: 53.5%, SD: 49.8%) compared to volumetric payments (mean: 14%, SD: 41%). Following the change in payment modalities, the share of local operational costs covered through local revenue improves by 39% when controlling for temperature and rainfall (Table 1, Model 6). This result is driven by the increase in monthly revenue generated through flat fee payments. Finally, working ratios are evolving over time, reflecting that volumetric payments translate into seasonal cost recovery peaks, whereas the working ratio for flat fee payments experiences a similar downward trend as collection efficiency (see Fig. 4).

On average, to sustain maintaining a handpump under the volumetric approach, a monthly subsidy of more than $20 is needed. With a monthly flat fee, an average subsidy requirement of less than $12 per month per waterpoint persists. This represents a positive development in the immediate period following the transition but requires longer term evaluation to substantiate this effect.

Discussion

Three findings from our study may contribute to delivering more sustainable rural water services amidst increasingly uncertain climates. First, drinking water use at handpumps is influenced by seasonal and contextual drivers across both payment modalities. Second, revealed water use and payment behaviours suggest regular fixed payments are preferred over volumetric tariffs for the reliable maintenance of handpumps, with implications for subsidy design. Third, professional service delivery models can guarantee rural drinking water supplies are reliable and provide performance data with relevant insights for policy and practice.

First, there is evidence that higher temperatures increase average water demand. Various empirical studies reveal such patterns for urban utilities around the world[55–57]. We find similar patterns of behaviour in rural Mali and estimate that a one degree increase in monthly temperatures increases daily demand by 180 litres per handpump. Unlike urban utilities[58,59], rural

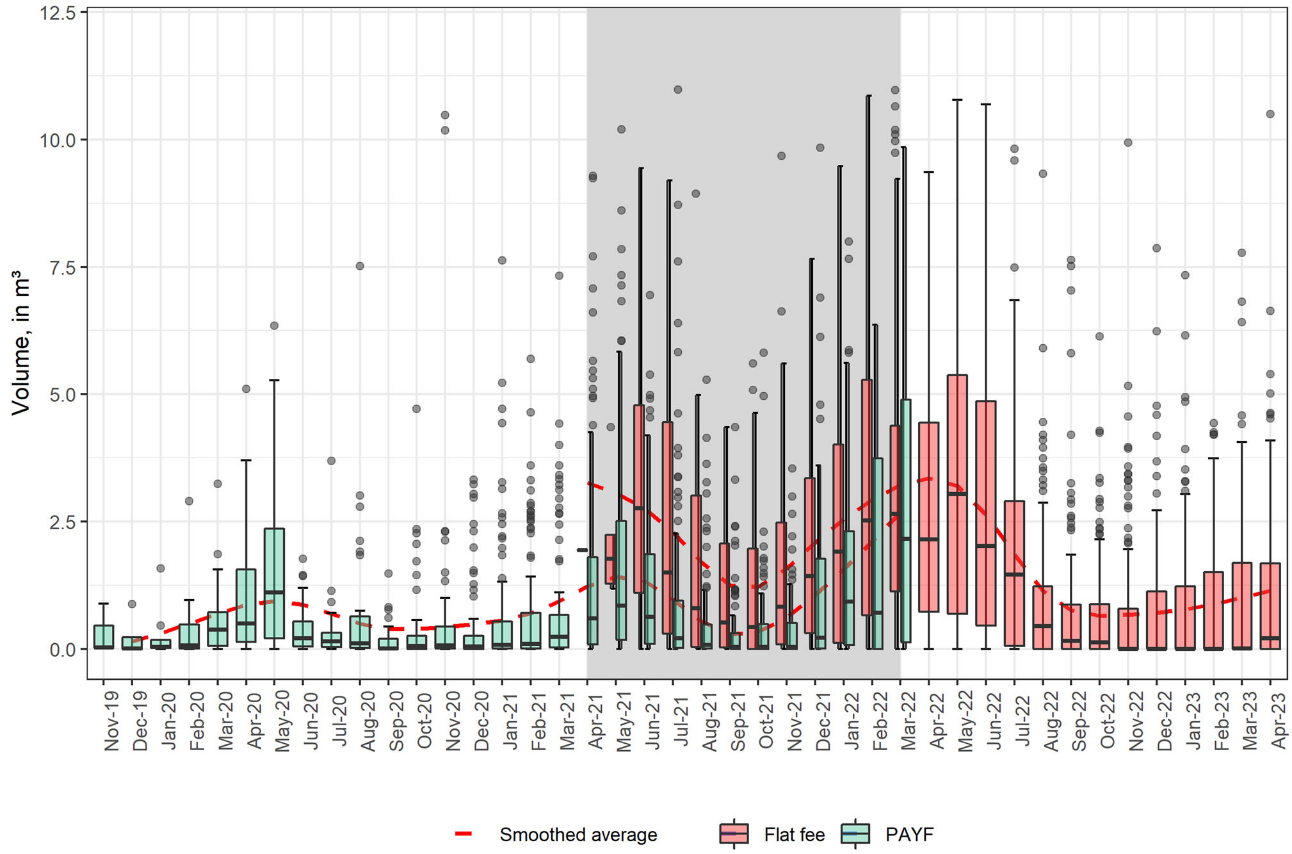

Fig. 2 | Daily volumetric water use per waterpoint, separating between payment modalities (n = 177 waterpoints). Box and whisker plots (centre line, median; box limits, upper and lower quartiles; whiskers, 1.5x interquartile range; points, outliers). Dashed line for average per payment modality. Shaded area highlights the period of the payment modality transition (April 2021 to March 2022).

Table 1 | Results of fixed-effects regression models

	Daily volumetric use (in m³)		Monthly revenue (in $)		Working ratio (in %)		Collection efficiency (in %)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Flat fee	**0.837***** (0.098) [0.64–1.03]	**0.908***** (0.102) [0.71–1.11]	**9.03*****(0.67) [7.7–10.3]	**9.37***** (0.68) [8.0–10.7]	**37.62***** (2.8) [32.1–43.1]	**39.04***** (2.8) [33.5–44.6]	**22.3***** (3) [16–28.7]	**24***** (3) [18–30]
Temp.		**0.180***** (0.016) [0.15–0.21]		**0.82***** (0.10) [0.61–1.02]		**3.4***** (0.45) [2.5–4.2]		2.6** (0.4) [2–3.3]
Rainfall		0.000 (0.000) [0.000–0.001]		0.009** (0.002) [0.005–0.01]		0.04** (0.01) [0.02–0.05]		0.00** (0.016) [0.0–0.0]
Nb of obs.	4413	4413	4413	4413	4413	4413	4413	4413
R^2	0.298	0.336	0.357	0.377	0.357	0.377	0.250	0.265
R^2 adj.	0.269	0.308	0.330	0.351	0.331	0.351	0.219	0.234

Robust standard errors, clustered at the waterpoint level, are reported in parentheses (). Confidence intervals are reported in brackets []. Significance levels: ** $p < 0.05$, *** $p < 0.01$. Bold for significance level of 1%. Meteorological controls include total rainfall in a month and average monthly temperature for each of the 23 municipalities where the 177 waterpoints are located.

waterpoints are not supported by a network of storage infrastructure but are constrained by the capacity of the waterpoint to lift or pump groundwater. With handpumps often limited by around 1000 litres per hour, the risk of failing to meet local demand in extended dry periods is increased.

The seasonality of waterpoint demand is clearly shown in our study. Across both payment modalities, dry season demand is far greater than during the wet season when alternative water sources become available, which are often favoured by rural people[60]. These insights are consistent with previous findings from Kenya, Ethiopia, Ghana, Rwanda, and Uganda on seasonal interactions of water demand with temperature peaks and rainfall[46–49]. Demand for waterpoints in the dry season is further complicated by non-drinking water demand by livestock, small businesses, and other productive uses[61–63]. In such periods of high demand where multiple water uses intersect, handpumps come under extreme pressure, emphasising the importance of adapting rural water services to climate risks.

The value of the measured water consumption data from Mali is that it reveals these patterns and peaks to inform policy and practice. For example, demand varies spatially, and future infrastructure investment may target locations under pressure as a priority. Equally, professional service providers ensure services are reliable in the dry season, for which they are held accountable, and thus can contribute to building resilience to the impacts of climate change[1]. Finally, understanding consumption patterns and payment behaviours may help to define appropriate subsidies.

Second, a subsidy is required for most rural water service providers except those targeting a few waterpoints in high density, relatively wealthy areas with limited water alternatives[5,31]. The more taxing policy question is

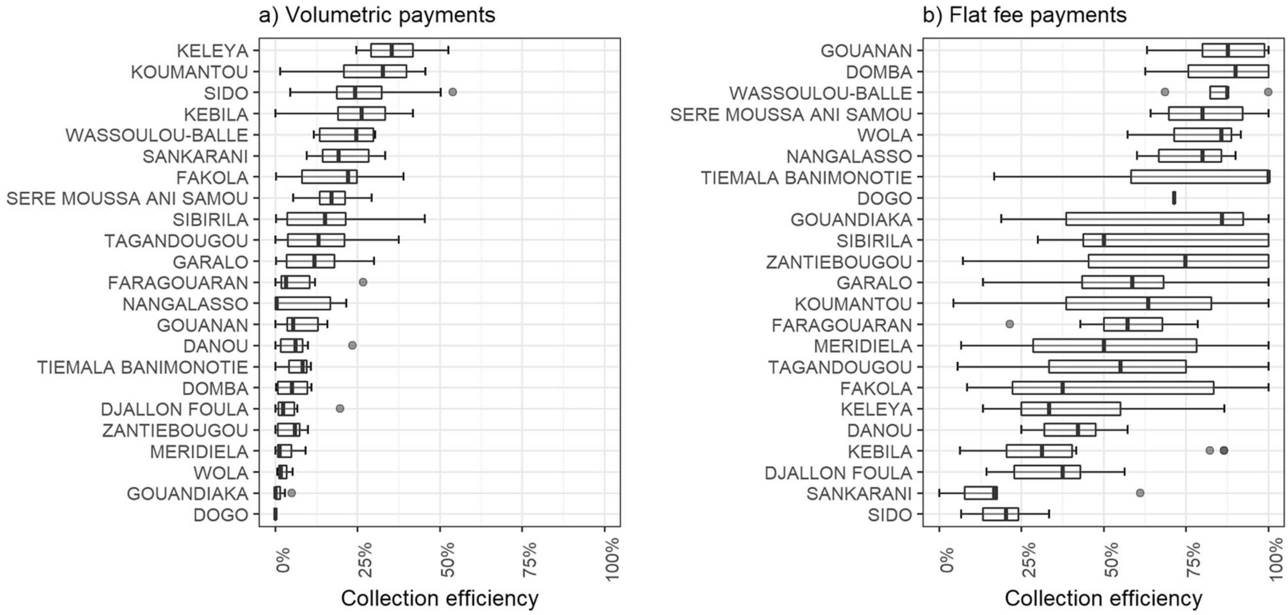

Fig. 3 | Collection efficiency per payment modality across 23 municipalities. a displays collection efficiency for volumetric payments, **b** for flat fees. Box plot present: median (centre line), upper and lower quartiles, interquartile range whiskers, outliers.

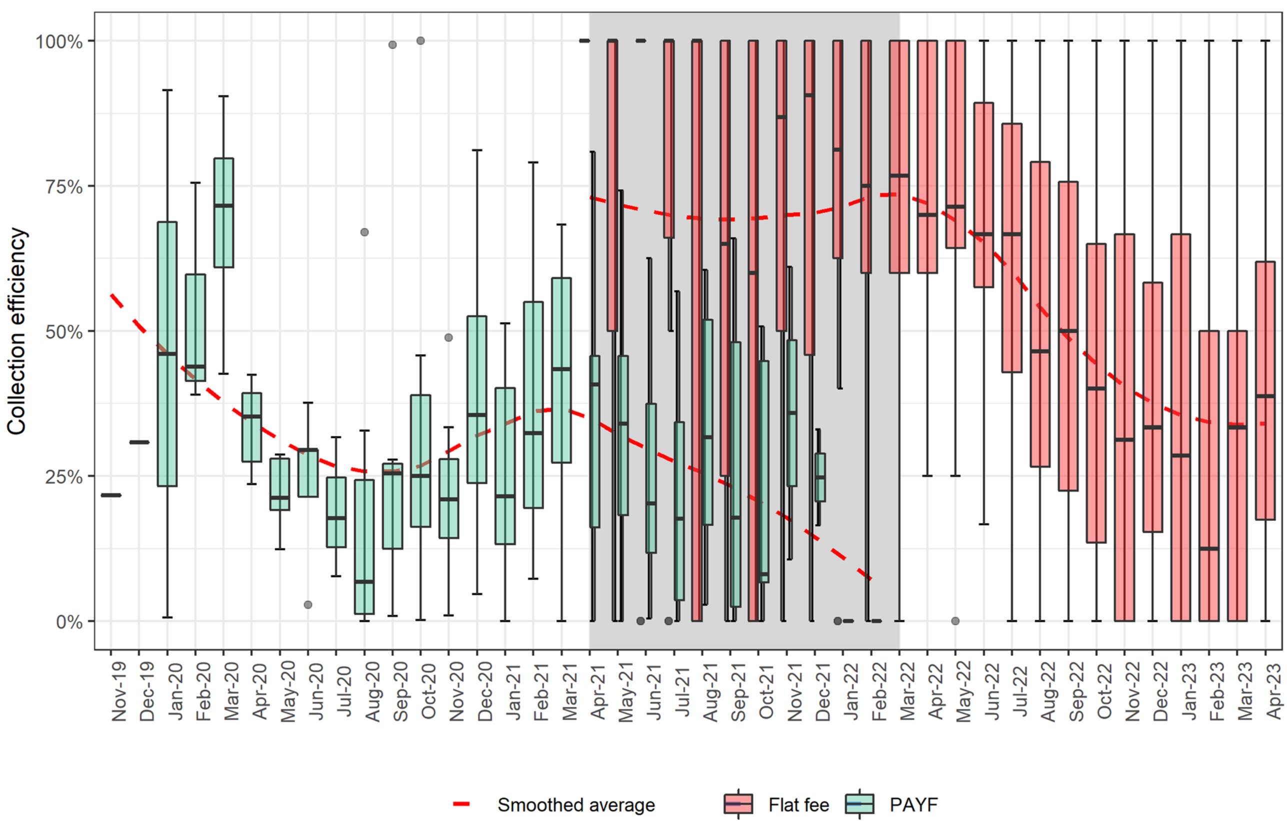

Fig. 4 | Monthly collection efficiency aggregated by municipality, separating between payment modalities. Box and whisker plots (centre line, median; box limits, upper and lower quartiles; whiskers, 1.5x interquartile range; points, outliers). Dashed line for mean per payment modality. Shaded area highlights the period of the payment modality transition (April 2021 to March 2022).

to determine an appropriate subsidy level which is affordable for a service level demanded by the population. Generally, tariff design in most rural contexts is a political decision based on limited or no data[24,25,27]. Here, we are unable to provide a detailed affordability analysis, but we can chart the challenges of collection efficiency and potential responses.

The shift from volumetric to flat fee payments offers some insights for policy and practice. The considerable increase in water consumed and revenue collected in the short term of the study suggests a user preference for flat fees. However, monthly flat fees are not a "one-size-fits-all" approach to effectively collect user payments in all contexts given the revealed variability

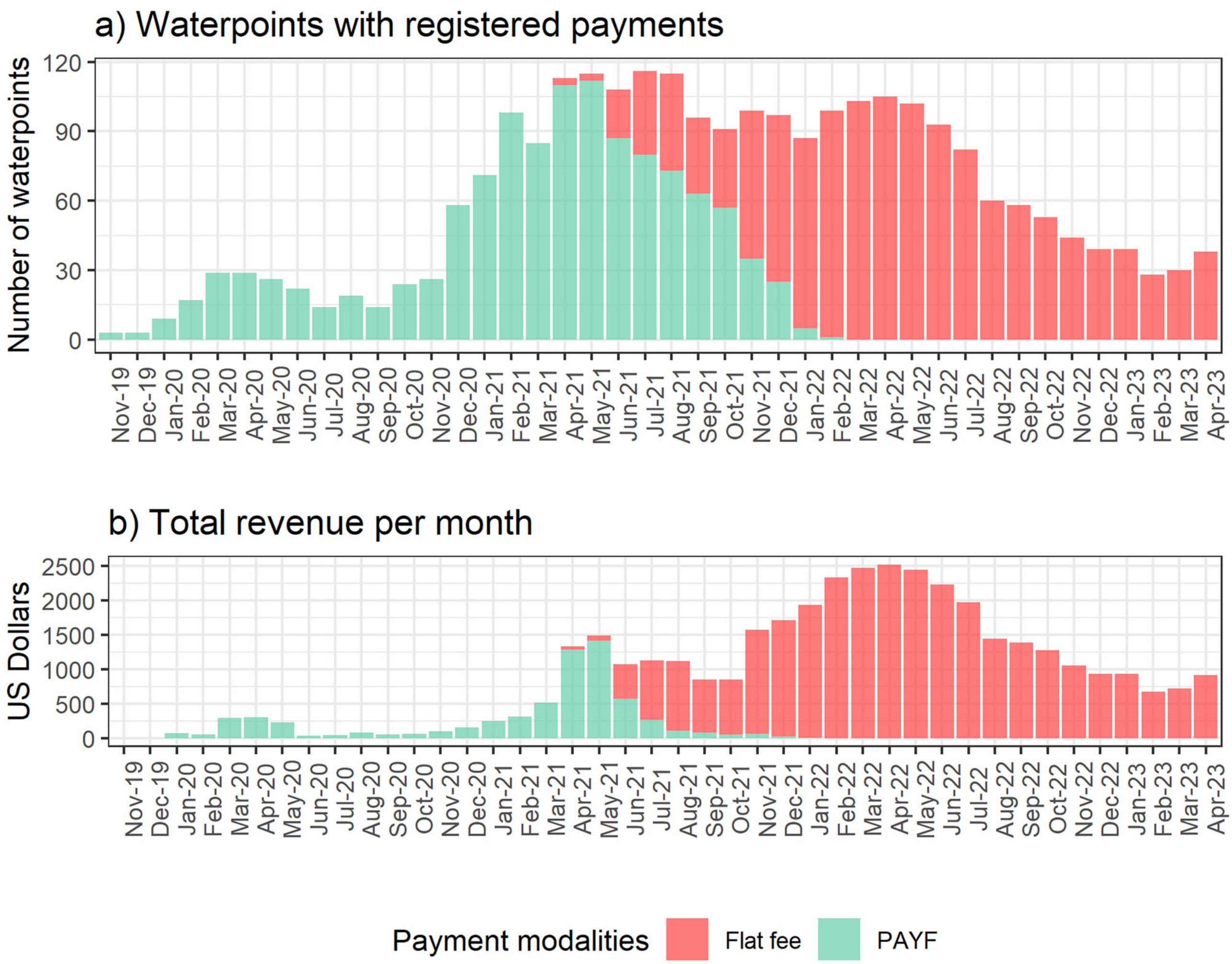

Fig. 5 | Scale of payments and total revenue. **a** Number of waterpoints per month registering a payment activity. **b** Total revenue generated per month. Bar plots separating between payment modalities. Total of 4413 monthly observations between 2019 to 2023 across 177 waterpoints.

in collection efficiency across municipalities. Previous research[8,42,53,64] shows that payment approaches and their respective revenue collection performance vary across local contexts due to multiple factors, such as the availability of alternative sources, user population size, social dynamics, and related coordination challenges, or established practices at the community level where multiple revenue collection approaches are likely to co-exist. Identifying which specific local characteristics affect collection efficiency across payment modalities could offer valuable insights for policy and practice and may ultimately inform rural water services that more adequately cater for local contexts.

In addition, performance in collection efficiency across both payment modalities registers a downward trend, leading to declining revenues over time. While we can only speculate on the drivers for this behaviour in our analysis, findings from other studies suggest that sustaining payments at handpumps is challenging as service levels require users to invest in time and physical effort to pump water[2,15,50,54].

Nevertheless, the combined change in water used and payments made indicates a volumetric tariff is socially unacceptable for reliable rural water supplies delivered through handpumps, emphasising that tariff designs which are considered effective and efficient for urban areas may not necessarily respond to the specific challenges characterising rural water. Importantly, our insights on quantities of water used reflect similar findings from rural Kenya where volumetric payments result in lower income groups reducing water usage[3]. Further research at the household level should assess the implications of payment modalities on water demand, with water user diaries being a potential method of investigation[65].

The short-term effect of the switch from volumetric to flat fee payments is a 40% reduction in the subsidy required for local operating costs at handpumps. Assuming this trend holds, at scale, this effect is substantial with the positive social multipliers of higher volumes of water being consumed with likely health and welfare benefits[1,66]. While groundwater resources need to be correctly managed and monitored, the volumetric increase in usage will have limited impact on groundwater availability[67,68].

Our third reflection is on the role of professional service delivery providers. UDUMA is one of an emerging cohort of professional operators which is offering a utility-style service model based on performance metrics[5,11,43,44]. Professional service providers are not necessarily private companies and may be social enterprises or NGOs[69–71]. As in this case, they have incentives to develop more effective delivery by adapting their business models. Here, we see the change in payment modality as a means to increase local revenues for reliable service provision. There are checks and balances in this professional approach with UDUMA being effectively regulated through contractual agreements with government oversight[37,72].

The performance data provided by professional service providers can support governments in having a clearer understanding of service provision. As noted, such insights reveal the seasonal patterns of water use which may influence what infrastructure investments may be appropriate. As capital investments for drinking water supplies are expected to increase in sub-Saharan Africa[73], evidence is needed to guide their allocation and to ensure investments are effective over time. It is now more clearly documented that in comparison to professional service providers repairing failed waterpoints in a few days, communities can take months to complete repairs[2,10,74], and that effectively maintaining existing infrastructure is cheaper than rehabilitating run-down assets[75,76].

Revenue collection and water consumption data can provide credible evidence to design tariffs and subsidies. Such empirical data will allow governments to more carefully assess if large loans without adequate consideration of subsidy requirements are the right approach. Equally, development banks focussed on providing loans may be under more scrutiny to provide value for money linking capital and operational expenditure to ensure sustainable services beyond short-term borrowing horizons. Such a combination of professional management models and adequate funding arrangements can contribute to ensuring that investments in water supply remain effective for the hardest to reach in rural Africa[1].

We have shown the implications of two prominent payment modalities for reliable rural water services on use and payment behaviours at handpumps in rural Mali. Our results indicate that flat fee payments contribute substantially to funding reliable service provision and stimulate water use. Yet, subsidies are still required to ensure rural people access safe water throughout the year, especially in periods of high demand. Increasing efforts in adaptation finance[77] may constitute an opportunity for addressing the subsidy gap for vulnerable rural water users. As our findings from Mali suggest, successful adaptation remains conditional on professional service delivery. Therefore, we propose linking infrastructure provisions with clear service delivery approaches to deliver more sustainable outcomes. While this would mean changing current practices, it would guarantee that infrastructure investments are effective for those facing the greatest climate risks in rural Africa. Finally, we emphasise that our empirical evidence is not based on a formal experiment and that our data are constrained by the period of the study and only cover handpumps. Therefore, it is unknown how our findings will hold over time and whether they may apply to other types of infrastructure, such as piped-water systems and kiosks, which are expanding in sub-Saharan Africa. While future trends of use and payment behaviours remain unclear, the value of performance data is that it enables policy, practice, and research to track these, and thereby provide an evidence base for more effective policy design and rural water service delivery.

Methods

Study context

The study site comprises the Region of Sikasso, located in south of Mali. The study utilises data from UDUMA Mali, a private company, providing reliable rural water services in 30 rural municipalities, the lowest governmental level in Mali's administrative structure[37]. Payment modalities, service levels, and volumetric tariffs are formally established in a management contract signed between UDUMA and local governments as service authorities. The provider delivers reliable maintenance services, guaranteeing high infrastructure uptime with short breakdown durations (less than 72 h).

UDUMA manages manual pumps (two types of pumps are concerned: Vergnet-Hydro and India Mark 2) equipped with a water meter, making it possible to monitor and link volumetric water use and respective payments for each waterpoint, identified through a unique waterpoint identifier. The meter readings are conducted on a monthly basis by trained UDUMA field staff and validated by supervisors.

The volumetric "pay-as-you-fetch" approach requires users to make direct payments to the caretaker at the waterpoint for every 20-litre container collected. For the monthly flat fee, field supervisors collect the monthly payment upfront from a representative of the user community. The community self-organises to pay the monthly flat fee.

Data collection, availability, and variable definition

The analysis is based on monthly use and payment records registered at individual waterpoints from November 2019 to April 2023. A total of 4447 monthly records across 177 unique waterpoints, situated in 23 municipalities, is available. The 177 individual waterpoints are never operational simultaneously due to UDUMA's gradual extension of its service model to the waterpoints located in its service area and non-payments of monthly flat fees. Given that operations of the identified waterpoints started at different time periods, the panel dataset is unbalanced.

For every individual waterpoint, at least two monthly volumetric use and payment records per payment modality are available. Data cleaning on volumetric use records was conducted to remove potentially faulty meter readings. After confirmation with UDUMA staff, daily use levels were capped at 11 m^3 per waterpoint, removing a total of 34 monthly observations (more detail provided in Supplementary Information under Supplementary Methods).

The final dataset consists of 4413 monthly observations, separated in 1885 monthly records under the volumetric modality, 2528 observations for monthly flat fees. Given this set-up, the analytical strategy of the paper explores how users respond to reliable maintenance services under different revenue collection approaches. We assess four outcomes of interest before and after the change in payment modalities (Table 2). Summary statistics for the outcomes of interest across the payment modalities are provided in the Supporting Information (Supplementary Table 1).

Revealed volumetric use is measured as average daily volume used per waterpoint in a month, providing observed data into the actual use of a waterpoint. The average daily volume is calculated for each waterpoint by dividing the total monthly volume through the number of days in the respective month. The average monthly revenue per waterpoint is calculated by dividing the total monthly revenue generated through the number of active waterpoints in the respective month.

The monthly working ratio provides information on cost recovery per waterpoint per month and is calculated as the share of recurring operation and maintenance costs covered through local revenue. UDUMA estimates that recurring local operation maintenance costs are of $24 per month and per waterpoint. UDUMA's local operation and maintenance costs include local human resources (remuneration of local technicians and supervisors), transport costs, costs for spare parts, water quality monitoring and repairs, and an annual fee paid to local governments. In WASHCost terminology[51,78], these costs include both operations and maintenance expenditure (OpEx) and expenditure on direct support (ExpDS). Other costs, such as Capital Expenditure, Capital Maintenance Expenditure, Cost of Capital, overheads for local administration and office costs or international project administration and management are excluded.

The metric of collection efficiency represents the ratio of expected to actual revenue collected in a month per waterpoint and is established separately for each payment modality. For volumetric payments, collection

Table 2 | Definition of outcomes of interest

Metric	Relevance	Measurement	Unit	Empirical data
Daily volume of water	Information on actual use of service	Average volume per day per waterpoint in a month	m^3	Routine meter readings
Monthly revenue	Information on user payments	• Total revenue per month • Average monthly revenue per waterpoint	$	Routine payment records
Monthly working ratio	Information on cost recovery	Ratio of O&M costs covered through local revenue	%	Routine payment records Cost estimates
Monthly collection efficiency	Information on user valuation of services	Ratio of revenue collected to revenue due in a month per waterpoint	%	Routine payment records and meter readings

efficiency is calculated as the ratio of volume of water paid divided by the volume of water billed in a month per waterpoint. For flat fee contributions, the metrics reflects whether a flat fee was paid or not in a given month per waterpoint.

The main predictor, the payment modality, is coded as a binary variable distinguishing between the volumetric (0) and flat fee (1) approach in the panel data at a clear cut-off point provided by the date at which the first flat fee payment at the individual handpump was registered. UDUMA gradually introduced the flat fee modality to all waterpoints between April 2021 to March 2022. The introduction of the treatment is not random, but follows a staggered adoption[79], with clear cut-off points for each waterpoint.

Recognising that changing climatic conditions may influence user behaviour[46–48,80], the longitudinal approach includes total amount of rainfall in a month and monthly average temperature estimates for each municipality for the period under investigation. Rainfall data was retrieved from Tropical Applications of Meteorology using SATellite data and ground-based observations, TAMSAT[81–83], whereas temperature data was generated using Copernicus Climate Change Service information[84].

Prior to data collection and analysis, ethical approval was obtained from the Central University Research Ethics Committee at the University of Oxford (references: SOGE 1A2020-195 and SOGE 1A2021-046).

Specification of the fixed-effects regression model

As indicated, the introduction of the change in payment modalities is not random but has been gradually rolled out by UDUMA to its entire handpump portfolio, generating observational data. In most non-experimental social science research individual units differ in so many respects that it is impossible to control for all of them. Fixed effect models using panel data allow to mitigate this limitation by comparing within unit change instead of estimating effects from a comparison between different units[85–87]. Therefore, we apply fixed-effects regression models to the longitudinal dataset to estimate the significance of the change in payment modalities on the response variables. Since each individual handpump is observed over multiple time periods, our models exploit the within variation per unit (each waterpoint is observed over multiple months under the two payment modalities). Fixed effect models allow the presence of arbitrary correlations between unobserved individual effects and covariates, and control for these unobservable factors to alleviate omitted variable bias[79,85,87].

Similar to Kulinkina et al.[33], we include observed time-variant confounders (rainfall and temperature data) to capture seasonal variation and entity fixed effects for each waterpoint. This strategy allows to avoid omitted variable bias arising from unobserved factors at the waterpoint level that are time-invariant, such as localised community practices or the number of alternative water sources surrounding the respective waterpoint. Therefore, the unique waterpoint ID number is included as a constant intercept in the regression model allowing to control for waterpoint-level heterogeneity. This removes the effect of time-invariant characteristics at the waterpoint level, and accounts for seasonal confounders (climate metrics) to estimate the effect of the main predictor, the change in payment modalities, on the outcome variables. We report robust standard errors, clustered at the waterpoint level, to account for autocorrelation occurring between periods within each unit[88,89]. All statistical analyses were conducted in R (Version 4.0.3).

Data availability

All data generated or analysed during this study are included in this published article and its Supplementary Information files. The file "Flatfee_-Data" (csv) includes all relevant data to replicate the analyses.

Received: 28 June 2023; Accepted: 29 May 2024;
Published online: 04 July 2024

References

1. WHO, UNICEF, & World Bank. State of the world's drinking water: an urgent call to action to accelerate progress on ensuring safe drinking water for all. https://apps.who.int/iris/handle/10665/363704 (2022).
2. Foster, T., Furey, S., Banks, B. & Willetts, J. Functionality of handpump water supplies: a review of data from sub-Saharan Africa and the Asia-Pacific region. *Int. J. Water Resour. Dev.* **36**, 855–869 (2020).
3. Foster, T. & Hope, R. Evaluating waterpoint sustainability and access implications of revenue collection approaches in rural Kenya. *Water Resour. Res.* **53**, 1473–1490 (2017).
4. Hope, R. Is community water management the community's choice? Implications for water and development policy in Africa. *Water Policy* **17**, 664–678 (2015).
5. McNicholl, D. et al. Performance-based funding for reliable rural water services in Africa. https://www.smithschool.ox.ac.uk/research/water/report-performance-based-funding.html (2019).
6. Banerjee, S. G. & Morella, E. *Africa's Water and Sanitation Infrastructure: Access, Affordability, and Alternatives* (The World Bank, 2011).
7. Hutchings, P. et al. A systematic review of success factors in the community management of rural water supplies over the past 30 years. *Water Policy* **17**, 963–983 (2015).
8. Koehler, J., Thomson, P. & Hope, R. Pump-priming payments for sustainable water services in rural Africa. *World Dev.* **74**, 397–411 (2015).
9. Whaley, L. et al. Evidence, ideology, and the policy of community management in Africa. *Env. Res. Lett*. **12** https://doi.org/10.1088/1748-9326/ab35be (2019).
10. Foster, T. et al. Investing in professionalized maintenance to increase social and economic returns from drinking water infrastructure in rural Kenya. (2022).
11. McNicholl, D. et al. Results-based contracts for rural water services. https://www.uptimewater.org/s/Results-Based-Contracts-for-Rural-Water- Services.pdf (2020).
12. Andres, L. A. et al. Doing more with less: smarter subsidies for water supply and sanitation. http://hdl.handle.net/10986/32277 (2019).
13. Fonseca, C., Smits, S., Kwabena, N., Naafs, A. & Franceys, R. Financing capital maintenance of rural water supply systems: current practices and future options. 40 (2013).
14. Hutton, G. & Varughese, M. *The Costs of Meeting the 2030 Sustainable Development Goal Targets on Drinking Water, Sanitation, and Hygiene* (World Bank, 2016).
15. Jones, S. Sharing the recurrent costs of rural water services in four municipalities supported by WaterAid in Mali. *Waterlines* **32**, 295–307 (2013).
16. Kolker, J., Kingdom, B. & Trémolet, S. Financing options for the 2030 water agenda. (2016).
17. Leigland, J., Trémolet, S. & Ikeda, J. *Achieving Universal Access to Water and Sanitation by 2030 The Role of Blended Finance*, 20 (World Bank Group, 2016).
18. Pories, L., Fonseca, C. & Delmon, V. Mobilising Finance for WASH: Getting the Foundation Right. 40 https://documents1.worldbank.org/curated/en/725521553154723194/pdf/Mobilising-Finance-for-WASH-Getting-the-Foundation-Right.pdf (2019).
19. Winpenny, J. et al. *Aid Flows to the Water Sector* (World Bank, 2016).
20. Winpenny, J. T. *et al*. *Financing Water for All* (World Water Council, 2003).
21. WHO. *National Systems to Support Drinking-Water, Sanitation and Hygiene: Global Status Report 2019. UN-Water Global Analysis and Assessment of Sanitation and Drinkingwater (GLAAS) 2019 Report* (WHO, 2019).
22. WHO. *Reflecting on TrackFin 2012-2020: Key Results, Lessons Learned, and the Way Forward* (WHO, 2021).

23. WHO. Financing Universal Water, Sanitation and Hygiene under the Sustainable Development Goals: UN-Water Global Analysis and Assessment of Sanitation and Drinking-Water: GLAAS 2017 Report. http://apps.who.int/iris/bitstream/10665/254999/1/9789241512190-eng.pdf?ua=1 (WHO, 2017).
24. Nauges, C. & Whittington, D. Evaluating the performance of alternative municipal water tariff designs: quantifying the tradeoffs between equity, economic efficiency, and cost recovery. *World Dev.* **91**, 125–143 (2017).
25. Whittington, D. Municipal water pricing and tariff design: a reform agenda for South Asia. *Water Policy* **5**, 61–76 (2003).
26. World Bank The demand for water in rural areas: determinants and policy implications. *World Bank Res. Obs.* **8**, 47–70 (1993).
27. Fuente, D. The design and evaluation of water tariffs: a systematic review. *Util. Policy* **61**, 100975 (2019).
28. OECD. *Guidelines for Performance-Based Contracts between Municipalities and Water Utilities. Lessons Learnt from Eastern Europe, Caucasus and Central Asia* (OECD, 2011).
29. Andres, L. A. et al. *Troubled Tariffs: Revisiting Water Pricing for Affordable and Sustainable Water Services* (World Bank, 2021).
30. Cook, J., Fuente, D. & Whittington, D. Choosing among pro-poor policy options in the delivery of municipal water services. *Water Econ. Policy* **06**, 1950013 (2020).
31. Hope, R., Thomson, P., Koehler, J. & Foster, T. Rethinking the economics of rural water in Africa. *Oxf. Rev. Econ. Policy* **36**, 171–190 (2020).
32. Ingram, W. & Memon, F. A. Rural water collection patterns: combining smart meter data with user experiences in Tanzania. *Water* **12**, 1164 (2020).
33. Kulinkina, A. V. et al. Piped water consumption in Ghana: a case study of temporal and spatial patterns of clean water demand relative to alternative water sources in rural small towns. *Sci. Total Environ.* **559**, 291–301 (2016).
34. Sharpe, T. et al. Electronic sensors to monitor functionality and usage trends of rural water infrastructure in Plateau State, Nigeria. *Dev. Eng*. 100100 https://doi.org/10.1016/j.deveng.2022.100100 (2022).
35. Thomson, P. Remote monitoring of rural water systems: a pathway to improved performance and sustainability? *WIREs Water* **8**, e1502 (2020).
36. Thomson, P. & Koehler, J. Performance-oriented monitoring for the water SDG—challenges, tensions and opportunities. *Aquat. Procedia* **6**, 87–95 (2016).
37. van der Wilk, N. *Conditions for Private Sector Involvement and Financing in the Rural Water Sector* (IRC, 2019).
38. Wutich, A. et al. A global agenda for household water security: measurement, monitoring, and management. *J. Am. Water Resour. Assoc.* **57**, 530–538 (2021).
39. Nagel, C., Beach, J., Iribagiza, C. & Thomas, E. A. Evaluating cellular instrumentation on rural handpumps to improve service delivery—a longitudinal study in rural Rwanda. *Environ. Sci. Technol.* **49**, 14292–14300 (2015).
40. Hope, R., Foster, T., Koehler, J. & Thomson, P. Rural Water Policy in Africa and Asia. in Water science policy and management: a global challenge (ed. Dadson, S. J.) 159–179 (John Wiley & Sons, Inc, 2019).
41. DNH. Stratégie Nationale de Développement de l'Alimentation en Eau Potable au Mali. (2007).
42. Jones, S. *Sharing the Recurrent Costs of Rural Water Supply in Mali: The Role of Wateraid in Promoting Sustainable Service Delivery* (University of London, 2013).
43. Nilsson, K., Hope, R., McNicholl, D., Nowicki, S. & Charles, K. Global Prospects to Deliver Safe Drinking Water Services for 100 Million Rural People by 2030. 68 https://reachwater.org.uk/wp-content/uploads/2021/10/100m_REACH_RWSN_Diagnostic-Report.pdf (2021).
44. McNicholl, D. et al. Delivering global rural water services through results-based contracts. https://www.uptimewater.org/s/Delivering-Global - Rural-Water-Services-through-Results-Based-Contracts.pdf (2021).
45. World Food Programme. West Africa: the 2021 rainy season in review. (2021).
46. MacAllister, D. J., MacDonald, A. M., Kebede, S., Godfrey, S. & Calow, R. Comparative performance of rural water supplies during drought. *Nat. Commun.* **11**, 1099 (2020).
47. Thomas, E. et al. Quantifying increased groundwater demand from prolonged drought in the East African Rift Valley. *Sci. Total Environ.* **666**, 1265–1272 (2019).
48. Thomson, P. et al. Rainfall and groundwater use in rural Kenya. *Sci. Total Environ.* **649**, 722–730 (2019).
49. Armstrong, A., Dyer, E., Koehler, J. & Hope, R. Intra-seasonal rainfall and piped water revenue variability in rural Africa. *Glob. Environ. Change* **76**, 102592 (2022).
50. Smith, D. W., Atwii Ongom, S. & Davis, J. Does professionalizing maintenance unlock demand for more reliable water supply? Experimental evidence from rural Uganda. *World Dev.* **161**, 106094 (2023).
51. WASHCost. Providing a basic level of water and sanitation services that last: COST BENCHMARKS. 4 (2012).
52. World Bank. Toward a universal measure of what works on rural water supply: rural water metrics global framework. https://openknowledge.worldbank.org/server/api/core/bitstreams/42a9968b-0ad0-5159-94ae-8f350d40e598/content (2017).
53. Foster, T. A critical mass analysis of community-based financing of water services in rural Kenya. *Water Resour. Rural Dev.* **10**, 1–13 (2017).
54. Katuva, J., Goodall, S., Harvey, P. A., Hope, R. & Trevett, A. FundiFix: exploring a new model for maintenance of rural water supplies. (2016).
55. Breyer, B. & Chang, H. Urban water consumption and weather variation in the Portland, Oregon metropolitan area. *Urban Clim.* **9**, 1–18 (2014).
56. Rasifaghihi, N., Li, S. S. & Haghighat, F. Forecast of urban water consumption under the impact of climate change. *Sustain. Cities Soc.* **52**, 101848 (2020).
57. Ziervogel, G., Shale, M. & Du, M. Climate change adaptation in a developing country context: the case of urban water supply in Cape Town. *Clim. Dev.* **2**, 94–110 (2010).
58. Krueger, E. H. et al. Resilience dynamics of urban water supply security and potential of tipping points. *Earths Future* **7**, 1167–1191 (2019).
59. Larsen, T. A., Hoffmann, S., Lüthi, C., Truffer, B. & Maurer, M. Emerging solutions to the water challenges of an urbanizing world. *Science* **352**, 928–933 (2016).
60. Mu, X., Whittington, D. & Briscoe, J. Modeling village water demand behavior: a discrete choice approach. *Water Resour. Res.* **26**, 521–529 (1990).
61. Elliott, M. et al. Addressing how multiple household water sources and uses build water resilience and support sustainable development. *Npj Clean. Water* **2**, 6 (2019).
62. Wagner, J., Cook, J. & Kimuyu, P. Household demand for water in rural Kenya. *Environ. Resour. Econ.* **74**, 1563–1584 (2019).
63. White, G. F., Bradley, D. J. & White, A. U. *Drawers of Water: Domestic Water Use in East Africa* (University of Chicago Press, 1972).
64. Koehler, J., Thomson, P., Goodall, S., Katuva, J. & Hope, R. Institutional pluralism and water user behavior in rural Africa. *World Dev.* **140**, 105231 (2021).
65. Wutich, A. Estimating household water use: a comparison of diary, prompted recall, and free recall methods. *Field Methods* **21**, 49–68 (2009).
66. Prüss-Ustün, A. et al. Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: an

updated analysis with a focus on low- and middle-income countries. *Int. J. Hyg. Environ. Health* **222**, 765–777 (2019).
67. MacAllister, D. J. et al. Contribution of physical factors to handpump borehole functionality in Africa. *Sci. Total Environ.* **851**, 158343 (2022).
68. MacDonald, A. M. et al. Mapping groundwater recharge in Africa from ground observations and implications for water security. *Environ. Res. Lett.* **16**, 034012 (2021).
69. Lockwood, H. Professionalized maintenance for rural water service provision: toward a common language and vision. https://www.globalwaters.org/sites/default/files/professionalized_maintenance_for_rural_water_service_provision_concept_note_20210308.pdf (2021).
70. Lockwood, H. Sustaining rural water—a comparative study of maintenance models for community-managed schemes. 90 (2019).
71. Cord, C. et al. Pathways to consumer demand and payment for professional rural water infrastructure maintenance across low-income contexts. *Sci. Total Environ.* **815**, 152906 (2022).
72. REAL-Water. Episode 2—an audacious plan to deliver safe reliable water to all of rural Benin … profitably. With UDUMA's Thierry Barbotte and Mikael Dupuis. (2022).
73. International High-Level Panel on Water Investments for Africa. *International High-Level Panel on Water Investments in Africa Report: How to Mobilise US$30 Billion Annually to Achieve Water Security and Sustainable Sanitation in Africa.* https://aipwater.org/wp-content/uploads/2023/03/How-to-Mobilise-US%EF%BF%BD30-Billion-Annually-to-Achieve-Water-Security-and-Sustainable-Sanitation-in-Africa-New-York-Version-21-March-2023.pdf (International High-Level Panel on Water Investments for Africa, 2023).
74. Danert, K. Stop the Rot Report I: Handpump Reliance, Functionality and Technical Failure. Action Research on Handpump Component Quality and Corrosion in Sub-Saharan Africa. 52 https://www.rural-water-supply.net/_ressources/documents/default/1-1046-2-1647360829.pdf (2022).
75. Harvey, A. Ten Factors for Viable Rural Water Services. 14 https://www.globalwaters.org/sites/default/files/whave-_ten_factors_final.pdf (2021).
76. Convergence. Working Group on blended finance for water infrastructure maintenance and fecal sludge management—outcome document. (2021).
77. UNEP. Adaptation Gap Report 2022: Too Little, Too Slow – Climate Adaptation Failure Puts World at Risk. 84 www.unep.org/adaptation-gap-report-2022 (2022).
78. Smits, S., Verhoeven, J., Moriarty, P., Fonseca, C. & Lockwood, H. Arrangements and Cost of Providing Support to Rural Water Service Providers. 48 https://www.ircwash.org/sites/default/files/Smits-2011-Arrangements.pdf (2011).
79. Cunningham, S. *Causal Inference: The Mixtape* (Yale University Press, 2021).
80. Armstrong, A., Hope, R. & Munday, C. Monitoring socio-climatic interactions to prioritise drinking water interventions in rural Africa. *Npj Clean. Water* **4**, 10 (2021).
81. Maidment, R. I. et al. A new, long-term daily satellite-based rainfall dataset for operational monitoring in Africa. *Sci. Data* **4**, 170063 (2017).
82. Maidment, R. I. et al. The 30 year TAMSAT African Rainfall Climatology And Time series (TARCAT) data set. *J. Geophys. Res. Atmos.* **119**, 10,619–10,644 (2014).
83. Tarnavsky, E. et al. Extension of the TAMSAT satellite-based rainfall monitoring over Africa and from 1983 to Present. *J. Appl. Meteorol. Climatol.* **53**, 2805–2822 (2014).
84. Copernicus Climate Change Service. ERA5-Land monthly averaged data from 2001 to present. ECMWF https://doi.org/10.24381/CDS.68D2BB30 (2019).
85. Best, H. & Wolf, C. *Fixed-Effects Panel Regression* (SAGE Publications Ltd, 2014).
86. Henningsen, A. & Henningsen, G. Analysis of Panel Data Using R. in Panel Data Econometrics (ed. Tsionas, M.) 345–396 (Elsevier, 2019). https://doi.org/10.1016/B978-0-12-814367-4.00012-5.
87. Wooldridge, J. *Econometric Analysis of Cross Section and Panel Data, 741* (The MIT Press, 2010).
88. Abadie, A., Athey, S., Imbens, G. W. & Wooldridge, J. M. When Should You Adjust Standard Errors for Clustering? *The Q. J. Econ*. **138**, 1–35 (2022).
89. Cameron, C. A. & Miller, D. L. A practitioner's guide to cluster-robust inference. *J. Hum. Resour.* **50**, 317–372 (2015).

Acknowledgements

J.W. has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Innovative Training Network NEWAVE—grant agreement No-. 861509. This article is an output from the REACH programme, funded by UK Aid from the UK Foreign, Commonwealth and Development Office (FCDO) for the benefit of developing countries (Programme Code 201880). However, the views expressed and information contained in it are not necessarily those of or endorsed by FCDO, which can accept no responsibility for such views or information or for any reliance placed on them.

Author contributions

J.W. conceived the study. J.W. and M.D. performed research (data collection). J.W. carried out the analyses. J.W. and R.H. wrote the manuscript. J.K. and M.D. contributed to writing (review & editing). All authors read and approved the final manuscript.

Competing Interests

The authors have organisational affiliations to disclose: M.D. is Managing Director of UDUMA, based in Ingré, France. UDUMA has provided data for this research work at no cost. UDUMA has an ongoing research collaboration with the University of Oxford. All other authors declare no financial or non-financial competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41545-024-00341-6.

Correspondence and requests for materials should be addressed to Johannes Wagner.