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Can solar water kiosks generate sustainable revenue streams for rural water services?

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ABSTRACT

Providing a sustainable supply of safe drinking water in rural Africa depends on sufficient revenue from user payments to maintain services. While handpumps have been the primary source of drinking water for rural Africans for decades, local revenue generation has been unstable, contributing to service disruptions and welfare losses. We examine the effect of upgrading manual handpumps to solar kiosks in rural Mali from 2019 to 2023. We model 452 monthly records of observed payments and metered water usage to estimate changes in volumetric use and revenue generation. Average revenues increase four-fold indicating stronger financial performance with solar kiosks. In contrast, we find no significant increase in the volume of water people use when a handpump is upgraded to a solar kiosk. We estimate that a 1 °C temperature increase is associated with a $9 increase in average monthly revenue and 366 more litres of water used every day per waterpoint. Our study suggests that rural Malians are more inclined to pay for water from professionally managed solar kiosks. However, seasonal volatility in water demand and uncertainty in the long-term revenue effect suggests caution in assuming solar kiosks are a definitive solution to the nuanced and dynamic nature of water user behaviours in rural Africa.

1. Introduction

The global challenge of providing safely managed drinking water services to two billion people (WHO et al., 2022) is amplified in rural Africa where approximately 25 %–30 % of waterpoints are non-functional at any point in time (Foster et al., 2020). Additionally, climate risks and weather extremes, including increased variability in precipitation patterns and sustained droughts and heatwaves, further strain the quality and quantity of water supplies (IPCC, 2022; WHO et al., 2022). In this context, new water supply technologies and management models are emerging to deliver more reliable and climate-resilient water services, particularly in low-income settings and rural areas (Hope et al., 2020; Howard et al., 2016; Macdonald et al., 2009).

As part of the global shift towards higher service levels by design, aiming to provide reliable, accessible, and safe drinking water to rural communities (UNGA, 2015), solar-powered water kiosks are gaining momentum across Africa as they use renewable energy to pump widely available groundwater resources (MacDonald et al., 2021; Meunier et al., 2023). Solar kiosks, in comparison to handpumps, reduce the physical effort required to pump groundwater, provide water on demand through taps, and cut queuing time (Kiprono & Llario, 2020; World Bank, 2018), which is especially beneficial for women and children who spend approximately 200 million hours every day collecting water (Graham et al., 2016). While solar-pumping technology offers various advantages, it still requires maintenance to provide services over time (Chandel et al., 2015; Foster et al., 2020).

Professional service delivery models have emerged across Africa to ensure the operational sustainability of rural water infrastructure investments (Nilsson et al., 2021). These models generally manage to repair broken rural water infrastructure within three days or less, an improvement compared to the weeks or months communities often take to complete repairs. Despite this higher operational performance, professional service delivery models rarely generate sufficient revenue via user payments to be financially viable (Foster et al., 2022; Smith et al., 2023). Revenue shortfalls are more pronounced for handpumps (McNicholl et al., 2019) which remain the most widely used water supply technology in rural Africa (Foster, 2013; Foster et al., 2020).

Studies in Kenya (Koehler et al., 2021) and Uganda (Smith et al.,

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2023) have investigated if professional maintenance services for rural handpumps, providing rapid responses to breakdowns, increase revenue generation. Both studies find that user payments remain limited and diminish over time. In the light of these findings, Smith et al. call for empirical investigations of user responses to service improvements "using real payments over meaningfully long periods of time" (2023, p. 13).

Assessments of user responses to hypothetical improvements in drinking water services suggest that user revenue is likely to be higher and more regular with households benefiting from individual piped connections (Mu et al., 1990; Van Houtven et al., 2017). While piped water supplies are only expanding slowly in rural areas (Armstrong, 2022; WHO et al., 2022), solar kiosks offer a service level improvement in comparison to handpumps by providing a piped supply to communal taps, eliminating the need for manual pumping. Yet it is unknown how a switch from handpumps to solar kiosks affects water use and payment behaviours and revenue generation. This paper seeks to address this knowledge gap and empirically evaluates the effects of an infrastructure upgrade in a real-world setting.

In Mali, UDUMA, a professional service delivery company, has raised private and public capital for government contracts aiming to provide reliable rural water services, subject to affordable user payments (van der Wilk, 2019). As the original program design shifted from managing handpumps to piloting solar kiosks, an opportunity emerged to evaluate the transition in 15 rural communities. Routinely monitored data on volumetric water production and user payments are available before and after the infrastructure change as part of UDUMA's professional management approach. We trace the changes from the introduction of the solar technology in comparison to the historical handpump data and evaluate the extent to which solar-powered water kiosks affect water use and revenue generation, conditional on seasonal fluctuations.

We track three performance metrics at the waterpoint level over three consecutive dry and wet seasons: average daily volume of water used, monthly payment collections, and monthly revenue. Our analysis covers 452 months of waterpoint performance data over the period from November 2019 to April 2023 across a total of 15 sites which transitioned from handpump to solar kiosk. Our analytical strategy applies interrupted time series and fixed effects regression models to estimate the effect of the technology upgrade on the outcomes of interest. We conduct additional statistical tests to ascertain the robustness of the analysis.

Our analysis has relevant implications for policy and practice interested in effective rural water service delivery. We find that, although user demand remains subject to seasonal fluxes, solar kiosks generate, on average, four-times higher monthly revenues than handpumps. Our study suggests that rural Malians are more inclined to pay for the water they consume when professionally delivered through solar kiosks. With billions of dollars of adaptation finance likely to emerge in the coming years (UNEP, 2022), there might be a case for investing in solar kiosks given their stronger financial performance. Yet, seasonal volatility in water demand and uncertainty in the long-term revenue effect suggest caution in assuming solar kiosks are a definitive solution to the context-specific and dynamic nature of water user behaviours in rural Africa.

2. Materials and methods

2.1. Study context and site selection

The study site comprises the Region of Sikasso, located in south of Mali. The area is characterised by an annual dry season from approximately March to June followed by a wet season from July to October, with annual rainfall of 510 to 1,400 mm and average temperatures of 24 to 32 °C (World Food Programme, 2021). Mali's overarching socio-political and security situation is volatile, with Sikasso being the region with the highest poverty incidence (INSTAT, 2019). The study utilises data from UDUMA, a private company, providing reliable rural water services in 30 rural municipalities, the lowest governmental level in Mali's administrative structure (van der Wilk, 2019).

UDUMA installs and maintains rural waterpoints fitted with water meters. Payment modalities, service levels, and volumetric tariffs are formally established in a management contract signed between UDUMA and local governments as service authorities. UDUMA is responsible for maintenance services, guaranteeing service reliability with short breakdown durations of less than 72 h, and must conduct regular water quality monitoring (UDUMA, 2017). As part of the contract, water users must pay a volumetric tariff of 500 FCFA ($0.80) per m3, in accordance with Mali's tariff policy for rural water supply (DNH, 2007). The "pay-as-you-fetch" (PAYF) approach requires users to make direct payments at the waterpoint for every 20-liter container collected.

Between March and May 2021, UDUMA sequentially converted boreholes equipped with manual handpumps (UDUMA manages two pump types: India Mark 2 and Vergnet-Hydro) to solar-powered water kiosks in ten sites (cohort 1). In December 2021, an additional cohort of five waterpoints under UDUMA's management received an identical infrastructure upgrade from handpump to solar kiosk (cohort 2). The infrastructure upgrade replacing a manual pump with a solar kiosk (Fig. 1) across the 15 sites was introduced by the service provider within existing contractual arrangements. This shift in UDUMA's original strategy from managing handpumps to piloting solar kiosks was motivated by unstable revenue generation and low water usage at handpumps. National and regional government entities in Mali supported UDUMA's shift towards installing solar kiosks.

The upgrade from a handpump to a solar kiosk reduced the physical effort for pumping, the time to fill a 20 L bucket, and the queuing time as a result of the three taps and a higher flow rate. While the tariff level, the volumetric payment modality (PAYF), the service quality, distance between the users' household and the waterpoint, and the socio-cultural context remain unchanged, a higher service level is provided. Table 1 summarises the main differences and similarities between the infrastructure types and related service levels.

UDUMA selected the sites (Fig. 2), reflecting the diverse geographical, socio-economic, and environmental conditions of its service area, to trial the solar kiosks (additional information can be found in Table S1, Supporting Information, SI). The site selection through the operator was informed by the following criteria: socio-political context and local security situation, environmental conditions (borehole yield and pump test) and population size (minimum 700 people per village), with the distinct service population per waterpoint unknown. We emphasise that UDUMA targeted sites with potential for success. The conditions for the installation of a solar kiosk are thus not random and the study is not based on a formal experiment. However, we use the two cohorts of waterpoints as an opportunity to explore the effects of an infrastructure upgrade on user behaviour.

Finally, we highlight that over a period of four months, from October 2021 to January 2022, UDUMA replaced its initial mobile money payment system with a cash-based payment system. The initial digital system required users to charge a payment card. At the waterpoint, users paid for the volume of water collected by using their card and a card reader device handled by the caretaker. The payment card is debited according to the volume of water collected (PAYF), with a volumetric tariff of 500 FCFA ($0.80) per m^3. Since January 2022, all payments are cash-based, following the same tariff ($0.80/$m^3$) and payment modality (PAYF) as the initial digital payment system. For cash payments, users pay the required volumetric payment amount directly in cash to the caretaker.

The shift from mobile money to cash payments was motivated by cost considerations given high operating costs for digital payment systems (software license, data collection devices, fees for digital payment provider, etc.). While this shift in the payment system stipulated internal changes at the provider level, the user experience did not fundamentally change. Before, during, and after the transition from digital to cash payments, users continued to make direct payments to the caretaker at

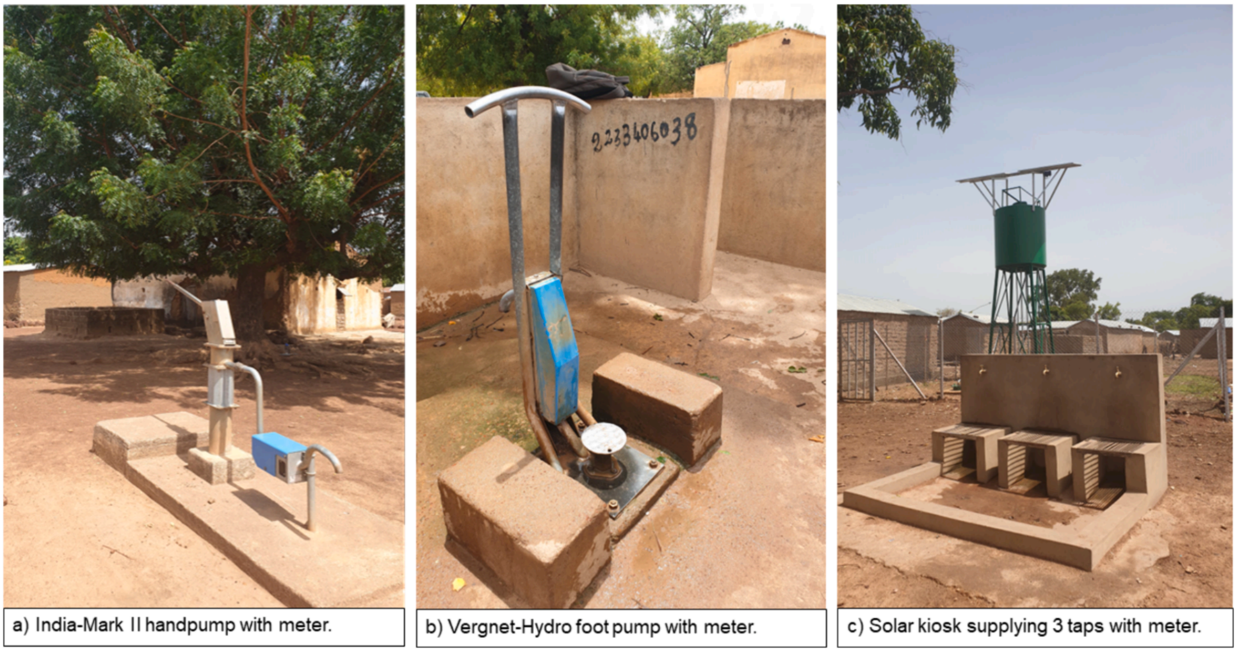

Fig. 1. Water supply technologies managed by UDUMA in the Region of Sikasso.

Table 1
Comparison of service attributes across technology types.

Attribute	Handpump	Solar kiosk
Tariff per m^3 (PAYF)	500 FCFA / $0.80	500 FCFA / $0.80
Service reliability	Guaranteed repair time of max. 3 days	Guaranteed repair time of max. 3 days
Water quality monitoring	Yes	Yes
Physical effort to fill a 20L bucket	60–80 pump strokes	No physical effort needed
Estimated time to fill 20L bucket	Approximately 2 min	Less than 1 min
Number of outlets at distribution point	1 spout	3 taps

Notes: Data on infrastructure performance (pump strokes and production capacity of each system) is based on field observations.

the waterpoint. We emphasise that the gradual change from digital to cash payments did not affect the tariff level ($0.80/m^3) or the PAYF payment modality. At any point in time, users are required to pay for the volume of water collected – regardless of if using the initial digital payment system or cash. Nevertheless, we recognise that the change in payment systems constitutes an additional limitation of the methodology of the analysis.

2.2. Data collection and variable definition

As part of UDUMA's professional management approach, data on water use and payments per individual waterpoint are collected every month. Since each waterpoint has a unique identification code, monthly water use records and payment data can be linked.

The volumetric meter readings are collected for each waterpoint by trained UDUMA field staff. Area managers visit the respective waterpoints and conduct meter readings at the end of a month. They record the meter's index with a mobile data-collection tool (Kizeo), by scanning the unique QR code of the waterpoint, entering the meter reading, and taking a photo of the meter. These data are time-stamped and stored online. The reliability of the metering data is controlled and validated by supervisors based at UDUMA's field office in Bougouni.

For the payment data, data collection differs if payments are made digitally or in cash. The initial digital payment system directly digitised the payment transaction and transferred the revenue to UDUMA. Total payments at an individual waterpoint were compiled and summarised per month. For cash payments, the area managers collect the cash revenue from the caretaker at each waterpoint as part of the monthly site visit. The area managers register the cash revenue generated at each waterpoint and send it to a local bank account using a mobile payment service (Orange money).

Water use is measured as average daily volume used per waterpoint in a month, whereas revenue-related metrics include payment collection efficiency and monthly revenue per waterpoint. We assess these indicators before and after the infrastructure shift. The average daily volume is calculated for each waterpoint by dividing the monthly volume of water used through the number of days in the respective month. Collection efficiency represents the ratio of volume of water paid divided by the volume of water billed in a month per waterpoint. Monthly revenue per waterpoint is based on UDUMA's sales records and reported in US Dollars. These performance metrics provide insights into the actual use of a waterpoint and can be considered as a proxy for the value users place on the service (Hope et al., 2020).

For the first cohort of ten waterpoints a total of 323 monthly records on water usage and payments is available from November 2019 to April 2023. This includes 98 months of data before the solar upgrade, and 225 months of data after the infrastructure change. The infrastructure shift happened gradually between March to May 2021 following a *staggered* adoption (Cunningham, 2021), with varying dates for each of the ten sites.

The second cohort of five waterpoints under UDUMA's management received an infrastructure upgrade from handpump to solar kiosk on 1 December 2021, a clear cut-off point. Payment data and volumetric use records cover a total of 129 monthly observations from March 2021 to April 2023, with 44 months of data before, and 85 months of data after the solar upgrade.

Recognising that changing climatic conditions, especially seasonal rainfall and temperature, may influence user demand (Armstrong et al., 2021; MacAllister et al., 2020; Thomas et al., 2019; Thomson et al., 2019), the empirical estimates account for the total amount of rainfall in a month and monthly average temperature for each site. Rainfall data was retrieved from Tropical Applications of Meteorology using SATellite data and ground-based observations, TAMSAT (Maidment et al., 2014;

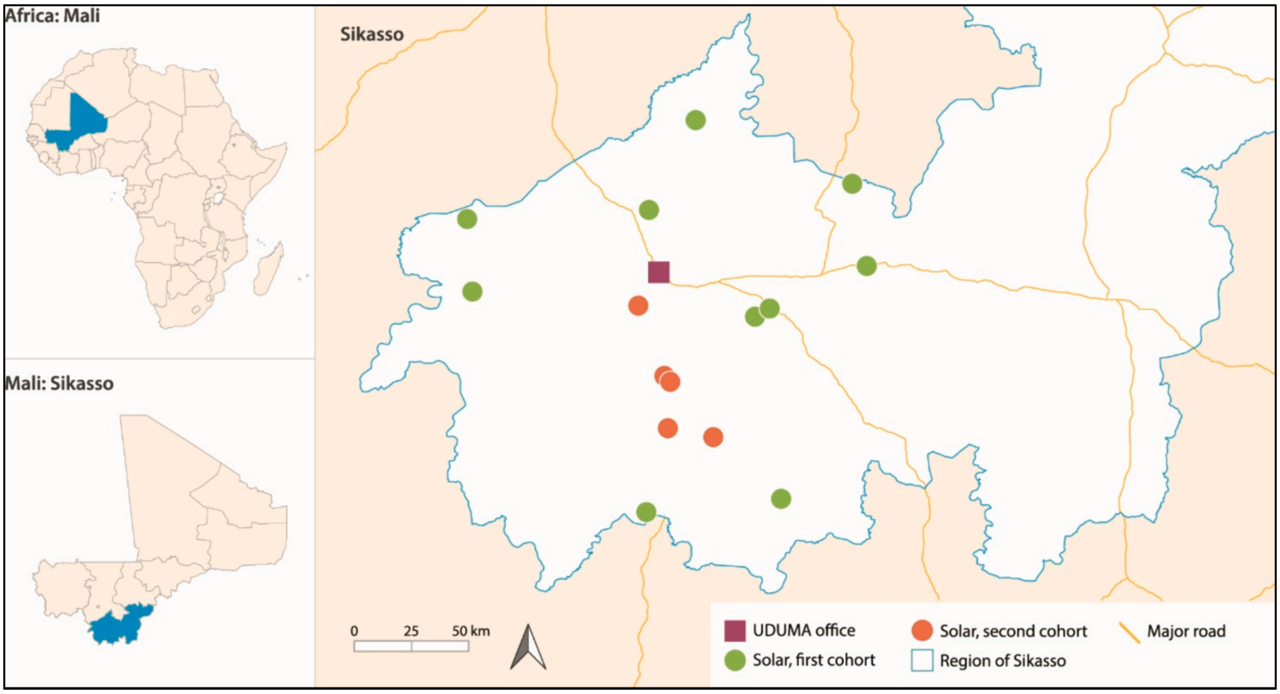

Fig. 2. Case study area in Sikasso, Mali. Map presenting the 15 sites where solar kiosks were installed across two separate cohorts of waterpoints.

2017; Tarnavsky et al., 2014), whereas temperature estimates were generated using Copernicus Climate Change Service information (Copernicus Climate Change Service, 2019). Summary statistics for these variables are provided in the Supporting Information (Table S1, SI).

Prior to data collection and analysis, ethical approval was obtained from the Research Ethics Committee at the lead author's university.

2.3. Empirical strategy and statistical models

To estimate the effect of infrastructure improvements on the three outcomes of interest, we exploit the infrastructure upgrade at a distinct time period and make use of the availability of longitudinal data on observed payments and metered water usage. The main independent variable, the infrastructure upgrade, is coded as a binary variable distinguishing between a handpump (0) and a solar kiosk (1) in the panel data at a clear cut-off point provided by the date at which the waterpoint was upgraded. To account for the staggered adoption and define the intervention period, in the case that the upgrade happened after the 15th day of the month, the month is classified as a handpump (binary = 0). Upgrades that occurred in the second half of the month are coded as solar only in the subsequent month (binary = 1). Given that operations of the identified waterpoints started at different time periods, the panel dataset is unbalanced.

Our estimates rely on interrupted time series (ITS) analysis which allows us to assess whether the switch from handpump to solar kiosk influences the level and the trend of the outcomes. Additionally, the ITS analysis accounts for autocorrelation of the outcome variables, therefore providing a more accurate estimate of the longitudinal effect of the infrastructure change (Kontopantelis et al., 2015; Linden, 2015; Lopez Bernal et al., 2016; Penfold & Zhang, 2013). An ITS design does not "require the intervention to be introduced overnight" (Lopez Bernal et al., 2016), however, there must be a clearly defined intervention period. In the case of the first cohort of ten waterpoints, the intervention period is between March and May 2021, and for the second cohort of five waterpoints the intervention period is 1 December 2021, a clear cut-off point (further detail on intervention period and time series choice in Section 2, SI).

The results for the ITS model emerge from the following econometric specification:

$$Y_t = \beta_0 + \beta_1(time) + \beta_2(intervention_t) + \beta_3(timeafterintervention_t) + \varepsilon_t$$

where Y_t is the outcome of interest, β_0 estimates the baseline level of the outcome, β_1 estimates the trend of the mean monthly outcome pre-intervention with a time unit increase, β_2 estimates the post-intervention level change in the mean monthly outcome, and β_3 the change in the trend, the slope change, after the intervention using the interaction between time and intervention.

More complete models include monthly rainfall and temperature to account for seasonal confounders, likely to affect the outcomes of interest. When controlling for climatic conditions, model tests (ACF, PACF, and Durbin Watson) indicate improvements in autocorrelation. ITS plots (Freyaldenhoven et al., 2021; Penfold & Zhang, 2013) visualise shifts in levels and trends across the outcomes (see Section 2.2, SI for further detail).

To check the consistency of the results of the ITS design, we also conduct fixed-effects regression estimations to the full panel data to assess the effect of the infrastructure upgrade on the three outcomes of interest. Our estimates rest on the following fixed-effects model:

$$Y_{t,i} = \beta_0 + \beta_1\left(time_{t,i}\right) + \beta_2\left(intervention_{t,i}\right) + \beta_3\left(timeafterintervention_{t,i}\right) + \alpha_i + \varepsilon_{ti}$$

where $Y_{t,i}$ is the outcome of interest for waterpoint i at time t, β_0 estimates the baseline level of the outcome, β_1 estimates the trend of the monthly outcome pre-intervention with a time unit increase, β_2 estimates the post-intervention level change in the monthly outcome, β_3 the change in the trend, the slope change, after the intervention using the interaction between time and intervention, and α is the unit-fixed effect for every individual waterpoint i.

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 (Best & Wolf, 2014; Cunningham, 2021; Wooldridge, 2010). We control for time-variant confounders (rainfall and temperature) and include a unit-fixed effects at the waterpoint level (the unique waterpoint ID is used a fixed intercept) to avoid omitted variable bias. We use robust standard errors, clustered at the waterpoint level, to account for autocorrelation occurring between periods within each unit (Abadie et al., 2022; Cameron & Miller, 2015). The results for the fixed-effects regression estimation are reported in Table S3, SI.

To further examine the ITS results from the first cohort, we run the ITS model with data from the second cohort of five waterpoints which received the upgrade from handpump to solar kiosk in December 2021. This approach allows us to compare the effect the solar upgrade exerts on the outcomes of interest across two separate cohorts of waterpoints, thereby enabling to assess consistency and divergency of empirical patterns across contexts.

A final check consists in accounting for seasonality in the intervention period of the first cohort of ten waterpoints by grouping the data by the time period in which the individual waterpoints received the infrastructure upgrade (Schochet, 2022). Grouping based on time periods allows for a more fine-grained approach and enables to check whether there are different changes in the coefficients based on intervention timing (results are reported in Table S4, SI). All statistical analyses were conducted in R (Version 4.0.3).

3. Results

We report summary statistics for the first cohort of ten waterpoints and present the results of the ITS model for both waterpoint cohorts to illustrate consistency and divergency across contexts. Summary statistics for the second waterpoint cohort, as well as the results of the robustness checks (fixed-effects regression model and ITS model accounting for seasonality during the intervention period) can be found in the Supporting Information and are referenced in the manuscript as necessary.

3.1. *Water use is not affected by the infrastructure upgrade but subject to seasonal variation*

Longitudinal monitoring across three consecutive dry and wet seasons reveals seasonal variation in daily water usage affecting both infrastructure types, with water usage varying importantly across sites (Fig. 3). Increases in daily use levels align with Mali's hot season (March to June), whereas water demand falls during the rainy season (July to October). While we observe an unconditional average increase in daily volumetric use when a handpump (mean: 1.36 m^3, median: 0.88 m3) is switched to a solar kiosk (mean: 1.84 m3, median: 0.94 m^3), our analyses indicate that this change is not significant (Table 2, and Tables S3 and S4 in SI).

Table 2 reports the results of the ITS regression models for both cohorts of waterpoints. The ITS approach allows to model the shift in magnitude occurring as a result of an intervention, measured by the difference in outcomes at time points immediately before and immediately after the solar upgrade (level change). Besides, our ITS models provide an estimate of the change in slope from pre- to post-intervention (trend change). Since the relevant diagnostics for model fit (R^2 and adjusted R^2) improve when controlling for seasonal confounders, we only describe the conditional models.

When controlling for temperature and rainfall, the results show no significant level or trend change following the switch from a handpump to a solar kiosk (Table 2). Model 2 indicates that for the first cohort of ten waterpoints, solely monthly temperatures are significantly associated with higher water use. An increase of 1 °C in monthly average temperature translates into additional daily water abstraction of 366 L per waterpoint. An ITS plot visualises this result (Figure S2, SI). Estimates for the second cohort of five waterpoints show a consistent pattern, with temperature being significantly associated with an increase in daily

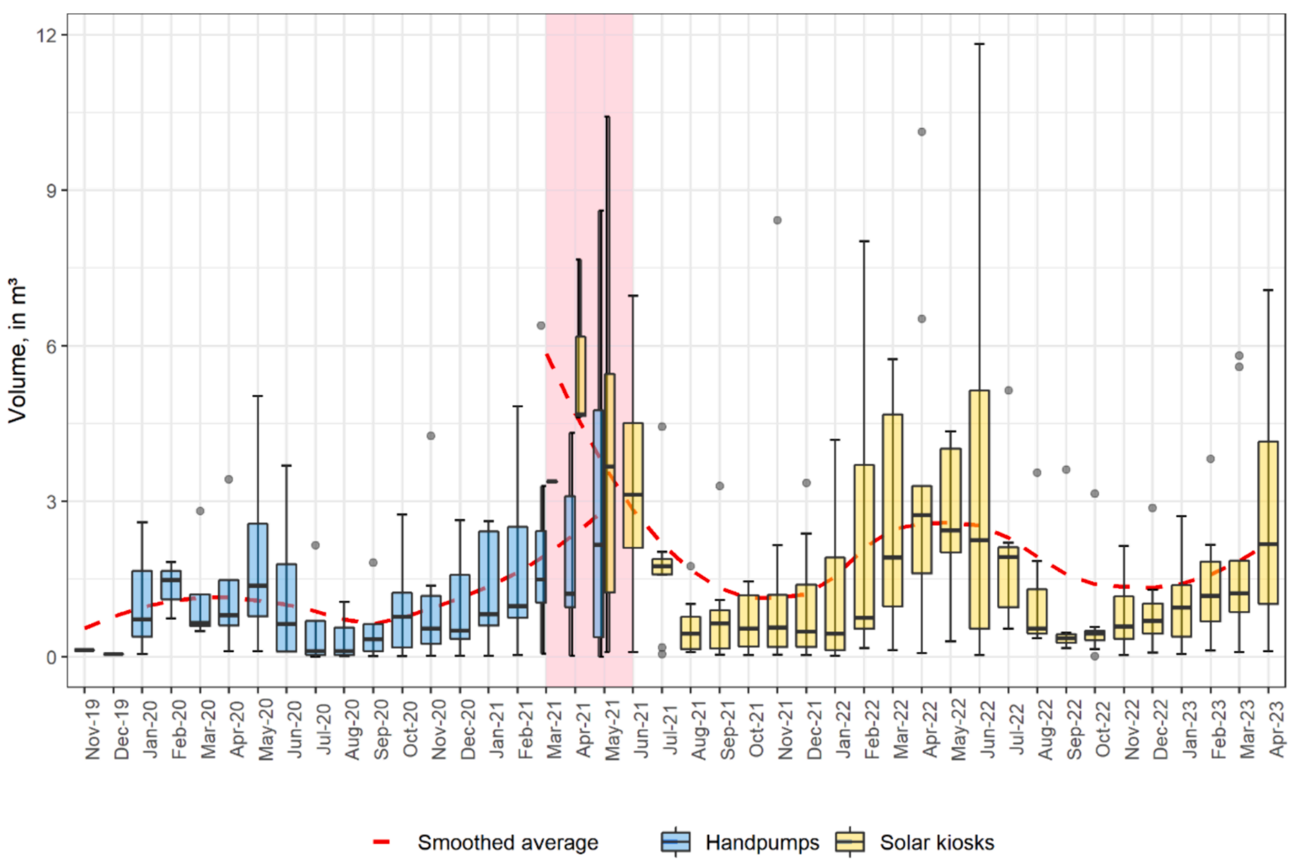

Fig. 3. Daily volumetric water use over time. Box and whisker plots (interquartile range and outliers) across the 10 waterpoints of the first cohort on daily volumetric use, separating between infrastructure types. Dashed line displays mean average. Shaded area highlights the period of the infrastructure transition (March to May 2021).

Table 2
ITS regression results for daily volumetric use (in m^3) for both waterpoint cohorts.

	First cohort (10 waterpoints)		Second cohort (5 waterpoints)	
	(1) Basic	(2) With controls	(3) Basic	(4) With controls
Level change after solar	−0.259(0.473)	0.383(0.430)	−0.295 (0.973)	−1.016 (0.658)
Trend change after solar	**−0.234***(0.06)**	0.032(0.084)	0.062 (0.183)	−0.197 (0.149)
Temperature		**0.366***(0.046)**		**0.352*** (0.056)**
Rain		0.003*(0.001)		0.001 (0.001)
Number of observations	29	29	26	26
R^2	0.063	0.624	0.155	0.702
R^2 adjusted	−0.049	0.542	0.040	0.628

Notes: Robust standard errors, clustered at the waterpoint level, are reported in parentheses. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Bold for significance level of 5 % and higher. Controls include monthly total rainfall and average monthly temperature for each of the sites. Level change refers to the shift in magnitude occurring as a result of the intervention, measured by the difference in outcomes at time points immediately before and immediately after the solar upgrade, and trend change refers to the change in slope from pre- to post-intervention.

water use of 352 L per waterpoint (Model 4).

The reported ITS estimates are consistent with the fixed-effects regression models (Table S3, SI). Finally, we find no effect of the infrastructure upgrade on daily water use when accounting for seasonality in the intervention period (Table S4, SI). Our regression models and robustness checks indicate that daily water use per waterpoint does not significantly increase when a handpump is upgraded to a solar kiosk. However, water use depends on climatic conditions, suggesting that higher monthly temperatures translate into increased water demand.

3.2. *Monthly revenues do increase four-fold following the introduction of the solar kiosks but are subject to seasonal fluctuations*

Summary statistics reveal that monthly revenue per waterpoint increases more than four-fold when replacing a handpump (mean: \$11.69, median: \$7.85) with a solar kiosk (mean: \$48.70, median: \$26.49). Yet its variation is higher for solar kiosk (standard deviation of \$54.69) compared to handpumps (standard deviation of \$12), with a maximum monthly revenue of \$267.

Monthly revenues, similar to the seasonal fluctuation in water demand, are also affected by seasonal trends (Fig. 4). Solar kiosks experience revenue shortfalls during the rainy season, reaching average decreases of 40 % compared to the annual mean revenue. Furthermore, there is high variation across the ten solar kiosks, as shown in Fig. 4, emphasising that volumetric water usage varies importantly across the sites, affecting monthly revenue.

The results of the ITS regression model for both waterpoint cohorts indicate that significant and large changes in monthly revenue are associated with the introduction of the solar kiosks and higher temperatures (Table 3). For the first cohort, the infrastructure upgrade is associated with a revenue increase of \$46 per month per waterpoint, when controlling for seasonal factors (Model 2). An ITS plot (Figure S2, SI) visualises the shift in revenue levels over time. Furthermore, the

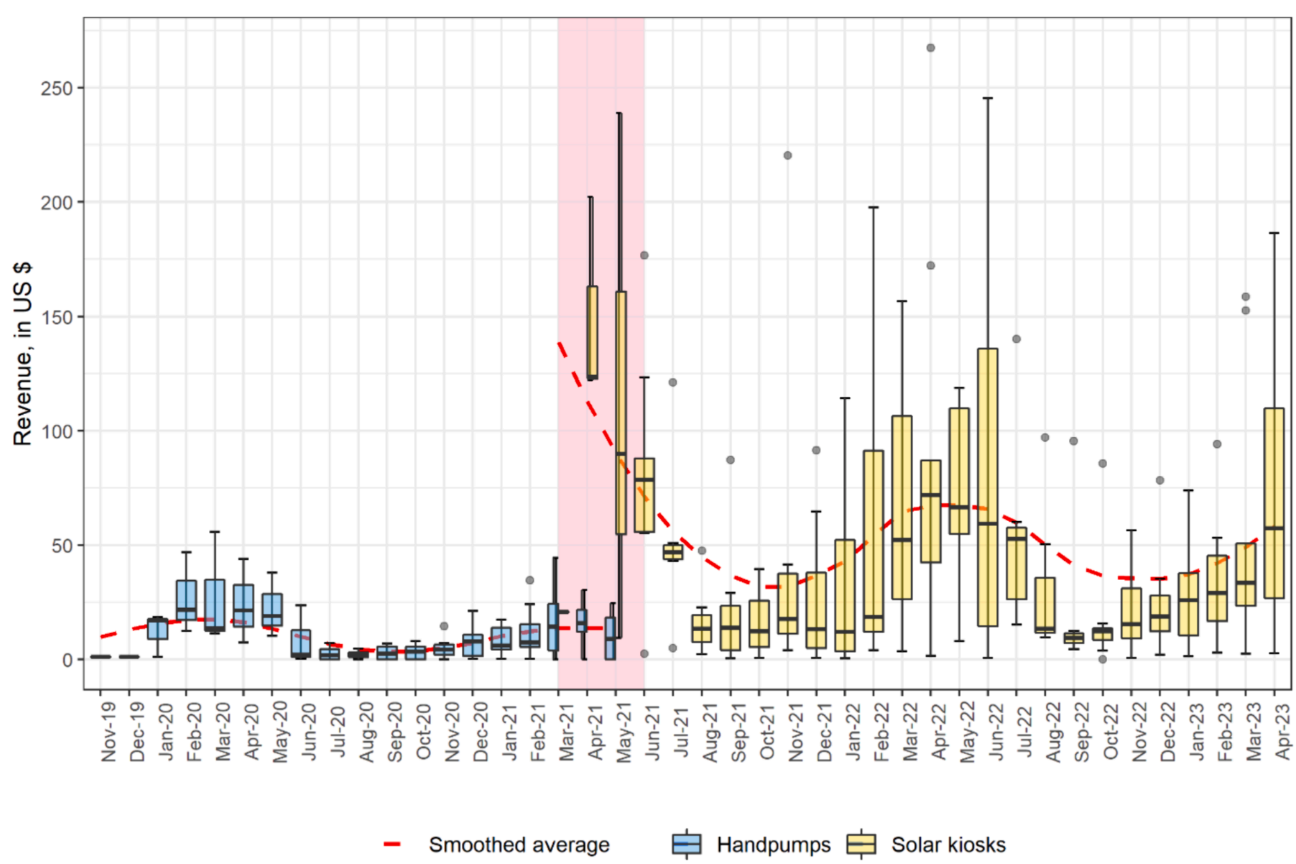

Fig. 4. Monthly revenue over time. Box and whisker plots (interquartile range and outliers) across the 10 waterpoints of the first cohort on monthly revenue per waterpoint, separating between infrastructure types. Dashed line displays mean average. Shaded area highlights the period of the infrastructure transition (March to May 2021).

Table 3
ITS regression results for monthly revenue (in $) for both waterpoint cohorts.

	First cohort (10 waterpoints)		Second cohort (5 waterpoints)	
	(1) Basic	(2) With controls	(3) Basic	(4) With controls
Level change after solar	**29.66*** (11.39)**	**46.19***(12.16)**	**45.65*** (14.94)**	**31.46***(10.68)**
Trend change after solar	**−2.64*** (0.88)**	4.13 (2.78)	3.27 (2.02)	−2.18 (2.23)
Temperature		**9.30*** (1.34)**		**7.56*** (1.57)**
Rain		0.07* (0.03)		0.03 (0.04)
Number of observations	29	29	26	26
R^2	0.310	0.729	0.382	0.781
R^2 adjusted	0.227	0.670	0.297	0.726

Notes: Robust standard errors, clustered at the waterpoint level, are reported in parentheses. Significance levels: * p < 0.1, ** p < 0.05, *** p < 0.01. Bold for significance level of 5 % and higher. Controls include monthly total rainfall and average monthly temperature for each of the sites. Level change refers to the shift in magnitude occurring as a result of the intervention, measured by the difference in outcomes at time points immediately before and immediately after the solar upgrade, and trend change refers to the change in slope from pre- to post-intervention.

estimates indicate that an increase of 1 °C in monthly average temperature translates into $9.30 more revenue per waterpoint per month, reflecting that revenue increases align with higher water demand during the annual dry season. ITS estimates for the second cohort of five waterpoints (Table 3) show similar results: the introduction of the solar kiosks is associated with a revenue increase of $31.46 per month per waterpoint (Model 4). Furthermore, increases in monthly average temperature are associated with higher monthly revenues. These findings are consistent with the revenue patterns of the first cohort.

The fixed-effects regression model yields similar results, with increases in monthly revenue associated with the infrastructure upgrade and higher temperatures (Table S3, SI). Finally, when accounting for seasonality in the intervention period, our findings remain consistent (Table S4, SI).

3.3. *Collection efficiency increases substantially following the technology shift and remains stable over time and across contexts*

The introduction of the solar kiosks is associated with a clear shift in payment collections. Descriptive data indicate that after a handpump is upgraded to a solar kiosk, collection efficiency increases to an average of 97 % (median: 100 %), whereas pre-upgrade average payment ratios were lower (mean: 40 %, median: 30 %). Fig. 5 depicts the extent to which the change in collection efficiency is large and sudden, with timing corresponding to the solar upgrade.

The change in collection efficiency (Fig. 5) across the infrastructure types requires further contextualisation given its implications for monthly revenues. Collection efficiency for handpumps experienced a steady down-ward trend since March 2020, with a steep decline in August 2020, to reach a flatlined threshold of about 25 % since October 2020. Users in Mali reveal a limited willingness to pay a volumetric tariff for using handpumps even if reliably managed.

This pattern might be driven by various external factors. For instance, COVID 19 took its toll on Mali, with the national government declaring a state of national health emergency on 26th March 2020. A

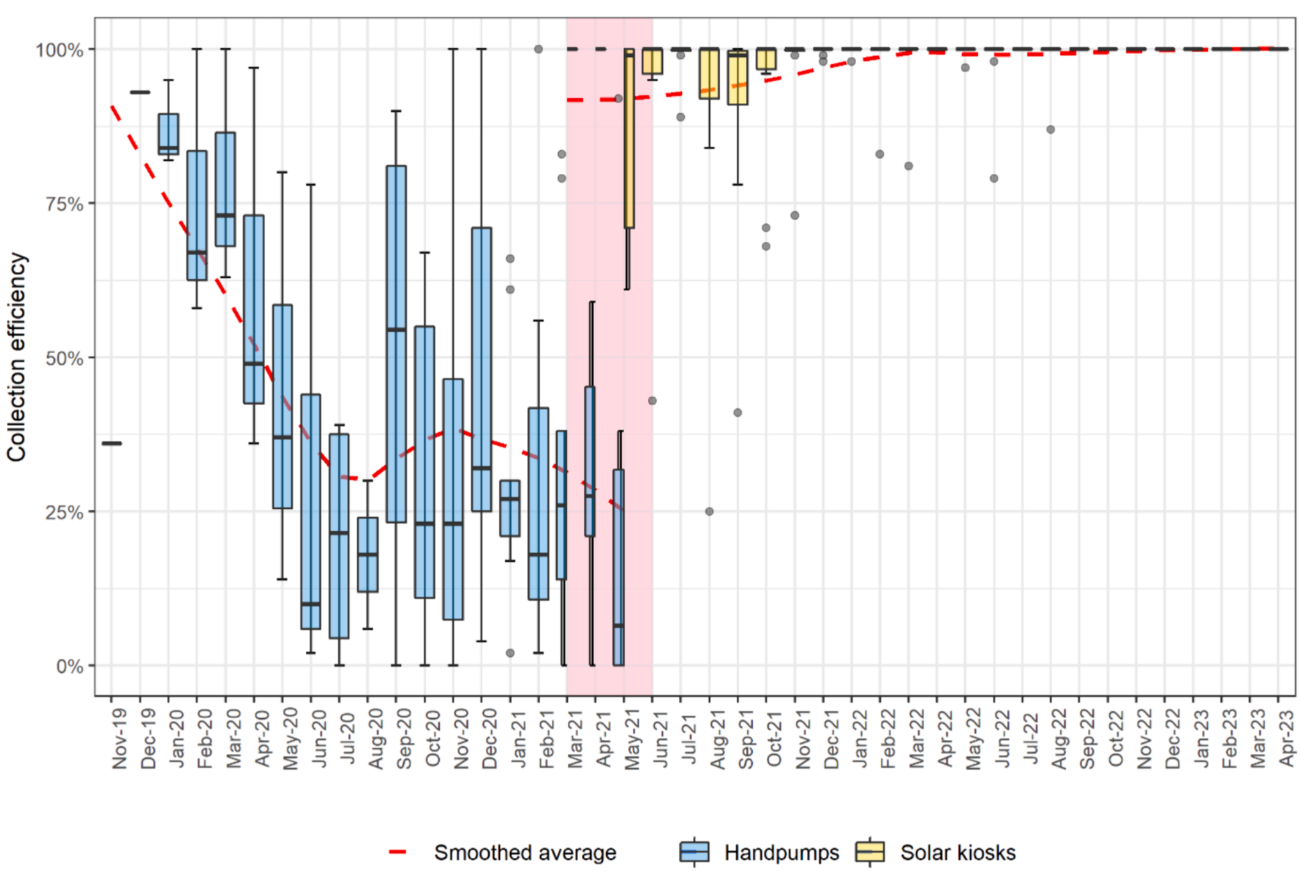

Fig. 5. Payment collection efficiency over time. Box and whisker plots (interquartile range and outliers) across the 10 waterpoints of the first cohort on payment collection, separating between infrastructure types. Dashed line displays mean average. Shaded area highlights the period of the infrastructure transition (March to May 2021).

coup by the Malian military on 18th August 2020, further destabilised Mali's fragile economy, contributing to the ongoing economic recession related to the pandemic (World Bank, 2021). A second coup on 24th May 2021 and an embargo by ECOWAS since January 2022 further increased the economic pressure on Mali. In addition, France withdrew its troops from Mali in September 2022, and put its official development aid on hold from November 2022. These factors may have affected livelihoods and hence the users' ability to pay. Yet, these broader socio-economic and political shocks do not seem to affect user payments at solar kiosks as their trend remains stable over time (Fig. 5 and Figure S2, SI).

The ITS regression results across both waterpoints cohorts support the descriptive insights (Table 4). Following the upgrade to solar kiosks, the level of payment collections increases significantly by 62.7 % for the first cohort of waterpoints. When controlling for seasonal confounders, there is no significant change in the collection efficiency trend following the solar upgrade, showing consistency over time (Model 2). An ITS plot (Figure S2, SI) visualises this result.

The second cohort registers a similar pattern, with a larger effect on payment collections of 98.2 % (Model 4). Furthermore, the positive and significant trend change of 5.1 % indicates that payments experience an upward increase following the solar upgrade, suggesting that payment behaviours at solar kiosks slightly improve over time. Unlike volumetric use and monthly revenues, the results across both cohorts reveal that collection efficiency remains unaffected by seasonal drivers since temperature and rainfall controls are not significant (Table 4).

Finally, the findings on collection efficiency are coherent when modelling the data through a fixed-effects regression (Table S3, SI) and when applying the seasonal robustness check (Table S4, SI).

Overall, our results are consistent with other studies indicating that enforcing volumetric payments is challenging when users must invest in time and physical effort to pump water (Foster, 2017; Foster et al., 2020; Jones, 2013; Katuva et al., 2016). Volumetric tariffs at solar kiosks, however, are more readily paid across the different sites, as the level change in collection efficiency followed by a stable trend with low within month variation indicates.

4. Discussion

Empirical insights from field implementation can help inform changes in policy and practice (Jury & Vaux, 2005; Koehler et al., 2022) to achieve and sustain universal delivery of safe drinking water in rural Africa. Three findings from this study may add to the understanding of how infrastructure and service delivery models can contribute to more resilient and sustainable rural water supplies. First, higher temperatures affect drinking water consumption patterns in rural Mali with implications for investments in infrastructure and service delivery. Second, funding drinking water services sustainably requires understanding water use and payment behaviours. Third, professional service providers can ensure investments in rural drinking water supplies deliver value over time.

Our results reveal that, although solar kiosks reduce the time burden and physical effort for collecting water compared to handpumps, average water use levels remain relatively similar across the two infrastructure types. On first sight, this is a counter-intuitive finding given the higher service level provided. However, even though people do not have to pump anymore to access water, solar kiosks do not lower the distance to the homestead. Users – especially women and girls – still have to walk to the source and carry water back home, which logistically limits water use at the household level (Thompson et al., 2001; White et al., 1972). In addition, the tariff level and structure might also influence users' behaviour. A study in rural Kenya found that volumetric tariffs reduce water usage amongst low-income groups (Foster & Hope, 2017). While these factors may hold relevance for our context, we suggest that future research should unravel the wider cultural, economic, social, or political drivers underlying the observed patterns revealed by our study.

We find that seasonality, especially higher temperatures, affect drinking water consumption patterns across both infrastructure types. This pattern is consistent with other studies from sub-Saharan Africa indicating that during dry seasons and droughts, when surface water availability is reduced, groundwater demand increases (MacAllister et al., 2020; Thomas et al., 2019; 2020). Revealing these seasonal interactions of demand, which are often not captured in national and global statistics derived from cross-sectional household surveys (Elliott et al., 2019), is important for informing policy and practice.

Our results show that a 1 °C rise in monthly average temperature is associated with an estimated daily increase of more than 350 L of water per waterpoint. While this is an estimate with uncertainty, dynamic and sustained peaks in water demand are likely to put infrastructure with limited production capacity, such as handpumps with a single outtake, under additional strain. In rural Africa, dominant technologies, especially handpumps, and community management approaches (Harvey & Reed, 2004; van den Broek & Brown, 2015; Whaley et al., 2019) are struggling to cope with climate-related stressors, as indicated by slow progress to meet the Sustainable Development Goal (SDG) 6.1 (UNICEF & WHO, 2022; WHO et al., 2022).

Recent research estimates that keeping to the 1.5 °C target agreed at the 2015 Paris climate conference would still mean that some 200 million people are exposed to unprecedented temperature increases (Rockström et al., 2023). Climate-resilient water supplies are important to adapt to these threats. Using solar energy to pump widely available groundwater resources may be an effective adaptation response, provided that groundwater resources are correctly managed and monitored

Table 4
ITS regression results for collection efficiency (in %) for both waterpoint cohorts.

	First cohort (10 waterpoints)		Second cohort (5 waterpoints)	
	(1) Basic	(2) With controls	(3) Basic	(4) With controls
Level change after solar	**61.10*** (2.2)**	**62.70*** (1.8)**	**97.30*** (3.40)**	**98.20*** (2.90)**
Trend change after solar	0.6(0.6)	0.6 (0.6)	**4.80*** (0.7)**	**5.1*** (0.9)**
Temperature		−0.00 (0.000)		−0.5 (0.7)
Rain		−0.1 (0.2)		0.0 (0.0)
Number of observations	29	29	26	26
R^2	0.990	0.991	0.987	0.987
R^2 adjusted	0.988	0.989	0.985	0.984

Notes: Robust standard errors, clustered at the waterpoint level, are reported in parentheses. Significance levels: * p < 0.1, ** p < 0.05, *** p < 0.01. Bold for significance level of 5 % and higher. Controls include monthly total rainfall and average monthly temperature for each of the sites. Level change refers to the shift in magnitude occurring as a result of the intervention, measured by the difference in outcomes at time points immediately before and immediately after the solar upgrade, and trend change refers to the change in slope from pre- to post-intervention.

(MacAllister et al., 2020; MacDonald et al., 2021; Meunier et al., 2023; Rodella et al., 2023). As our assessment reveals, water demand varies importantly across sites, and future infrastructure investments may target locations under pressure as a priority. With capital investments in water infrastructure expected to increase in Africa within the next decade (International High-Level Panel on Water Investments for Africa, 2023), evidence to guide their allocation and to ensure their effectiveness is instrumental to achieve SDG 6.1 by 2030.

Second, our results show that solar kiosks can generate up to four-times higher revenues compared to handpumps. This is driven by consistent improvements in collection efficiency. The considerable increase in payments collected and revenue generated in the short term of the study suggests a user preference for solar kiosks which are professionally managed. While it is not possible to ascertain why rural Malians pay more reliably for drinking water at solar kiosks, there is evidence that improving service delivery by reducing time costs associated with fetching water, increasing convenience, or ensuring higher reliability creates user value (Hope et al., 2020; Hope & Ballon, 2021; Van Houtven et al., 2017). Further empirical understanding of the observed revenue increases and changes in payment behaviours is needed, highlighting an important area for future research.

Our analysis offers some insights for policy and practice as it contributes new evidence on the role service improvements play in unlocking user payments, which are the primary source for a sustainable funding model (Fonseca et al., 2013; Hope et al., 2020). While donor and government water investments have largely focused on funding capital costs for infrastructure in rural Africa, there is increasing urgency to understand how operational costs can be integrated into more sustainable funding models (Hutton & Varughese, 2016). Africa's graveyard of well-meaning intentions leaving roughly one out of four handpumps non-functional at any point in time (Foster, 2013; Foster et al., 2020) demands funding of rural water infrastructure to more explicitly link investments with service delivery. Critical to this transition is to shift from a least-cost approach to a more value-driven model to fund operating costs of rural water services (Garrick et al., 2017; Hope et al., 2019; 2020). Solar kiosks might be a promising approach if their deployment leads to added value for water users, translating into improved payment behaviours and higher revenues, which is fundamental to secure investments over the longer term.

Yet, solar kiosks remain subject to seasonal water demand, emphasising the dynamic nature of water use behaviours in rural Africa (Armstrong et al., 2022; MacAllister et al., 2020; Thomas et al., 2019; Thomson et al., 2019). As shown in this study, demand at professionally managed solar kiosks fluctuates, with water use and revenue peaks biased to the dry season. Identifying strategies to incentivise rural populations to use safe drinking water sources in periods of rainfall would not only generate additional revenues but would also contribute to achieving likely health and welfare benefits associated with higher volumes of safe water being consumed (Prüss-Ustün et al., 2019; WHO et al., 2022).

Providing piped water to the home may not overcome fluctuations in revenue or water consumption (Armstrong et al., 2022; Armstrong, 2022). Based on data from Ghana, Rwanda, and Uganda, Armstrong et al. show that extended rainfall periods can reduce revenue by up to 30 % compared to dry periods – regardless of whether supplies are provided off- or on-premises (2022). We find similar patterns of seasonally fluctuating demand and revenues at handpumps and solar kiosks. For this reason, understanding how tariff design can support revenue generation to promote operator sustainability is important. For instance, regular flat fees instead of volumetric tariffs may be a more socially acceptable payment method (Foster & Hope, 2017) and could incentivise rural populations to rely on improved waterpoints throughout the year. Future research may engage with professional service providers which offer high quality and standardised operational and financial data to assess how different payment modalities affect water use and revenue outcomes (McNicholl et al., 2019).

Third, cross-country evidence from rural Africa shows that higher operational and financial performance can be achieved by professional service providers compared to community-based management (Foster et al., 2022; Smith et al., 2023). Professional service providers have incentives to develop more effective delivery to enhance their revenues. Our results show that professionally managed solar kiosks register consistent user payments throughout seasons, translating into substantially higher local revenues compared to handpumps. Strategic investments in solar kiosks could be scaled up through professional service delivery models, as communities seldomly have the technical skills required to keep such systems functioning (Rahmani et al., 2024). This could contribute to infrastructure assets lasting in line with their expected lifespan instead of current rates of failure and abandonment two to three years after installation (Foster et al., 2020) and may ultimately guarantee that infrastructure investments effectively deliver on their intended results.

5. Conclusion

We investigated the effects of infrastructure upgrades on rural water user behaviours with relevant implications for policy and practice. Our observational study finds that solar kiosks can generate higher monthly revenues compared to handpumps, supporting wider efforts to increase rural water sustainability. While consistent payment collections suggest that users are more inclined to pay for the water they use when professionally delivered through solar kiosks, water demand remains seasonal, translating into fluctuating revenues. These findings highlight the importance of environmental drivers influencing water demand and suggest caution in assuming that technology offers definitive solutions to dynamic rural water user behaviours.

The improved revenue and payment performance following the solar upgrade emphasise the importance of aligning investments with user preferences to fund service delivery more effectively. As professional service providers are becoming more common across rural Africa, there might be an opportunity to leveraging the potential of new technologies, such as solar-powered water kiosks, to reach SDG 6.1. While this would mean changing current practices, it would guarantee that investments in solar kiosks provide an effective and lasting response to current rural water challenges and future climate risks.

Finally, we emphasise that the sample size of our observational study is limited, underscoring the need to further study the implications of infrastructure upgrades on water use and payment behaviours at scale. Our results emerge from 452 monthly records of water use and payment data, spanning three consecutive dry and wet seasons, in a small number of communities. Larger samples and longer time series are required to better understand the long run potential and broader applicability of solar kiosks as uncertainty in the long-term effects prevails. Finally, more evidence is needed to reveal why users do not change their water use behaviours despite the improved service level provided through solar kiosks. This may inform relevant interventions aimed at shifting water consumption from unimproved to improved sources and could generate additional revenues to sustain service delivery.

CRediT authorship contribution statement

Johannes Wagner: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sara Merner:** Data curation, Formal analysis, Software, Visualization, Writing – review & editing. **Stefania Innocenti:** Methodology, Writing – review & editing. **Alinta Geling:** Investigation, Resources, Writing – review & editing. **Rob Hope:** Funding acquisition, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data underlying this study are available in the published article and its Supporting Information.

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Appendix A. Supporting Information

The Supporting Information includes additional details on data availability, methods, and results, including regression tables and ITS plots. The supplementary data to this article can be found online at https://doi.org/10.1016/j.worlddev.2024.106787.

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