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Piped water revenue and investment strategies in rural Africa

Andrew Armstrong[1,2,*], Rob Hope[1,2] and Johanna Koehler[2,3]

[1] School of Geography and the Environment, University of Oxford, United Kingdom
[2] Smith School of Enterprise and the Environment, University of Oxford, United Kingdom
[3] Institute for Environmental Studies, Vrije Universiteit Amsterdam, The Netherlands
[*] Author to whom any correspondence should be addressed.

E-mail: andrew.armstrong@ouce.ox.ac.uk

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Abstract

Viable pathways to universal safely managed drinking water access in rural Africa involve a blend of infrastructure types, service delivery arrangements, and sources of finance. Priorities are shaped by institutional and economic barriers and are often based on assumptions regarding user demand and revenue sustainability. Improved understanding of how alternative approaches affect revenue generated from user payments can enhance long-term viability and repayment capacity of rural piped water services. We analyse more than 3,900 monthly records from operators in Ghana, Rwanda, and Uganda and model revenue patterns for novel service area archetypes. Results indicate on and off premises connections exhibit complementary revenue patterns, with volumetric revenue determined by tariff level rather than connection type and waterpoints with the greatest dispensing capacity generating the most aggregate revenue. The prepaid credit payment approach, which is increasingly promoted to enhance revenue collection efficiency, is not associated with revenue advantages compared to pay-as-you-fetch and monthly billing approaches when tariff level is controlled. These patterns are recurrent at multi- and single country scales and across service areas where public and enterprise-led investment approaches to infrastructure development are taken, suggesting the findings may be applicable beyond the study domain. Infrastructure investment strategies can promote revenue and equity goals through off-site piped water, but more evidence is needed to understand the trade-offs of prepaid credit systems.

1. Introduction

Since the turn of the 21st century, access to piped drinking water infrastructure has been extended to about 375 million people living in rural areas of the world (figure 1). However, the progress that has been achieved over two decades is modest in comparison to the rural population of 1.3 billion that still does not access a primary drinking water source on household premises (figure 2). The ambitious Sustainable Development Goal of establishing universal household-level access to safe, reliable, and affordable drinking water by 2030 (SDG 6.1) has incentivised and shaped the rural water investment strategies of many low- and middle-income countries. Consequently, piped water infrastructure is expected to play an increasing role in supplying safely managed services to rural populations. This applies particularly to sub-Saharan Africa where population growth is occurring in large villages, small towns, and transitional areas outside of urban settings (Güneralp *et al* 2017, UN-Habitat 2020), yet rural on premises accessibility is the lowest in the world and the rate of change must be increased by a factor of 11 to achieve SDG 6.1 on time (UNICEF and World Health Organization 2021).

Progress towards universal safely managed drinking water access in rural Africa has been hindered by limited economies of scale due to low population density, poor institutional accountability, and inadequate financial flows (Hope *et al* 2020, Humphreys *et al* 2018). The finance gap is especially striking. More than ten times the average annual rate of global government and donor spending over the past two decades is needed to attain rural drinking water targets established by SDG 6.1 (World Bank and UNICEF 2017). Delivery of

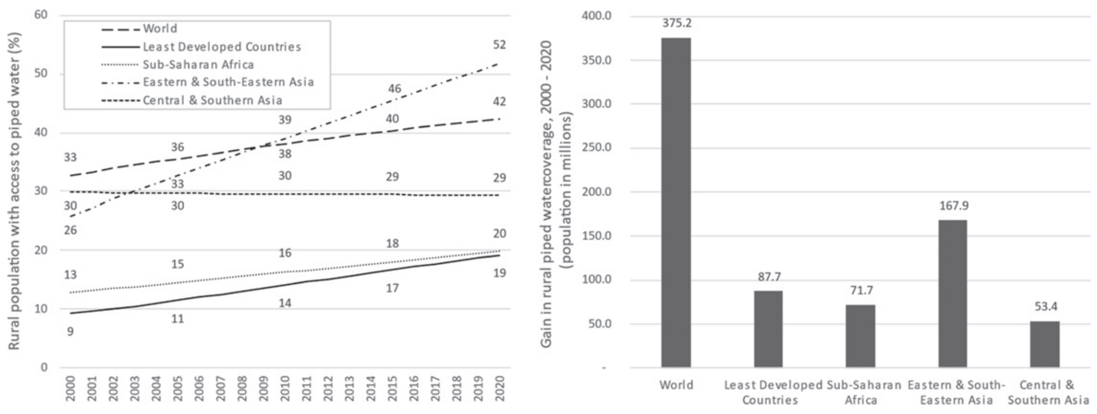

Figure 1. Gains in rural piped water coverage in selected regions, 2000–2020 (UNICEF and World Health Organization 2021).

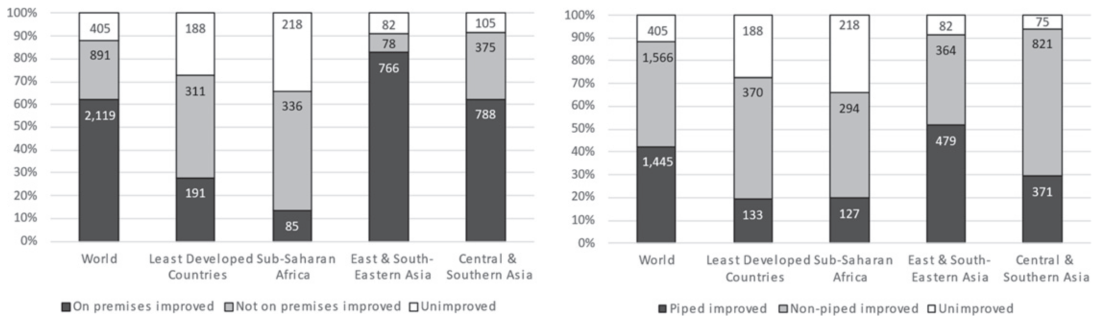

Figure 2. Rural drinking water accessibility and piped coverage in selected regions, 2020 estimates in millions. Improved drinking water sources are those which, by nature of their design and construction, have the potential to deliver safe water. Unimproved drinking water sources include unprotected dug wells, unprotected springs, and surface water (UNICEF and World Health Organization 2021).

finance is expected to become even more challenging in the coming decade as the cost of operating and maintaining existing water infrastructure, which governments typically aim to cover with tariff revenues, exceeds new capital investments that are traditionally funded with tax revenues and transfers (Hutton and Varughese 2016).

Considering widespread institutional and economic barriers, viable pathways to universal safely managed drinking water access in rural Africa involve a blend of infrastructure types, service delivery arrangements, and sources of finance. A common strategy for making progressive but economical improvements is to upgrade boreholes fitted with handpumps to motorised schemes with kiosks or standpipe access points. Once piped schemes are constructed, planners can sequence and optimise different types of waterpoint connections and payment approaches over time in a manner that balances financial viability and social equity (Mugisha and Borisova 2010). This strategy is intended to achieve incrementally higher levels of quantity, quality, accessibility, and reliability until a future point in time when it is feasible to extend private connections or for households to construct their own boreholes. Operation and maintenance of such diverse infrastructures can be effectively supported by service delivery arrangements that enable responsibilities and risks to be shared across government, private sector, and community actors (Koehler *et al* 2018). Countries that take steps to create a viable and creditworthy financial ecosystem may be able to attract new sources of funding and finance that can be combined to facilitate water investments in a manner that achieves national and international development priorities (Advani 2016, Money 2018, OECD 2018, Pories *et al* 2019). Immediate priorities towards this end are to maximise revenue from user payments and deliver subsidies more effectively (Goksu *et al* 2017).

Despite the recognised importance of water tariffs in addressing ongoing finance challenges and the nearly ubiquitous policy requiring cash contributions from users who can afford it, it is estimated that fewer than two in five rural African households pay for water (Banerjee and Morella 2011, Foster and Hope 2017). As a result, less than a third of countries manage to fully fund recurring rural water supply costs with tariff revenue (GLAAS 2019). Several systemic issues work to counteract the sufficiency and reliability of rural water revenues. Tariff levels are set below what is needed to recover basic operational and maintenance costs (Leigland *et al* 2016) because cost recovery goals often exist in tension with political agendas and tariff strategies that are intended to protect poor populations. There is also a paucity of incentives to adhere to established policies involving life-cycle cost analysis, tariff setting, and payment collection, and monitoring systems are inadequate to enable effective regulation of these processes (Harvey 2007, World Bank 1999). Poor enforcement is exacerbated by the fact that rural service providers, who are often unpaid volunteers, frequently lack the professional skills to administer appropriate payment rules. As rural piped water infrastructure increases in complexity, improved governance and professionalised service provision are likely to become even more vital for supporting financially viable services (World Bank 2017).

Rural piped water investments that seek to enhance tariff revenues are predicated on assumptions of how user payment behaviours will respond to changes in service and tariff levels. This is particularly challenging considering the complex water use patterns of rural households, who collect water from a variety of sources that are offered at various price points and fluctuate in availability throughout the year (Elliott *et al* 2019, Hoque and Hope 2018, Thomson *et al* 2018). Rational choice models that have quantified the effects of factors that influence why people choose to access one rural water source over others find proximity, reliability, aesthetics, and low price to be significant determinants (Briscoe *et al* 1981, Gross and Elshiewy 2019, Mu *et al* 1990, Wagner *et al* 2019), and there is evidence that similar factors influence payment behaviours. Rural households are less likely to want to pay for water the further the source is from their residence, especially when alternative water sources are nearby (Koehler *et al* 2015). High continuity and low maintenance response time (Hope 2015, Hope and Ballon 2019) as well as service delivery arrangements that are perceived as more reliable (Hope 2015, Hutchings *et al* 2017, Koehler *et al* 2015, Koehler *et al* 2018) have also been associated with increased willingness to pay. Furthermore, Foster and Hope (2016) identified a significant association between aesthetic parameters of water quality, namely pH and electrical conductivity, and rural water user payments.

The method employed to collect user payments for rural piped water services also influences payment behaviours, collection efficiency, revenue generation, and operational cost and complexity. Foster and Hope (2017) investigated several modalities utilised to collect payments for rural handpump maintenance services and found the pay-as-you-fetch (PAYF) approach generates more revenue overall and per volume than flat fees collected periodically, presumably because it prevents free riding and enables smaller, more manageable payments over time. Innovative payment approaches that utilise mobile communication technology may also help to enhance tariff revenues as rural water infrastructure and service delivery grows in complexity (Hope *et al* 2012).

Prepaid credit payments are increasingly sought to reduce or altogether eliminate manual cash transactions and foster transparency, affordability, and convenience (Heymans *et al* 2014). These systems allow water users to purchase electronic or physical credit on mobile devices, from vendors, or at automated credit and water dispensing stations, which are sometimes referred to as water automated teller machines ('ATMs') or smart water meters and redeem the credit for water at the preferred time and point of collection. However, documented experience with the approach in urban settings since being pioneered in South Africa in the early 1990s indicates these benefits are often tempered by expensive and unreliable technology as well as persistent, underlying issues related to poor management (ibid). Although evaluation of the prepaid systems in rural settings is limited, questions around effective management and perverse economic and social consequences are also noted (Komakech *et al* 2020, Sherry *et al* 2019). The current state of knowledge makes it difficult to anticipate the various ways rural households might respond to the prepaid credit approach which in turn poses challenges for revenue planning. For instance, users may pre-purchase enough credit to collect water for several days or even weeks. Alternatively, due to limited cash on hand or wariness of the payment system, households may routinely purchase just enough credit to meet their daily water needs, essentially aligning with the PAYF approach. Furthermore, clusters of households may choose to collectively purchase credit and in bulk to reduce the transaction costs.

Decision frameworks can support planners as they optimise water infrastructure investments for future social and environmental conditions (Murgatroyd and Hall 2021, Roman *et al* 2021) but require a robust empirical basis to minimise uncertainty. Existing evidence of financial performance in the water supply sector is biased to urban piped systems (Andres *et al* 2019) with one example of rural cost recovery across multiple countries (McNicholl *et al* 2019). Because of this evidence gap, rural piped water investment strategies that involve decisions regarding infrastructure, service delivery, and finance are based on uninformed assumptions regarding user demand and revenue sustainability. The ensuing patchwork of poorly-maintained infrastructure and uncoordinated services results in neighbouring waterpoints competing for scant revenue (Foster and Hope 2016) and seldomly provides a level of quantity, quality, accessibility, and reliability for which users value and will pay (Hope 2015, Hope and Ballon 2019). Improved understanding of how waterpoint types and densities and tariff approaches influence rural water supply, demand, and revenues can enhance financial viability and repayment capacity of piped services.

We address this evidence gap with an empirical analysis of novel rural piped water service area archetypes constructed from a multi-country, longitudinal dataset to answer two questions. First, how do rates of revenue generated from user payments differ across rural piped water infrastructure types and payment approaches? Second, what broad implications do these findings hold for piped water investment strategies in rural Africa?

2. Methods

2.1. Data classification and cleaning

This study utilises data from five piped water operators spanning the years 2016 to 2019. Two of the agencies are international nongovernmental organisations that operate as social enterprises, one across five regions in Ghana and the other across eight districts in Uganda. Three of the agencies are private companies that offer a range of engineering, construction, and management services. One of these operates piped water schemes in 12 districts in Rwanda, and the other two operate in a single district in Uganda. The context of these operations is described further in the results section.

We extract, clean, and analyse more than 3,900 monthly records of volumetric water usage and revenue from user payments corresponding to the service areas of individual piped schemes operated by these agencies. Our infrastructure typology is aligned with the WHO and UNICEF Joint Monitoring Programme's drinking water service ladder (UNICEF and World Health Organization 2021), which considers accessibility on or off premises in its differentiation between safely managed and basic service levels. We classify standpipes and kiosks as off premises connections. Taps located in private homes or yards or dedicated for use at educational, religious, or healthcare facilities are designated as on premises connections. Mixed schemes that include both on and off premises connections are split into separate, geographically coincidental service areas so that all units of analysis share a common and static waterpoint connection type and operator. Revenue records are summarised and evaluated per unit volume to normalise for scheme size and service population and enable comparison between waterpoint connection types with different dispensing capacities. Differences in the revenue rates we calculate between service areas are therefore not attributable to differences in number of users or consumption rates. We also report water usage corresponding to each connection type to reveal relative differences in magnitude of demand. To ensure the analysis is based on like-for-like comparison of operating conditions to the furthest extent possible, we include records where both connection types are in service in the geographic vicinity or where off premises connections were upgraded to on premises connections during the observation period but omit records from areas where only one connection type was available to users over the timespan of available data.

Monthly records are further characterised by the approach taken to collect user payments, the corresponding tariff level in local currency, and the number of waterpoints in the service area, all of which vary over time. Payments are collected from users who access off premises connections by one of two approaches: the conventional PAYF approach, where users pay a standpipe or kiosk attendant when they collect water from the waterpoint, and the prepaid credit approach, where users pre-purchase electronic credit that can later be redeemed at the waterpoint. For on premises connections, users pay either by conventional billing based on metered usage during the previous billing cycle or by prepaid credit where water is purchased in bulk and dispensed via an electronic meter. All tariffs observed across the dataset are based on a volumetric water usage charge for all consumption levels, either per container or cubic metre. Users with on premises connections are commonly required to pay a one-off connection fee, but on premises tariffs do not contain a recurring fixed service charge in any case. We convert all revenue rates and tariff levels to 2019 US dollars per cubic metre by applying deflator factors obtained from the World Bank Development Indicators database (World Bank 2020) and converting from local currency at purchasing power parity for private consumption.

Reliable and normalised population estimates are not available for the observed piped water service areas, which prevents analysis of per capita demand. However, we can assess the degree of rurality and compare the size of water user catchment area by estimating the population density of each service area using Facebook Connectivity Lab's high resolution population datasets available from the Humanitarian Data Exchange (Facebook Connectivity Lab and CIESIN 2016). These datasets combine satellite imagery and national census data to estimate the number of people residing in 1-arc-second-by-1-arc-second grid cells for most countries. The most recent estimates are available for 2019. Using GIS software (Esri ArcMap 10.8), we approximate the number of people per square kilometre corresponding to a geographic coordinate at the centre of each service area by summing the grid cells available in the Ghana, Rwanda, and Uganda datasets that are located within a 5 km radius and dividing by the geometric area.

We conduct iterative unstructured interviews with data specialists representing each operator as a first step to normalise and address anomalies in data records. We then exclude records from the analysis if fewer than twelve concurrent months of water usage and payment records are available for the service area. This approach ensures the analysis spans at least one annual rainfall cycle in each service area recognizing that seasonal and other temporal factors might influence operational performance, user payments, and revenue generation (Armstrong *et al* 2021). The data cannot be fully controlled for extended periods of service disruption, administrative failure to collect user payments, or data recording errors which would have an unknown effect on revenue. To account for such cases, single months with no recorded revenue are assumed to represent true drops in demand while two or more consecutive months with no recorded revenue, regardless of whether water usage was recorded, are assumed to indicate an operational issue, and are excluded. We also exclude monthly records that report revenue was collected when no water was used, which result from arrears payments or recording errors. Arrears are otherwise lumped into monthly revenue, introducing a known source of error that is discussed elsewhere in this paper. Lastly, we identify and exclude extreme outliers that result from factors such as abrupt administrative billing adjustments, delayed billing, infrastructure upgrades, and other data errors. Values greater than three standard deviations from the mean for each country are identified within all revenue and usage records. From these outliers, records are excluded if they are more than one order of magnitude greater than values in the months immediately preceding or following and if there are no other months with recorded values of a similar magnitude. Water usage outliers are also excluded if the value is an order of magnitude lower than anticipated based on the concurrent monthly revenue record. This methodology leads to exclusion of less than 1% of the overall dataset.

These criteria introduce a selection bias in our dataset towards operators that enforce regular financial contributions from end users and keep high quality records, which are a rarity in sub-Saharan Africa (Jimenez and Perez-Foguet 2010). We acknowledge our results are aspirational due to this unavoidable bias because the study is focussed on understanding rates of revenue generation rather than rates of nonpayment.

2.2. Rationale for service area archetypes

As an alternative to case-based research, we align our study with a methodological approach known as archetype analysis in sustainability research to enhance transferability of findings while avoiding overgeneralisation (Sietz *et al* 2019). Even after cleaning, our dataset is influenced by exogenous factors which are neither explicit in the records nor manifested in extreme outliers and therefore cannot be controlled or resolved. Such factors include density of competing waterpoints (Koehler *et al* 2015, Kulinkina *et al* 2016), operator-specific efficiencies, infrastructure age (Grant *et al* 2020), and local socioeconomic vulnerabilities (Foster and Hope 2017). Furthermore, the financial performance of each operator is dependent on contextual factors that exert multiscale influence on individual service areas. Archetype analysis aims to bridge such gaps between local nuances and global narratives by decomposing disparate case studies into archetypal mechanisms characterised by distinct attributes, identifying recurrent outcome patterns and the conditions under which they occur, and reconstructing generalised findings (Oberlack *et al* 2019). The approach contributes to alignment of knowledge and decision-making scales by causally connecting local phenomena to national and global processes (Adger *et al* 2003). Archetype analysis has been used to examine a range of socioecological challenges including land use, water resource management, energy production, and climate vulnerability. The approach has been applied to water governance (Gotgelf *et al* 2020) and municipal water services (Noiva *et al* 2016, Rahill-Marier *et al* 2013) but to our knowledge this study is the first time it has been adapted for rural water supply.

Archetypes are typically defined by striking a balance between theory, known attributes, and empirical evidence (Eisenack *et al* 2019). We construct archetypes that represent cases of conceptual and empirical interest at macro and micro contextual scales using clusters of piped water service areas with distinct characteristics. We do not conduct our analysis at the individual operator level where exogenous factors are prone to exert the most bias on revenue rates. Instead, service area archetypes are constructed at levels where multiple operators are represented. We first cluster service areas at multi- and single country operational scales to evaluate revenue rates across the full dataset and compare the influence of country-level enabling environment for rural water services. We assume service areas operating in the same country are subject to similar environmental, structural, and institutional factors that control how large-scale programs are implemented and sustained (Jiménez *et al* 2015). Second, we cluster service areas based on whether the initial investment was led by the state or by a private enterprise to demonstrate the microscale influence of factors that correlate with the planning and implementation approach such as origin of infrastructure, design philosophy, project delivery method, and sources of up-front project finance. Public rural water infrastructure investments that are financed by taxes and international transfers are likely to adhere to a structured procurement process with a technocratic design philosophy. Ongoing operation and maintenance of government-owned assets may be delegated to private operators, but the role of innovation in addressing critical population size, density, and fluctuation challenges is often limited (Humphreys *et al* 2018). Public infrastructure projects also commonly suffer from inefficiencies due to poor budgetary planning, allocation, and implementation (IMF 2020). On the other hand, rural water infrastructure investments that are led by private enterprises can follow a more flexible, commercial approach in the planning, implementation, and delivery of water services but may do so by raising tariffs (Davis 2005).

We anticipate these contrasting approaches influence revenue generation from user payments in the observed service areas.

For quantitative analysis, we evaluate homogeneity of mean volumetric revenue across the service areas and operators included within each archetype via student's t-test or one-way ANOVA, as appropriate. We then identify recurring revenue patterns from descriptive statistics and regression effects across the archetypes. An important distinction is our analysis does not explicitly aim to compare revenue generation between the archetypes because the implications would be limited to the nuanced context of the observed service areas. Instead, we look for inferences regarding revenue rates that are evident across several of the archetypes which are transferrable beyond the study domain.

2.3. Regression approach

Parameter estimates from generalised estimating equations (GEEs) are used to determine whether connection type and payment approach exhibit an association with revenue in each service area archetype while controlling for tariff level. The GEE method (Zeger *et al* 1988) is chosen over other regression approaches because monthly records are clustered by operator which violates the independence assumption inherent in other generalized linear regression methods. The GEE method makes it possible to evaluate different correlation structures which can adjust for this clustering by defining within-subject variables. Furthermore, the GEE method fits well into our overall methodological approach because it estimates population-averaged effects, which in this study are revenue rates generated in the service area archetypes, when covariates are unknown or unable to be controlled (Muff *et al* 2016). Since we address potential biases through interpretation of revenue patterns across multiple service area archetypes, we do not need to account extensively for covariates in the regression models.

Separate GEE models are run for each service area archetype. All modelling is conducted in IBM SPSS (IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY: IBM Corp) with monthly records as repeated measures, service areas as subjects, and operator as a within-subject variable. We construct a log-transformed, continuous response variable from volumetric revenue ($\$/m^3$) because the records follow a right-skewed, log-normal distribution. Three explanatory variables are utilised in the models: tariff level, connection type, and payment approach. Tariff levels (2019 $\$/m^3$ at PPP) are centred on the mean for all records included in each archetype and modelled as a continuous covariate. Connection type (on premises; off premises) is modelled as a categorical factor. Payment approach is correlated with waterpoint connection type: all service areas that utilise PAYF payments contain off premises connections and all service areas that utilise monthly billing contain on premises connections. Therefore, a transformed binary variable based on utilisation of prepaid credit (conventional payments; prepaid credit payments) is included in the models as a categorical factor. We run each model once with an unstructured correlation matrix and again with an autoregressive correlation matrix, the latter of which considers correlations to be highest for time-adjacent records and to systematically decrease with increasing time distance between records. The correlation matrix with the lowest quasi-likelihood of independence criterion (QIC) statistic is determined to exemplify the best fit. Finally, we evaluate the sensitivity of the estimated parameters of each model by 'leave-one-out' analysis, where records corresponding to each operator and year are systematically excluded from the constructed archetype and the model parameters re-estimated.

3. Results

3.1. Service area archetypes

The operating context for each of the constructed service area archetypes is summarised in table 1. Data are available from one operator in both Ghana and Rwanda. Therefore, we are only able to construct one archetype for the single country operating context based on service areas operating in Uganda (archetype 2). It is not feasible to characterise archetype 2 to the extent necessary to evaluate whether it is representative of Uganda at a national scale or to enable direct comparison with other locales in Africa. However, several aspects of the archetype's operating context can help to situate it within the region. First, rural water service levels in Uganda are reflective of the subcontinent but are increasing at a faster rate. Estimated coverage of basic or higher services in rural Uganda was 48% and increasing by 1.7% per year in 2020. Coverage across rural sub-Saharan Africa in 2020 was slightly higher at 49% but was increasing at just 0.9% per year (UNICEF and World Health Organization 2021). Second, public sector management in Uganda is below average for the world but relatively strong for the region. The country has ranked higher in key governance metrics over the past five years than the rest of sub-Saharan Africa, particularly in government effectiveness (average 31st global percentile compared to 26th, respectively) and regulatory quality (average 43rd global percentile compared to 28th, respectively) (World Bank 2018b). Third, Uganda's approach to performance-based public drinking water management (Muhairwe 2009), which now extends into rural areas (Huston *et al* 2021), influences many of Ugandan service areas we observe in this study. Two of the three operators represented in archetype 2 function in a single district in Uganda under a joint agreement with a parastatal rural water utility, the Mid-Western Umbrella of

Table 1. Operating context of service area archetypes.

Service area archetype	Avg. population density in 2019 (per/km^2) (IQR)	Countries	Number of operators	Primary power supply for schemes	Water distribution method	Status of schemes at operator contract
1. Multi-country	485 (339)	Ghana, Rwanda, Uganda	5	Gravity, diesel, or solar	Kiosks and networks	New and existing
2. Single country	366 (102)	Uganda	3	Diesel or solar	Kiosks and networks	New and existing
3. Enterprise	478 (335)	Ghana, Uganda	2	Solar	Kiosks and networks	New
4. Public	492 (212)	Rwanda, Uganda	3	Gravity, diesel, or solar	Networks	New and existing

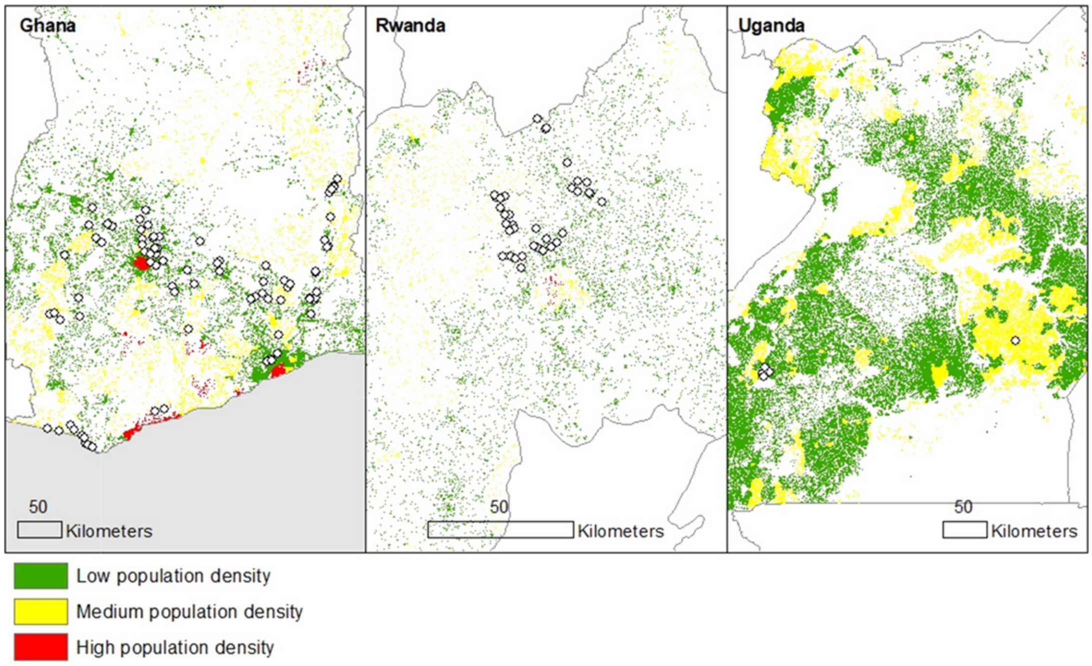

Figure 3. The average estimated population density of the observed service areas in Ghana, Rwanda, and Uganda is 474, 530, and 366 people per square kilometre, respectively. These locations, which are depicted as white dots in the figure, appear to be in areas of low to medium population density relative to each country. Population densities in the figure are graded by Jenks natural breaks classification method at the country level.

Water and Sanitation Authority. The operators are responsible for daily operation, maintenance, and revenue collection activities but the utility provides funds for fuel and spare parts. All revenues are shared between the operator and the utility. This progressive service delivery model is embedded in Uganda's national operation and maintenance framework for rural water infrastructure (Republic of Uganda 2020) and is being replicated to various degrees across sub-Saharan Africa (Adank *et al* 2021).

Two additional archetypes are constructed based on investment approach. First, the enterprise archetype (archetype 3) extracts data from service areas in Ghana and Uganda that primarily rely on solar power to pump and treat water and utilise kiosks and gravity-fed networks for distribution to users. This archetype reflects an approach where private operators assume responsibility for water supply infrastructure under build-operate agreements before it is constructed and leverage non-governmental funds to cover capital expenses. The operators take an entrepreneurial approach that aims to enhance service quality and water sales while minimising ongoing costs when designing the up-front infrastructure and business model. Second, data are extracted from public infrastructure investments in Rwanda and Uganda to construct the final archetype (archetype 4). In these service areas, the investment approach reflects a state-led model where government oversees construction or rehabilitation and retains ownership of water supply infrastructure while private agencies are contracted for operation and maintenance. Kiosks are not utilised in the service areas in archetype 4. Instead, users who do not have access to on premises connections collect water solely from standpipes.

Although we cannot make inferences about the presence or state of water supply infrastructure in the service areas used to construct each archetype, the population densities are statistically similar (one-way ANOVA, $p > 0.05$). Any differences in revenue patterns between the archetypes are therefore not likely attributable to the size of service populations beyond limitations imposed by the dispensing capacity and physical location of waterpoints. The 95% confidence interval for the estimated population densities of all observed service areas ranges from 402 to 545 people/km^2. For reference, this is higher than the overall population density of Ghana

Table 2. Results of means tests on log-transformed volumetric revenue across service areas and operators included in each archetype.

	Service areas[a]		Operators		
Service area archetype	*F*	*P*[b]	*F*	*P*[b]	Homogeneous subsets[c]
1. Multi-country	16.3	<0.001	152.5	<0.001	Operators 2, 3, and 4; operators 3 and 5
2. Single country	15.8	<0.001	9.5	<0.001	Operators 3 and 4
3. Enterprise	8.8	<0.001	20.6	<0.001[d]	Not applicable
4. Public	18.4	<0.001	93.4	<0.001	None

[a]Post hoc tests are not performed across service areas due to the large number of groupings.
[b]Significant at $\alpha = 0.05$.
[c]Homogeneous subsets are identified across operator means by Tukey's HSD.
[d]Operator means for archetype 3 are tested via independent samples student's t-test. All other means are tested via one-way ANOVA.

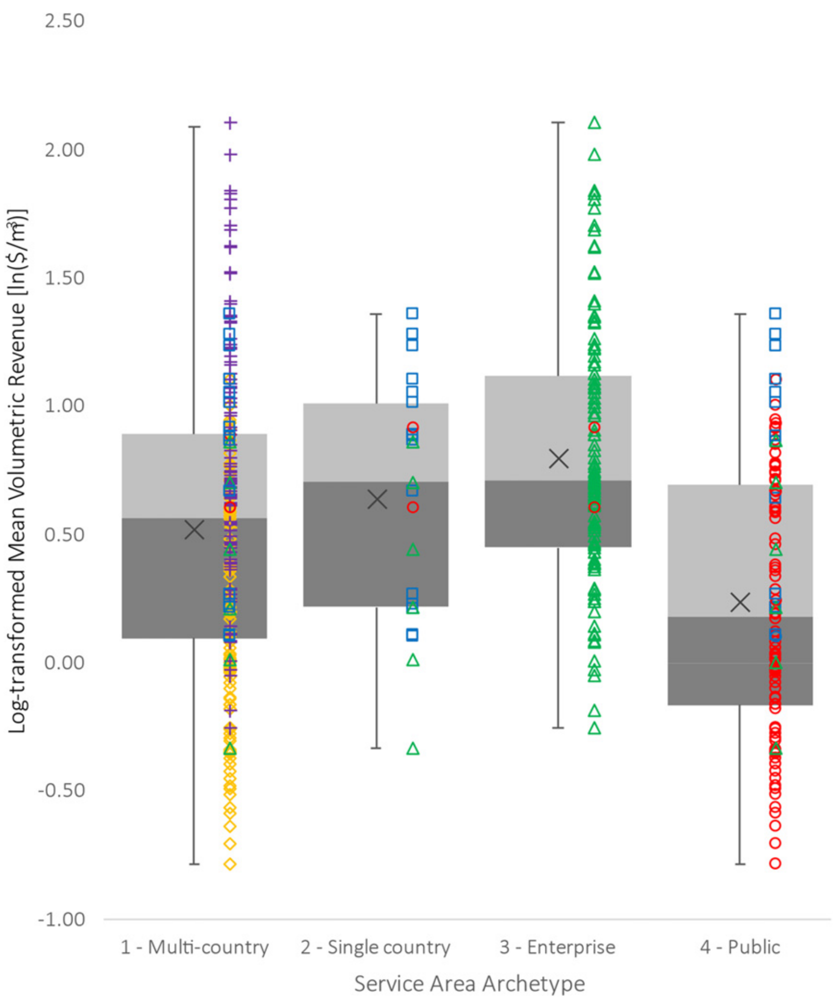

Figure 4. Log-transformed mean revenue rates appear weighted across operators in archetypes 1, 2 and 4 but are normally distributed across service areas within each archetype. Box plot elements: markers correspond to log-transformed mean volumetric revenue for service areas used to construct archetypes; marker types and colours correspond to operators; mean markers, median centre lines, upper and lower quartile box limits, and whiskers for minimum and maximum values within 1.5× IQR illustrate statistics for the constructed archetypes.

and Uganda (131 and 213 people/km^2, respectively) but in agreement with that of Rwanda (499 people/km^2) (World Bank 2018a). The UN Statistics Commission's *Degree of Urbanisation* method defines population densities above 1,500 people/km^2 as 'urban' and below 300 people/km^2 as 'rural' (European Commission 2020). Accordingly, the archetypes can be described as small-scale piped service areas in large villages, small towns, or transitional areas between rural and urban settings. This statement is further supported by figure 3, which locates the observed service areas in proximity to areas of relatively low to medium population density in Ghana, Rwanda, and Uganda. Piped water services require a consolidated and moderately sized user base to generate sufficient tariff revenue, and the archetypes are situated near this threshold of economic viability.

Table 3. Summary statistics from monthly records.

Service area archetype		Service areas[a]	Waterpoints Total[b]	Waterpoints Avg. service area	Attribute	Months	Mean	Med	IQR	SD
1. Multi-country	Off premises	96	867	9	Tariff ($/m^3)	1697	2.12	2.49	0.79	1.06
					Volume (m^3/wp/mo)	1693	55.42	38.32	60.55	67.95
					Revenue ($/m^3)	1680	1.61	1.61	0.89	0.94
	PAYF	88	814	9	Tariff ($/m^3)	1515	2.12	2.49	0.79	1.07
					Volume (m^3/wp/mo)	1511	55.65	38.32	60.55	69.81
					Revenue ($/m^3)	1498	1.59	1.61	0.88	0.95
	Prepaid credit	17	115	7	Tariff ($/m^3)	182	2.30	2.49	0.04	0.99
					Volume (m^3/wp/mo)	182	77.69	79.57	73.51	49.61
					Revenue ($/m^3)	182	1.87	1.95	0.53	0.85
	On premises	124	3074	25	Tariff ($/m^3)	2206	2.30	2.49	1.26	1.00
					Volume (m^3/wp/mo)	2198	13.52	5.35	10.02	36.13
					Revenue ($/m^3)	2094	2.87	2.46	2.10	2.28
	Monthly billing	109	2844	26	Tariff ($/m^3)	1850	2.26	2.49	1.31	1.06
					Volume (m^3/wp/mo)	1844	14.85	6.35	11.85	39.13
					Revenue ($/m^3)	1757	2.83	2.21	2.07	2.06
	Prepaid credit	40	798	20	Tariff ($/m^3)	356	2.53	2.49	0.00	0.49
					Volume (m^3/wp/mo)	354	4.79	3.88	2.24	4.65
					Revenue ($/m^3)	337	3.59	3.36	1.50	2.93
2. Single country	Off premises	8	91	11	Tariff ($/m^3)	216	1.76	1.83	0.23	1.35
					Volume (m^3/wp/mo)	216	19.88	11.89	8.69	21.66
					Revenue ($/m^3)	216	1.49	1.55	0.26	1.12
	PAYF	5	68	14	Tariff ($/m^3)	123	1.81	1.83	0.10	1.39
					Volume (m^3/wp/mo)	123	14.96	11.98	4.09	11.12
					Revenue ($/m^3)	123	1.44	1.60	0.18	1.13
	Prepaid credit	4	35	9	Tariff ($/m^3)	93	1.90	1.83	0.48	1.30
					Volume (m^3/wp/mo)	93	24.26	10.91	34.47	29.45
					Revenue ($/m^3)	93	1.73	1.55	0.57	1.09
	On premises	15	663	44	Tariff ($/m^3)	332	3.33	3.48	0.36	0.86
					Volume (m^3/wp/mo)	332	5.95	2.33	2.97	10.03
					Revenue ($/m^3)	320	2.81	2.78	0.99	1.58
	Monthly billing	13	637	49	Tariff ($/m^3)	294	3.39	3.48	0.32	0.86
					Volume (m^3/wp/mo)	294	5.29	2.20	1.93	10.26
					Revenue ($/m^3)	282	2.83	2.78	1.34	1.62
	Prepaid credit	2	26	13	Tariff ($/m^3)	38	2.95	2.95	1.02	0.85
					Volume (m^3/wp/mo)	38	10.21	10.21	13.78	7.42
					Revenue ($/m^3)	38	2.68	2.68	0.48	1.22
3. Enterprise	Off premises	59	373	6	Tariff ($/m^3)	728	2.61	2.49	0.00	0.52
					Volume (m^3/wp/mo)	726	69.97	56.58	59.20	57.18
					Revenue ($/m^3)	720	1.83	1.74	0.56	0.64
	PAYF	54	343	6	Tariff ($/m^3)	624	2.64	2.49	0.00	0.54
					Volume (m^3/wp/mo)	622	70.32	57.41	57.84	57.57
					Revenue ($/m^3)	616	1.81	1.69	0.61	0.67
	Prepaid credit	14	92	7	Tariff ($/m^3)	104	2.42	2.49	0.00	0.26
					Volume (m^3/wp/mo)	104	87.69	90.85	74.81	54.81
					Revenue ($/m^3)	104	1.96	2.01	0.50	0.49
	On premises	53	888	17	Tariff ($/m^3)	514	2.57	2.49	0.00	0.46
					Volume (m^3/wp/mo)	512	7.48	4.78	3.30	15.63
					Revenue ($/m^3)	476	4.12	3.51	2.22	3.41
	Monthly billing	39	662	17	Tariff ($/m^3)	181	2.59	2.49	0.00	0.53
					Volume (m^3/wp/mo)	181	9.26	5.07	5.31	24.59
					Revenue ($/m^3)	162	4.46	3.83	3.87	4.07
	Prepaid credit	39	795	20	Tariff ($/m^3)	333	2.51	2.49	0.00	0.39
					Volume (m^3/wp/mo)	331	4.83	3.88	2.24	4.75
					Revenue ($/m^3)	314	3.61	3.37	1.50	3.00

(continued on next page)

Table 3. Continued

Service area archetype		Service areas[a]	Waterpoints: Total[b]	Waterpoints: Avg. service area	Attribute	Months	Mean	Med	IQR	SD
4. Public	Off premises	37	494	14	Tariff ($/m^3$)	969	1.33	1.05	1.11	1.09
					Volume (m^3/wp/mo)	967	32.23	17.67	20.97	40.14
					Revenue ($/m^3$)	960	1.26	0.96	0.96	1.60
	PAYF	34	471	14	Tariff ($/m^3$)	891	1.30	0.80	1.26	0.98
					Volume (m^3/wp/mo)	889	32.34	17.92	20.97	73.96
					Revenue ($/m^3$)	882	1.24	0.84	1.05	1.04
	Prepaid credit	3	23	8	Tariff ($/m^3$)	78	1.72	1.83	0.18	1.39
					Volume (m^3/wp/mo)	78	31.01	11.79	30.59	30.28
					Revenue ($/m^3$)	78	1.49	1.51	0.10	1.12
	On premises	71	2187	34	Tariff ($/m^3$)	1692	2.10	1.79	1.74	1.03
					Volume (m^3/wp/mo)	1686	17.76	6.68	15.04	71.43
					Revenue ($/m^3$)	1618	1.94	1.77	1.38	1.05
	Monthly billing	70	2183	31	Tariff ($/m^3$)	1669	2.08	1.75	1.66	1.08
					Volume (m^3/wp/mo)	1663	17.97	6.79	15.17	40.39
					Revenue ($/m^3$)	1595	1.93	1.71	1.38	1.59
	Prepaid credit	1	4	4	Tariff ($/m^3$)	23	3.46	3.46	0.00	0.88
					Volume (m^3/wp/mo)	23	3.32	3.32	0.00	2.01
					Revenue ($/m^3$)	23	2.92	2.92	0.00	1.54

[a]Payment approach statistics are presented as subsets of infrastructure type statistics. Counts do not sum to the value of some parent rows because individual service areas are categorised by a constant infrastructure type but can alternate between payment approaches over time.
[b]Sum of the average number of waterpoints for each service area across all included records.

Although the archetypes are not representative of sparsely populated, traditionally rural areas, the study findings apply to rural growth centres where the African population is anticipated to increase the most in the coming decades.

3.2. Archetype validation

Results of means tests on log-transformed volumetric revenue for the service areas and operators represented in each archetype are summarised in table 2 and illustrated in figure 4.

Mean revenue rates are statistically different between individual service areas and operators ($p < 0.001$) in all four archetypes (table 2). However, the box plots depicted in figure 4 reveal the rates are normally distributed across the services areas within each archetype. Summary statistics and regression results for the service area archetypes are therefore unlikely to be skewed. Between-group differences are most noticeable when comparing means for operators in archetypes 1 ($F = 152.5$) and 4 ($F = 93.4$). Revenue means also appear weighted, but to a lesser degree, across operators in archetype 2. These observations suggest exogenous factors related to individual operators likely influence revenue in the service area archetypes and reinforce the methodological approach taken to construct archetypes from records corresponding to more than one operator.

3.3. Revenue records

Summary statistics for tariff levels, monthly waterpoint volumes dispensed, and volumetric revenue for each service area archetype, disaggregated by connection type and payment approach, are summarised in table 3. Mean tariff levels and volumetric revenues are also depicted graphically in figure 5. The observed tariff levels agree with utility benchmarks from Ghana, Rwanda, and Uganda available in the IBNET database which range from 0.85 to 3.35 2019 US dollars per cubic metre at purchasing power parity (IBNET 2020). Off premises connections generate considerable volumetric revenue but mean rates are higher for on premises connections in all four archetypes (figure 5). Higher tariff levels, rather than improved collection efficiencies, appear to drive higher revenue from on premises connections in archetypes 2 and 4. Figure 5 illustrates that tariff levels for on premises connections are generally higher than for off premises connections in the two archetypes, but the difference between the tariff level and revenue rate is not consistently lower for on premises connections. Despite small variation in tariff level, on premises connections in archetypes 1 and 3 generate revenue at higher rates than both off premises connections and mean tariff levels due to the inclusion of arrears payments in the monthly revenue records.

Although off premise standpipes and kiosks generate lower volumetric revenue than on premises connections, they facilitate more usage per waterpoint in all four archetypes (table 4). Notably, a large proportion of the off premises connections in archetype 3 are high-capacity kiosks that dispense nearly one order of magnitude greater volume per waterpoint (69.97 m^3/waterpoint/month) than on premises connections

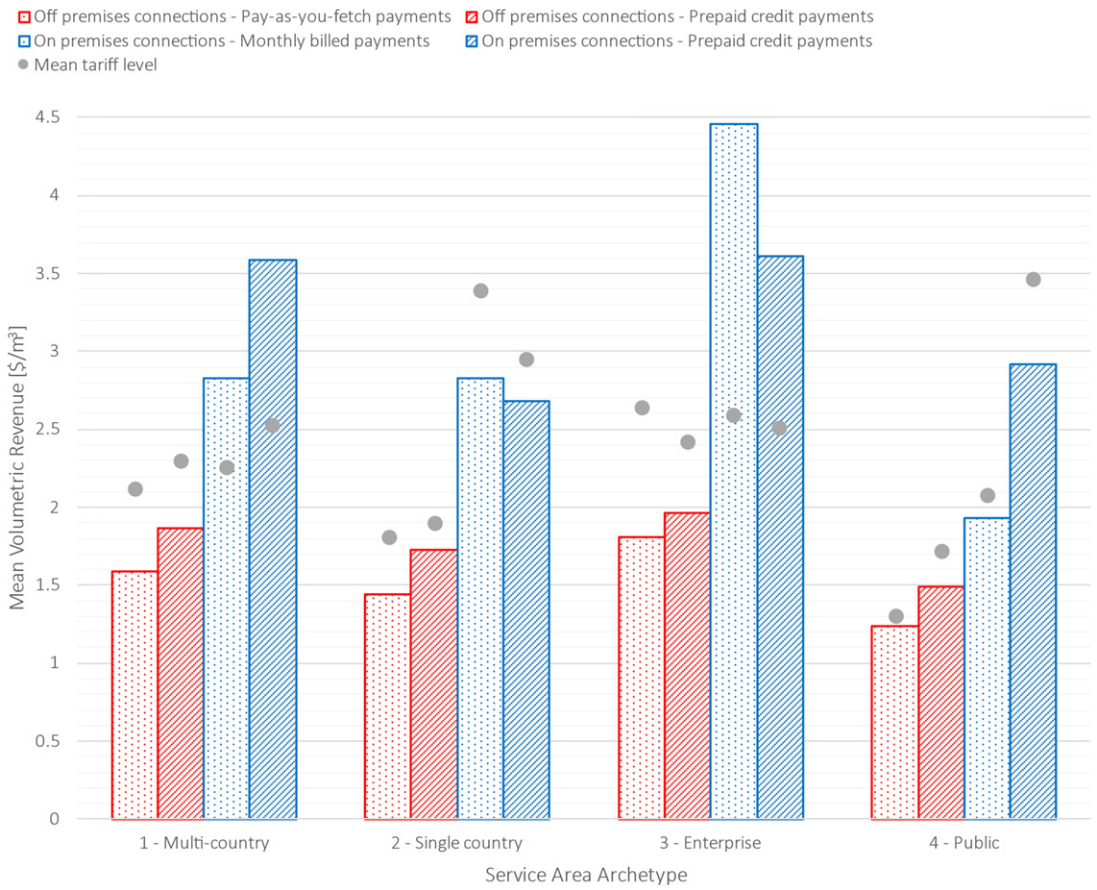

Figure 5. On premises connections generate higher volumetric revenue than off premises connections in all archetypes. Revenue rates appear to correlate with tariff levels and are higher than tariff levels for on premises connections in archetypes 1 and 3 due to the inclusion of arrears payments in monthly revenue records.

Table 4. Summary of average waterpoint usage and revenues in each service area archetype.

Service area archetype		Volumetric usage (m^3/waterpoint/month)	Volumetric revenue (\$/m^3)	Total monthly revenue (\$/service area/month)
1. Multi-country	Off premises	55.42	1.61	538
	On premises	13.52	2.87	319
2. Single country	Off premises	19.88	1.49	235
	On premises	5.95	2.81	378
3. Enterprise	Off premises	69.97	1.83	752
	On premises	7.48	4.12	302
4. Public	Off premises	32.23	1.26	381
	On premises	17.76	1.94	324

(7.48 m^3/waterpoint/month). In three of the four service area archetypes, more total monthly revenue is generated from the waterpoint types that facilitate the highest water use: off premises connections generate an average $291, $450, and $57 more aggregate revenue per service area per month than on premises connections in archetypes 1, 3, and 4, respectively. The higher waterpoint dispensing capacity and larger user base of off premises connections in these archetypes appear to provide more of an overall revenue benefit than the greater number of waterpoints and higher volumetric revenue rate of on premises connections.

Figure 5 also illustrates the influence of payment approach on volumetric revenue rates in the service area archetypes. Prepaid credit payments appear to be linked with higher revenue rates than conventional payments in some cases, such as when paired with off premises connections in all four archetypes and with on premises connections in archetypes 1 and 4. However, there is no pattern that would suggest the approach is clearly and consistently generating higher rates of revenue. In fact, the revenue benefits associated with prepaid credit payments appear just as likely to be a result of higher tariff levels as higher collection efficiencies. Furthermore, for records associated with prepaid meters in particular, the time lag between instance of credit purchase and redemption is only partially accounted for by summing revenues and volumes over the month.

Table 5. Modelled effects of tariff level, on premises connections, and prepaid credit on volumetric revenue (log-transformed response variable) in each service area archetype.

Service area archetype	β	SE	95% confidence interval Lower	Upper	P
1. Multi-country					
Reference case (intercept)	**0.474**	**0.0201**	**0.435**	**0.514**	**<0.001**
Tariff level[a]	**0.470**	**0.0319**	**0.407**	**0.532**	**<0.001**
On premises connections[b]	−0.034	0.0429	−0.118	0.050	0.429
Prepaid credit[b]	−0.075	0.0691	−0.210	0.061	0.279
2. Single country					
Reference case (intercept)	**0.698**	**0.0523**	**0.598**	**0.801**	**<0.001**
Tariff level[a]	**0.399**	**0.0503**	**0.301**	**0.498**	**<0.001**
On premises connections[b]	−0.119	0.0803	−0.276	0.038	0.139
Prepaid credit[b]	−0.071	0.0591	−0.187	0.044	0.227
3. Enterprise					
Reference case (intercept)	**0.735**	**0.0392**	**0.659**	**0.812**	**<0.001**
Tariff level[a]	**0.371**	**0.0724**	**0.229**	**0.512**	**<0.001**
On premises connections[b]	−0.040	0.1738	−0.380	0.301	0.820
Prepaid credit[b]	−0.442	0.2602	−0.952	0.068	0.089
4. Public					
Reference case (intercept)	**0.249**	**0.0240**	**0.202**	**0.296**	**<0.001**
Tariff level[a]	**0.493**	**0.0464**	**0.402**	**0.584**	**<0.001**
On premises connections[b]	−0.080	0.0551	−0.188	0.028	0.148
Prepaid credit[b]	**−0.166**	**0.0418**	**−0.248**	**−0.084**	**<0.001**

[a]Tariff level is centred on the mean of service areas used to construct each archetype and modelled as a main effect.
[b]On premises connections and prepaid credit parameters are modelled as interactions with mean-centred tariff level.

This potential bias may cause the calculated volumetric revenue rates associated with prepaid credit payments to be systematically higher than actual and inflate the apparent benefit of the approach.

3.4. GEE models

The estimated effects of on premises connections and prepaid credit on volumetric revenue, modelled separately for each service area archetype and controlled for tariff level, are summarised in table 5 and plotted in figure 6. The reference case, or intercept, in each of the archetype models corresponds to volumetric revenue generated by off premises connections with PAYF payments at tariff levels centred on the mean for the archetype. The tariff level parameter indicates the main effect of tariff level variation on volumetric revenue. The β values corresponding to on premises connections and prepaid credit indicate the estimated interaction effect of the parameter relative to the reference case at equivalent tariff levels. The QIC goodness-of-fit statistics for each model are lower when parameters are estimated with an autoregressive correlation matrix than when unstructured, indicating a better fit when time-adjacent records are assumed to be correlated.

A pattern is evident within the regression results that supports observations from the summary statistics. This pattern is consistent across all four service area archetypes and is generally unaffected when records corresponding to individual operators and years are sequentially excluded from the GEE models (see results of leave-one-out analysis in the supplemental table (https://stacks.iop.org/ERIS/2/035003/mmedia)). Off premises connections and PAYF payments (the reference case) are associated with significant revenue rates ($p < 0.001$) in all four archetypes. The 95% confidence intervals for these reference cases reflect the relative magnitudes of revenue record means depicted in figure 5. However, when tariff level is controlled, on premises connections are not associated with revenue rates that are significantly different from the reference case ($p < 0.05$) in any service area archetype or across the entire range of observed tariff levels (figure 6). Furthermore, prepaid credit payments are not associated with greater revenue rates than conventional payment approaches at equivalent tariff levels in any of the archetypes. The slight yet significant negative effect of prepaid credit payments identified in archetype 4 ($\beta = -0.166$, $p < 0.001$) should be regarded with reservation because the effect estimate is based on less than 4% of the records used to construct the archetype.

This consistent pattern suggests higher tariff levels contribute to the apparent revenue benefits associated with on premises connections and prepaid credit payments in the archetypes. It follows that revenue rates are significantly, consistently, and positively correlated with tariff levels in the regression model for each archetype. These results indicate that variations in tariff levels within the archetypes result in changes in revenue that are

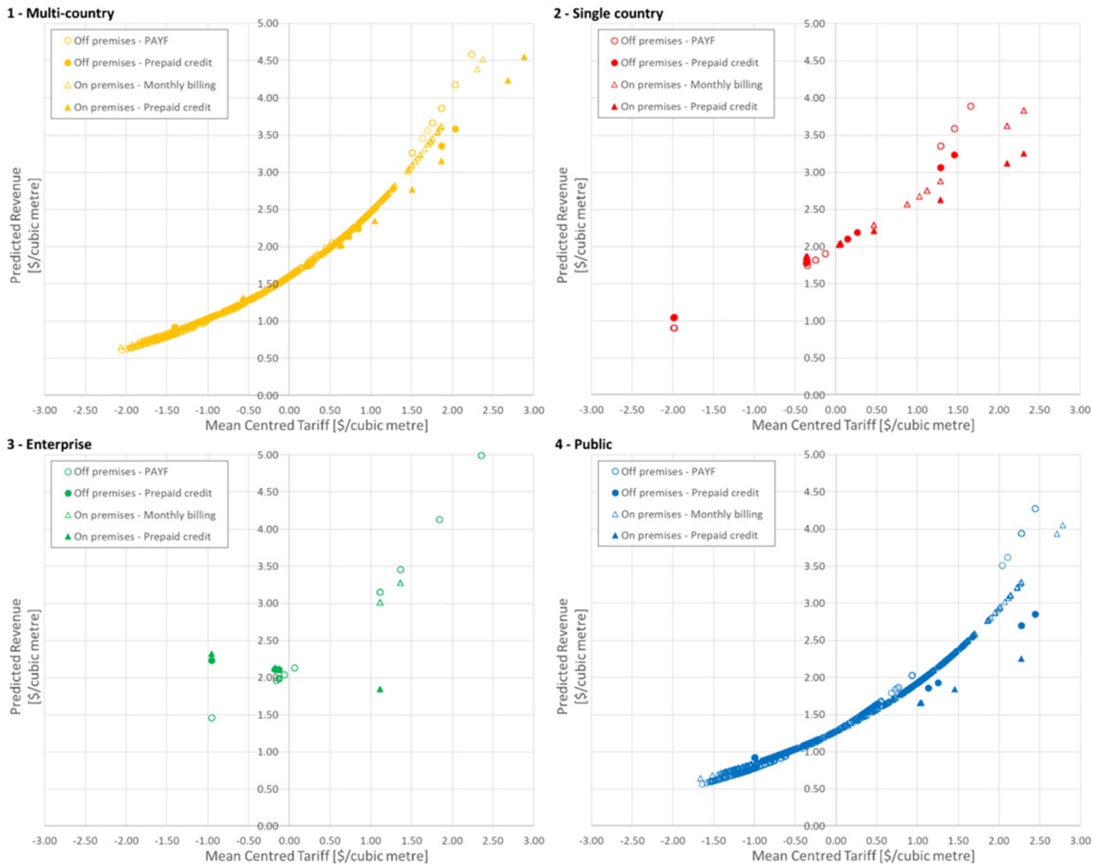

Figure 6. Model-predicted volumetric revenue by tariff level, connection type, and payment approach for service area archetypes: 1. Multi-country, 2. Single country, 3. Enterprise, and 4. Public.

similar in magnitude and direction. The estimated β values for each model can be used to simulate revenue rates at different tariff levels and demonstrate this overall effect. For example, when conventional payments are utilised, a simulated 1% tariff level increase above the mean results in revenue rate increases of 1.0%, 1.1%, 1.0%, and 0.9% in archetypes 1, 2, 3 and 4, respectively.

4. Discussion

This empirical analysis offers three insights concerning viable pathways for achieving universal access to safely managed and affordable drinking water services in rural Africa. First, the revenue patterns we identify are recurrent across operating contexts and investment approaches as identified in the service area archetypes, suggesting the findings may be applicable beyond the study domain. Second, volumetric revenue from rural piped water services is determined by tariff level rather than connection type, and off premises connections with the greatest dispensing capacity generate the most aggregate revenue. Third, at equivalent tariff levels, prepaid credit payments for rural piped water services are associated with similar rates of volumetric revenue generation as conventional PAYF and monthly billing approaches. We discuss how these insights support the argument that piped water services which utilise a blend of connection types and payment approaches contribute to viable and equitable infrastructure investment strategies in rural Africa.

4.1. Revenue patterns across service area archetypes

A feature of this study is its use of archetype analysis, which has not been previously applied to rural water supply, in contrast to place-based analysis, which is commonly applied. Archetype analysis enables identification of both consistencies and abnormalities in the way waterpoint connection type, payment approach, and tariff level influence revenue generation across service area archetypes that represent distinct operating contexts and investment approaches.

We observe heterogeneity in average revenue rates for each service area archetype that generally aligns with anticipated results considering the conceptual basis used to construct them. For example, the highest revenue rates are seen in service areas representing enterprise-led investments where a more commercially oriented approach is employed than those representing public investments, where the lowest rates are observed. We also see differences in water usage rates between the archetypes, which is known to result at least in part from differing dispensing capacities of off premises waterpoints.

Although these outcome variations are notable, our evaluation of the causal mechanisms that are common across archetypes produces the most transferrable findings. The revenue patterns we identify in the regression results are recurrent at multi- and single country scales and across service areas where public and enterprise-led investment approaches to infrastructure development are taken. It therefore appears the exogenous factors which might influence revenue generation and form the basis of the service area archetypes are less important than the explicit factors which are able to be controlled in the regression models.

We acknowledge our dataset is not representative of every rural water service delivery context on the African subcontinent and is biased towards high-performing operators that maintain quality records. We therefore cannot draw conclusive findings that apply beyond the study domain. However, consistency across the archetypes suggests our findings are pertinent on a wider scale which can be examined with further testing of additional datasets.

4.2. Revenue from on and off premises connections

Our findings illustrate how rural piped water services provided on and off premises exhibit complementary revenue patterns that can be combined at incremental stages of infrastructure development to enhance revenue from user payments. We find on premises connections are associated with volumetric revenue gains compared to off premises connections in all service area archetypes. However, this advantage is linked to tariff increases and on premises connections are associated with an average 17% higher tariff level in three of the four service area archetypes. We also find off premises connections with high dispensing capacities generate the most aggregate revenue.

Piped water investments are inherently capital-intensive, but construction of dedicated on premises connections incurs an additional sizeable per capita cost compared to off premises kiosks and standpipes (Burr and Fonseca 2013). Rural water investment strategies therefore often incorporate intermediate upgrades from improved to piped services with a blend of both on and off premises connections. The patterns we observe, which have also been recognised by urban utilities (Foster and Briceno-Garmendia 2010), suggest rural off premises connections can generate substantial revenue in these transitional scenarios, contributing to the overall financial viability of the service in proportion with on premises connections and at lower tariff levels. The performance of archetype 3 particularly demonstrates that an entrepreneurial planning and management approach coupled with high dispensing capacity waterpoints such as kiosks can lead to higher rates of total revenue generated from off premises than on premises connections.

We also find on premises connections yield unique revenue benefits in narrow market segments where users can afford to pay higher tariffs. There are several plausible reasons why on premises connections in our dataset are linked with higher tariffs. The tariff structures may aim to recover incremental private connection costs, to deliver targeted subsidies to off premises users, or simply to take advantage of a higher willingness to pay for on premises services. Regardless, as previous studies have found (Carrard *et al* 2019, Kayaga and Franceys 2007), it is typically only the relatively wealthy who are able to pay for the higher costs associated with up-front connection and ongoing access. Piped services provided on premises to these users are less labour-intensive for operators to deliver and typically incur less recurring cost than off premises services, which require kiosk and standpipe attendants to be paid (Rusca and Schwartz 2018). It is therefore possible that higher unit revenues from on premises connections translate into higher net income, which is broadly linked to more reliable water services (Kaminsky and Kumpel 2018, Rouse 2013).

Our data does not allow visibility into the price users actually pay for different waterpoint connection types in the service areas, which in urban Africa is known to be much higher than the tariff due to unregulated mark-ups by standpipe attendants and vendors (Foster and Briceno-Garmendia 2010). However, the results indicate providing water services exclusively on premises poses a potential affordability risk to poorer households who may be unable to afford the up-front or ongoing cash expense associated with higher service charges. Diminished demand can be anticipated as these users opt to collect lower priced water from informal or unimproved sources rather than purchasing through on premises connections. Our regression results also indicate on premises connections would generate similar rates of revenue as off premises connections if tariffs were universally reduced to comparable levels to enhance affordability. Either of these outcomes could ultimately undermine the sustainability and equity goals the infrastructure investment set out to accomplish.

Targeted subsidies and cash assistance programs, such as the option for users to make payments in arrears seen in archetypes 1 and 2, may help to address affordability issues but are challenging to implement effectively in practice (Andres *et al* 2019, Cook *et al* 2019). Alternatively, standpipes and kiosks can facilitate social protections within areas served by schemes with mixed connection types because they do not require users to pay connection fees and enable better targeting of subsidies (Andres *et al* 2019, Komives *et al* 2005). Although a substantial expenditure of time is required to access water from off premises sources (UNICEF, WHO and UN-Water 2021), it may be a trade-off that some rural users are willing to make when faced with higher cost of on premises access.

We do not debate the social and economic benefits associated with accessing water services in close proximity to households, such as has been recently reported by Winter *et al* (2021). Neither do we question the audacious SDG 6.1 goal of universal access to safely managed water services. Rather, we advocate for evidence-based investment pathways to that end. On premises services will yield broad and holistic returns over time. However, massive capital and recurring funding gaps must be addressed for the infrastructure to continue delivering services until its full value is realised. Our findings contribute empirical evidence to this practical challenge. Well-managed piped off premises connections can meet all criteria for safely managed service except for, of course, being accessible on premises. Investments in blended service levels or universal off premises connections may in fact be the most equitable pathway in some rural contexts, and indeed may be the only viable option in areas where the population density is below a threshold at which further capital investment in on premises extensions is tenable.

4.3. Revenue from conventional and prepaid credit payments

Finally, our analysis clarifies how prepaid credit and conventional user payment approaches impact financial viability of safely managed water services in rural Africa. Conventional approaches such as PAYF and monthly, post-use billing incur high labour costs and are often associated with generally low payment collection efficiency. On the other hand, automated, prepaid credit approaches minimise ongoing labour costs and theoretically enhance payment collection, yet usually incur additional hardware and ongoing data and mobile money transaction costs. Prepaid credit may be further associated with non-cash benefits such as reduced consumer loss to unregulated third-party vendors, enhanced data quantity and quality, and better targeting of welfare support programmes for vulnerable populations (Hope *et al* 2012, Thomas 2018) as well as social risks such as limited access to or affordability of the credit-based payment modality. When these trade-offs are fully considered, either payment approach could yield a favourable return on investment depending on the context, demand response, and planning priorities.

Although a full life-cycle cost analysis is not feasible with our dataset, we can compare the relative revenue rates of the two payment approaches to inform evidence-based planning. Descriptive statistics of revenue records indicate prepaid credit is often associated with higher revenue rates than conventional payment approaches, especially when paired with off premises connections. This finding seems intuitive because electronic prepaid credit payments are expected to be more accountable thus associated with higher collection efficiency and revenue rates than PAYF payments collected by kiosk and standpipe attendants. However, our regression results reveal that the apparent revenue benefit associated with prepaid credit payments is linked to higher tariff levels and not necessarily enhanced collection efficiency. If tariffs must be set at a higher level to realise revenue gains from prepaid credit payments, the adverse social impact may negate any other intended financial or economic benefits.

We do not argue against the prepaid credit approach, but our findings suggest it should be carefully adopted with realistic revenue expectations and a holistic consideration of the social and economic implications. Further research is also needed to examine at greater depth the relationship between the payment approaches observed in this study and payment collection efficiency.

4.4. Limitations

We identify five limitations to our study, which have informed the analytical approach. First, site selection is determined by collaborating agencies with sufficient and relevant data to enable the analysis. Inevitably, this is not representative, nor do we claim it is. However, it does provide a cross-section of variability central to the study questions and archetypal approach. Second, the original data are prone to inadvertent recording errors and manipulation which can lead to imprecise or inaccurate results and data quality could not be directly verified. This has been addressed through a systematic internal data validation process involving dispersion and outlier analysis of revenue and water usage records across all known service area characteristics. When possible, records have been corrected based on consultation with the operators. Anomalies and outliers have been excluded only when necessary, according to the methodologies described. Additional data limitations, such as time-bound data gaps or inclusion of arrears in monthly revenue records, have also been considered. Third, accurate data on number of water users over time are not consistently available. This prevents analysis of variables that are useful for deciphering revenue patterns such as service area penetration and per capita water usage across waterpoint connection types. We are therefore only able to examine aggregate water usage.

Fourth, operational conditions are not fully understood during the analytical window. For example, the presence and condition of alternative water supply infrastructure and changes in social and economic conditions are unknown. These effects are more likely local than regional. Fifth, operational data on the reliability of scheme performance is not fully understood. There is an implicit assumption that all schemes operate in a relatively consistent manner. Although these biases cannot be eliminated, they have been carefully considered in the overarching research design. We endeavour to address contextual limitations of the dataset by applying archetype analysis and articulating findings which can be generalised beyond the cases of individual operators.

5. Conclusion

We assemble and draw on a rare collection of secondary data to analyse the influence of piped water infrastructure types and user payment approaches on revenue patterns across novel rural service area archetypes. We find off-site piped water services that are paired with the conventional PAYF payment approach can mitigate equity and affordability risks while serving as a viable and catalytic step in the pathway towards safely managed services in rural areas. More evidence is needed to understand the trade-offs of prepaid credit systems, and we recommend such approaches be regarded with scrutiny to prevent perverse outcomes for vulnerable user groups. Our archetypal framework is broadly applicable across sub-Saharan Africa and can be further validated and strengthened with additional datasets. The evidence we present can aid rural water planners as they consider infrastructure investment strategies that sequence and optimise the number of on and off premises connections and payment approaches to balance economic and social returns.

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Data availability statement

The operational data analysed during this study are part of an ongoing PhD project and were obtained through bilateral agreements with piped water operators. Anonymised data will be deposited in a suitable repository at the completion of the PhD project and are available on reasonable request from the lead author. Population density data are available at https://dataforgood.facebook.com/. Currency conversion and deflator factors and governance metrics utilised in the study are available at https://databank.worldbank.org/home. Referenced tariff benchmarks are available at https://ib-net.org/.

Competing interests

The authors declare no competing interests.

Contributions

AA conceived the study and carried out the data collection, curation, and analyses with input from RH and JK; AA prepared the original manuscript draft; RH and JK reviewed and edited the manuscript.

ORCID iDs

Andrew Armstrong https://orcid.org/0000-0003-2605-7921
Rob Hope https://orcid.org/0000-0001-9971-9397
Johanna Koehler https://orcid.org/0000-0002-9045-4844

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