Revenue patterns of piped water services in rural Africa

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A thesis submitted for the degree of

Doctor of Philosophy

School of Geography and the Environment

Smith School of Enterprise and the Environment

Trinity Term 2022

Abstract

Rural Africa lags behind all other global regions in progress towards establishing universal and equitable access to safely managed drinking water. This challenge is marked by a notional interest in piped water for achieving service level goals while increasing demand and financial viability. Yet, a paucity of reliable information and evidence perpetuates unrealistic assumptions of how infrastructure and payment collection alternatives influence seasonal revenue generation. The emergence of professional service delivery models offers new sources of operational and financial data with potential to address knowledge gaps and inform viable, resilient, and equitable drinking water investments.

The primary aim of this project is to understand how seasonal patterns of domestic water use and payments affect revenue from piped water services in rural Africa. Empirical analyses have drawn on longitudinal records from Ghana, Kenya, Malawi, Rwanda, Tanzania, and Uganda that cumulatively span more than 500 service-years. In contrast to conventional assumptions, findings suggest household-level services exhibit similar seasonal revenue variability as off-site services and are not consistently associated with higher revenue when tariff level is controlled. Piped service areas with consistent seasonal rainfall have a third less revenue during wet months. Furthermore, prepaid credit payments do not consistently improve revenue generation compared to conventional payment approaches.

Three recommendations for rural water policy and practice are highlighted from this research. First, the threat of seasonal revenue variability to rural piped water services can be characterised by assessing rainfall patterns on localised, intra-seasonal scales. Second, complementary revenue patterns of on- and off-premises services can be leveraged at incremental stages of infrastructure investment. Third, caution should be exercised when considering prepaid credit over conventional payment approaches to prevent unrealistic revenue expectations and perverse outcomes.

Acknowledgements

I extend sincere gratitude to my co-supervisors, Professor Rob Hope and Dr Johanna Koehler, for their unwavering wisdom, accessibility, and support. Their guidance has deeply enriched this project and I enjoy their collaboration. I thank Dr Callum Munday, Zachary Spavins-Hicks, and Dr Ellen Dyer for their advice and contributions towards analysing and interpreting rainfall data. I also thank the agencies that granted access to the data which made this project possible, including Ayateke Star, Biguli Traders Association, Mid-Western Umbrella of Water and Sanitation Authority (Uganda), Power Technical Services, Safe Water Network, Water4, Water For People, and Water Mission. I am particularly grateful to Lauren Cuscuna, Carlos Batarda, Philip Deal, Richard Moore, Mike Staub, and Sam Knobeloch for their support in mining and cleaning data, providing localised insight, and answering countless questions.

I am also profoundly grateful to my parents and parents-in-law. They have been selfless and generous with their time and resources, particularly over the past three years, and I have relied on their encouragement and support.

It is impossible to articulate the fullness of my appreciation to MaryGene and Smith, Pierce, and Callum in a few sentences. They have reoriented their lives, made countless sacrifices, and remained patient with me during this DPhil journey. I will always be thankful for their daily, unconditional love.

Finally, I thank God for the funding and incredible opportunity to engage in such meaningful work. Financial support for the project was provided in part from Water Mission through the generous contribution of an anonymous donor, and through the REACH programme by UK Aid from the UK Foreign, Commonwealth and Development Office (FCDO) for the benefit of developing countries (Programme Code 201880). However, the views I express and information I present are not those of or endorsed by Water Mission or FCDO, which accept no responsibility for such views or information or for any reliance placed on them.

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Chapter 1: Introduction

1.1. Research Motivation

The Sustainable Development Goal of achieving universal and equitable access to safely managed drinking water (SDG 6.1) establishes a clear mandate for countries to ensure household-level access is available to everyone, including people living in rural areas that are the most difficult to reach. To attain this goal in rural sub-Saharan Africa, where the world’s largest underserved population resides, services need to be upgraded for more than half a billion people and in more than half of all schools (UNICEF and World Health Organization, 2021). This represents roughly 87 percent of the rural population and more than double the urban population that lacks adequate drinking water service on the subcontinent (ibid.), and will cost an estimated USD $5.9 billion per year (Hutton and Varughese, 2016). This amount is nearly four times the average investment needed to accomplish the same objective in rural areas of other low- and middle-income regions (ibid.).

The nature of this substantive funding challenge is also evolving as primary focus shifts from constructing new infrastructure, which has historically dominated government and donor interests, to operating and maintaining what already exists. By 2030, recurring water service delivery costs that are typically planned to be covered with tariff revenues will be an estimated 1.6 times higher than one-off capital costs that have traditionally been resourced from tax and donor funds (ibid.). Yet only around five percent of African countries are reportedly able to fund more than 80 percent of recurring rural water supply costs with tariff revenue (World Health Organization, 2019). The most recent estimates suggest fewer than three in ten rural households on the continent pay for water (Afrobarometer, 2022, Foster and Hope, 2017). Enhancing user payments for rural water services is a clear and urgent prerequisite to realising SDG 6.1 in rural Africa and is thus a core motivation for this project. The remainder of this chapter addresses why a special interest has been taken in piped water and concludes with a descriptive outline of the thesis.

The magnitude of SDG6.1 compounded with macro-level demographic and climate trends necessitates a shift in conventional engineering, management, and economic paradigms (Sadoff et al., 2020). While private boreholes and other forms of self-supply or water vending can be employed towards reaching SDG 6.1 in rural areas, piped supply is often considered the most effective, efficient, and resilient way to deliver safe and reliable services on premises (Milman et al., 2021). User and revenue bases must be condensed and moderately sized for piped water to be economically viable, limiting its applicability in sparsely populated areas. However, transitional population centres outside of traditional urban areas are suitable for small to medium-sized piped water schemes (Humphreys et al., 2018). Such settings are anticipated to be a focal point for planning and delivering municipal services in Africa over the coming decade as an increasing majority of the rural population relocates to large villages and small towns (Güneralp et al., 2017, UN-Habitat, 2020). Furthermore, as global temperatures vary, extreme weather events such as droughts, flash floods, and severe storms threaten the quantity and quality of surface and groundwater sources and the physical infrastructures that supply drinking water to rural residents (Howard et al., 2016). Piped services, particularly those that rely on groundwater and incorporate treatment processes, are considered more resilient to water supply and quality shocks due to climate change than alternatives (Luh et al., 2017).

By nature of their design and construction, piped supplies have the potential to deliver safe water in close proximity to users and can integrate a variety of waterpoint types including taps or standpipes in dwellings, yards, shared plots, or public spaces (UNICEF and World Health Organization, 2021). These distinct physical characteristics can yield socioeconomic returns. Time savings afforded by standpipes and household connections that decrease the distance travelled and time spent fetching water, which has been valued at roughly 50 percent of after-tax wages (Whittington and Cook, 2019), can promote well-being and economic development of rural African households (Bisung and Elliott, 2018) and of women and girls (Winter et al., 2021b). Piped systems generally supply higher quality water than alternatives at the point-of-collection (Bain et al., 2021) and are thought to reduce storage duration and hence protect water quality and health at the point-of-use, despite some evidence to the contrary (Winter et al., 2021a, Wolf et al., 2022). Systematic review and meta-analysis efforts have found extending treated, piped services onto household premises reduces incidence of waterborne and water-washed diseases and growth stunting (Overbo et al., 2016), yielding the largest decrease in childhood diarrheal illness of any water supply intervention (Wolf et al., 2018). On aggregate, universal access to piped services and sewer connections across sub-Saharan Africa has been estimated to yield as much as USD $65 billion annually in improved health and productivity (Hutton et al., 2007).

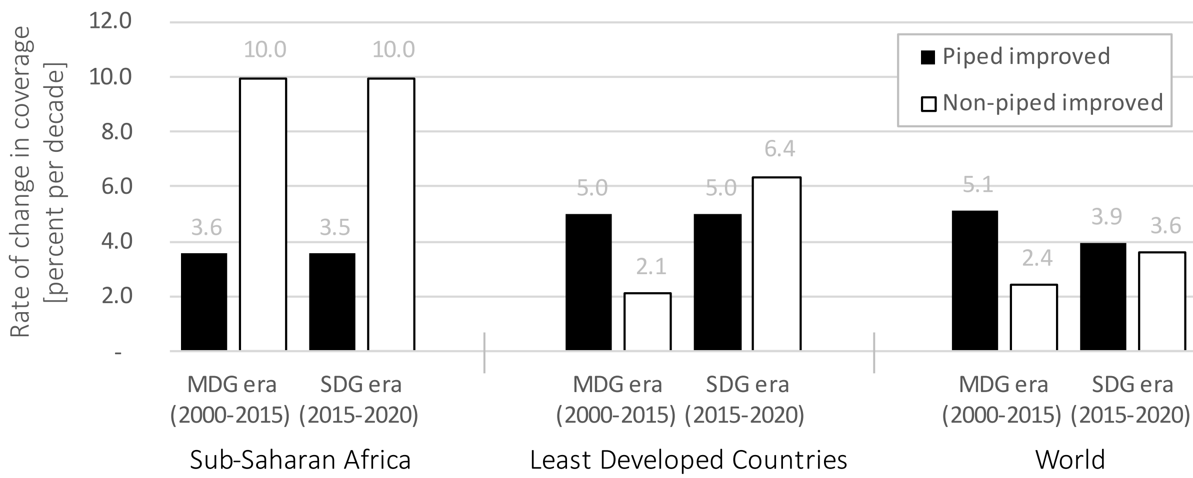


Figure 1.1. Rate of change in rural improved water coverage with piped and non-piped services in selected regions between the first five years of the SDG era and the preceding fifteen-year Millennium Development Goal (MDG) period, when household-level access was not emphasised. Improved drinking water sources are those which, by nature of their design and construction, have the potential to deliver safe water. Estimates are in percent per decade. (UNICEF and World Health Organization, 2021)

Despite these recognised advantages, the global pace of extending piped water services into rural areas has remained moderate and unchanged for two decades (Figure 1.1). Five years into the SDG era, the goals do not yet appear to have catalysed rural piped water investments in sub-Saharan Africa, least developed countries, or the world. Notably, piped water expansion in rural Africa lags behind other least developed countries and investments in non-piped infrastructure continue to outpace piped services. Slow progress has persisted in part due to the investment risk associated with high capital expenditures and uncertain financial returns in poorly regulated environments (Alaerts, 2019). Fundamentally, effective planning and delivery of both piped and non-piped drinking water services in rural Africa is hindered by limited and unreliable information.

Water service data pertaining to user demand and operational financing are biased to urban settings (Andres et al., 2019). Without clear and empirically grounded plans for recouping costs of delivering services in rural areas, African governments often adopt a least-cost logic that prioritises coverage with non-piped infrastructure over sustainability and allocates ongoing risks to local communities. Alternatively, when piped water is considered, investments are planned and financed under an urban paradigm transferred from the Global North (Braadbaart, 2012). The complex seasonal water use and payment behaviours of rural households are particularly not well understood (Elliott et al., 2019, Hoque and Hope, 2018), and unrealistic demand and revenue assumptions are seldomly realised. Both approaches have resulted in a status quo of sub-standard drinking water service in rural Africa. As socio-climatic interactions converge across the continent (Conway and Schipper, 2011), rainfall-related demand and revenue variability pose a potentially increasing financial threat. Improved understanding of how piped waterpoint types and tariff approaches influence seasonal demand and revenues in rural Africa is needed to enhance viability and resiliency of drinking water services and ultimately to realise SDG 6.1 on the continent. New information flows from professional service providers (McNicholl et al., 2019) can help reframe the conventional calculus by revealing the preferences of rural water users and enabling services to be delivered in a manner that adds value, unlocks payment behaviours, and mitigates financial threats (Hope et al., 2020).

1.2. Thesis Structure

The first chapter of this thesis introduces the rationale for investigating seasonal revenue patterns of piped water services in rural Africa, which is the primary aim of the project. Chapter two presents a survey of the literature that inspires this aim. Section 2.1 explores institutional arrangements for piped water in rural Africa and highlights opportunities afforded by the emergence of professional service delivery models. Section 2.2 summarises why and how user payments are the platform for sustaining services. The literature reviewed in section 2.3 illustrates how further research and evidence on seasonal demand for piped water may enhance financial viability and climate resiliency. The chapter concludes by identifying specific knowledge gaps which focus the research.

The thesis then turns towards the project's aims and methods. Chapter three first defines overarching and key questions (KQs) of the research in response to knowledge gaps identified in chapter two. Each research question has been addressed in a separate peer-reviewed publication and the remainder of the thesis is structured around these papers. Section 3.2 describes a stepwise analytical approach taken over the course of the three studies. Data collection, management, and cleaning steps are discussed in sections 3.3 and 3.4 as well as the regression and clustering approaches applied in the second and third papers. Ethical considerations and specific limitations to the research are outlined in section 3.5 and 3.6, respectively. Section 3.7 clarifies the nature of collaborations and division of responsibilities with other individuals who have contributed to the three studies and corresponding papers.

Chapter four is comprised of the first paper in the project and is co-authored with Callum Munday (University of Oxford, School of Geography and the Environment) and Rob Hope (University of Oxford, Smith School of Enterprise and Environment). The study explores how interactions between operational factors and seasonal rainfall affect water usage from rural piped schemes in Kenya, Malawi, Tanzania, and Uganda (KQ1) and how these patterns can warn of a threat to sustainability. The paper is published in the February 2021 edition of *npj Clean Water* (Armstrong et al., 2021).

Chapter five is comprised of the second paper in the project and is co-authored with Ellen Dyer (University of Oxford, School of Geography and the Environment), Johanna Koehler (Vrije Universiteit Amsterdam, Institute for Environmental Studies), and Rob Hope. The study seeks to understand how intra-seasonal rainfall dynamics affect revenue patterns of observed piped water services in rural Ghana, Rwanda, and Uganda (KQ2). It explores several rainfall metrics which are useful for characterising seasonal revenue variability and whether tariff level, connection type, and payment approach influence seasonal revenue patterns. The paper is published in the September 2022 edition of *Global Environmental Change* (Armstrong et al., 2022a).

Chapter six is comprised of the third and final paper in the project and is co-authored with Rob Hope and Johanna Koehler. The study examines how different piped water infrastructure types and payment approaches affect revenue patterns across service area archetypes in rural Ghana, Rwanda, and Uganda (KQ3). It also explores implications of the findings for piped water investment strategies in sub-Saharan Africa. The paper is published in the July 2022 edition of *Environmental Research: Infrastructure and Sustainability* (Armstrong et al., 2022b).

Chapter seven synthesises the research and concludes the thesis. The original empirical and methodological contributions of the three individual papers are summarised in section 7.1. Section 7.2 then explains the implications of these findings for policy and practice and makes specific recommendations. Finally, section 7.3 outlines directions for future studies to build on this research.

Chapter 2: Survey of Literature

2.1. Scope

This chapter surveys the literature relevant to expansion of safe and reliable piped water services in rural Africa. It first examines the institutional landscape, highlighting opportunities for addressing chronic challenges in theory and practice. It then reviews the state of knowledge regarding revenue from user payments, which is situated within a broader discussion of funding and finance for water services in rural Africa. The literature that is pertinent to household demand for rural water services is summarised to illustrate the influence of seasonal use of multiple water sources. Although bodies of literature pertaining to water security, water resource management, water quality, and sanitation and hygiene service delivery are relevant to the project in a holistic sense, they are not reviewed in this chapter. Furthermore, due to the empirical nature of the project, theoretical literature is highlighted but not covered at depth. The chapter closes by defining explicit knowledge gaps which have framed the project.

2.2. Institutional Arrangements

Institutional models for piped water in rural Africa are historically rooted in community management. The paradigm emerged in the late 1980s (Arlosoroff et al., 1987, Churchill et al., 1987) and was a cornerstone of the influential Dublin Statement on Water and Sustainable Development (ICWE, 1992). Its participatory agenda coupled with a strong focus on user contributions has since become entrenched in rural water policy across the continent and the world (Schouten and Moriarty, 2003), driving norms for planning, design, and delivery of projects and services. Community management is underpinned by a premise that, due to proximity and vested interest, water users are better positioned to make decisions about water supplies than governments or donors and therefore should lead in investing, organising, maintaining, and providing oversight (Briscoe and de Ferranti, 1988). Non-local actors are meant to shift from direct service provision to facilitation, leveraging the preferences, abilities, and financial resources of local stakeholders to sustain services (ibid.). In practice, this means governments plan and fund infrastructure with support from donors, then monitor and regulate services while most responsibility for managing and funding ongoing operation and maintenance is delegated to communities.

In the absence of external technical, administrative, and financial support, community management of rural waterpoints has been linked with service outcomes that are less than desirable (Foster, 2013, Hutchings et al., 2015, Sara and Katz, 2010, Whaley et al., 2019, Whittington et al., 2009). Evidence from national-scale monitoring initiatives in six African countries indicates cross-sectional non-functionality of rural, community managed piped schemes varies widely across administrative regions but can reach as high as 60 percent and is similar to that of non-piped waterpoints (Banks and Furey, 2016, Cronk and Bartram, 2017). Declining performance has also been reported across rural community managed piped schemes in India (Reddy et al., 2010), Nicaragua (Borja-Vega et al., 2017), Columbia, and Bolivia (Cannon, 2021).

In light of this mediocre track record, the effectiveness and ideological fit of community management in the rural water sector are subjects of ongoing debate (Harvey and Reed, 2006, Hope, 2015, RWSN, 2010, Whaley and Cleaver, 2017, Whaley et al., 2021). There is a consensus among academics and practitioners that the deficiencies of the model relate more to institutional design than resources or skills. In shifting responsibility from national to local, community management allocates operational and financial risk to individual communities who are unable to take advantage of economies of scale. Information asymmetry masks realities and separates water users from government and private sector actors leading to slow repairs and long periods of downtime with limited accountability and recourse (Hope et al., 2012). Misinformed and uncoordinated services result in neighbouring waterpoints competing for scant revenue (Koehler et al., 2015) and seldomly provide a level of quantity, quality, accessibility, and reliability for which users value and will pay (Hope, 2015, Hope and Ballon, 2019, 2021).

Effective management of drinking water supplies, whether piped or non-piped, involves operating and maintaining infrastructure, collecting revenues, administering finances, monitoring and ensuring regulatory compliance, and engaging in strategic business planning (Baietti et al., 2006). As rural piped schemes increase in technical complexity, these ongoing responsibilities are at times contracted to private operators (Kleemeier, 2010) or assumed in part or in full by public or private utilities (Adank et al., 2021). However, performance of piped services managed by private operators and utilities is historically tenuous and is often no better than that of community managed and non-piped services (Prasad, 2006). Globally, an estimated one in five piped schemes managed by utilities provides intermittent service, supplying an average of just 12.5 hours of service per day (Kumpel and Nelson, 2016) and posing risks to domestic affordability and public health (Bivins et al., 2017, Mitlin et al., 2019). Moreover, as much as 40 to 50 percent of water supplied by utilities is lost as nonrevenue water due to leaks, illegal connections, metering errors, and unpaid water bills (Kingdom et al., 2006). Build-operate agreements that allow private operators to assume responsibility for drinking water infrastructure prior to construction may enable a more flexible, entrepreneurial approach to be taken during planning and delivery (Bhatnagar et al., 2017), leading to enhanced service quality and viability yet often at higher tariff rates (Davis, 2005).

These known operational challenges, together with the shortcomings of community management and the steady expansion of piped water into rural areas, have motivated exploration of alternative approaches that distribute responsibility between public and private stakeholders (Hutchings, 2018, Kleemeier and Lockwood, 2012) and are oriented toward professionalisation and long-term service delivery (Lockwood and Smits, 2011, Moriarty et al., 2013). Cultural theory (Douglas, 1992) offers insight into service delivery approaches which facilitate such cooperation and risk-sharing, particularly concerning the service level and payment preferences of rural water users and systems of values that connect institutions (Rayner, 1991, Wildavsky, 1987). Applying the theory to rural handpumps maintained by a private service provider in Kenya, Koehler and colleagues (2018, 2021) demonstrate how pluralist arrangements which allow bureaucratic, market, and community management cultures to co-exist can facilitate improved service levels, information flows, and finance. This so-called rural waterpoint management culture framework has not been empirically applied to piped services.

In pluralist governance arrangements, disagreements inevitably arise between stakeholders who conform predominantly to opposing management cultures. Potential stalemates can be avoided by “clumsy solutions” that iteratively and creatively combine seemingly irreconcilable perspectives to define and resolve wicked problems (Ney and Verweij, 2015). Antireductionist management arrangements that enable public-private partnership contracts to be tailored through iterative processes appear promising for piped water supplies in small towns (Schwartz and Tutusaus Luque, 2019). Cleaver (2012) describes this approach as forming institutions through “bricolage”, or the patching together of old norms, reinvented traditions, and new arrangements under legitimately recognised authority.

With advancement and practical application, these theories hold potential for addressing the basic institutional conundrums that impede and impair piped water supply in rural Africa. Hope et al. (2020) argue institutional arrangements that network drinking water infrastructure, management responsibilities, and information at scale may help to overcome evolving challenges. Professional service providers operating and maintaining an exclusive portfolio of water supply infrastructure can take advantage of economies of scale while being held accountable for service outcomes (ibid.). Such arrangements enable the idiosyncratic operational and financial risks of individual water service areas to be pooled and shared appropriately across government, private sector, and community actors (Koehler et al., 2018). Networked services can also reduce information asymmetry and enhance transparency between water users and authorities during planning and delivery, notably by taking advantage of the increasing cost-effectiveness and reach of information and communication technologies such as mobile data collection, smart water meters, and *in situ* sensors (Hope et al., 2012, REAL-Water, 2022, Thomson, 2021).

2.3. User Payments

The drinking water sector is funded by a mix of public and private revenues, some of which need to be repaid (Goksu et al., 2017). Nonrepayable funding for water is obtained from domestic tariff and tax revenues and grant-based transfers from donors, with tariffs or user payments traditionally being the most reliable source (Winpenny, 2003). When these funds are insufficient to meet needs, investments are pre-financed with concessional loans provided at low interest rates and private commercial loans offered at market rates which must be repaid from revenues generated by user payments.

The UN-Water's periodic global analysis and assessment of sanitation and drinking water (GLAAS) report provides some insight into the relative significance of these different funding sources. In the countries that voluntarily participate in the GLAAS survey, half of which are low and lower-middle income, domestic tax revenues have consistently accounted for one quarter of funding for all water, sanitation, and hygiene related expenditures (World Health Organization, 2019). Repayable finance, the majority of which comes from concessional loans, constitutes less than ten percent of funding and international grant-based transfers less than five percent (ibid.). Strikingly, water users globally contribute two thirds or more of all expenditures on water, sanitation, and hygiene through tariffs (ibid.). Furthermore, the level of domestic private funding from households is underestimated because it is predominately based on national surveys which collect data on regular payments made to service providers for primary drinking water sources. Irregular payments, expenditure on secondary sources, and investments in self-supply are typically not included and therefore these estimates do not capture households' full out-of-pocket expenses (Fischer et al., 2020, Vedachalam et al., 2017). Although the exact amount of household expenditure on water is not well understood, particularly in rural areas of low- and middle-income countries where reliable data is largely unavailable, the relative contribution to the sector's funding blend is substantial (Danert and Hutton, 2020).

Revenues from water user payments are vital for funding recurring operation and maintenance as well as reducing the risk of investment in a historically under-funded sector. In spite of steadily increasing trends in national budget allocations and official development finance to water during the period of the Millennium Development Goals (Winpenny et al., 2016), the average USD $1.4 billion spent per year on rural water supply globally over the past two decades is more than an order of magnitude lower than what is needed to extend and sustain household-level access to all rural populations in the foreseeable future (World Bank and UNICEF, 2017). The current rate of spending in sub-Saharan Africa is also well under the estimated need. Total expenditure as a percentage of gross domestic product on water, sanitation, and hygiene in the 22 African countries that have responded to the GLAAS survey, excluding domestic tariffs, is more than two and a half times less than the estimated capital expenditure required to achieve SDG 6.1 and 6.2 targets (Hutton and Varughese, 2016, World Health Organization, 2022). Although low levels of spending are partially reflective of national priorities and local public funding allocations (Humphreys et al., 2018), it is widely accepted that funding flows to the water sector are inadequate.

Awareness of the water sector funding gap and how it might be addressed is not new or debated. A consensus that existing tax and tariff resources should be used more efficiently and leveraged to attract non-traditional sources of repayable finance has existed for over two decades (Winpenny, 2003). It has been envisioned that these steps would stabilise the domestic funding base while attracting commercial finance into the sector, enabling various financial streams to be blended in a way that achieves national and international development priorities (Money, 2018). However, commercial finance for water supply infrastructure in low- and middle-income countries has essentially failed to materialise despite a steady sector-wide effort (Akhmouch and Kauffmann, 2013, Alaerts, 2019). This is in part due to the intrinsic risk profiles of water infrastructure investments made over long time horizons and low profit incentives associated with relatively small projects, high transaction costs, and limited economies of scale (Alaerts, 2019, Machete and Marques, 2021). Chronically weak regulatory and enabling environments in developing economies limit capacity to absorb commercial finance and prepare viable proposals (Alaerts, 2019).

Better fiscal planning, clear policy and regulatory incentives, and stronger enforcement mechanisms are needed to improve financial performance of service providers and create a credit worthy environment for private investment over the long term (OECD, 2018, Pories et al., 2019). Macrolevel climate and demographic trends may eventually facilitate a convergence of water and financial sector interests, resulting in synergistic opportunities for commercial finance (Alaerts, 2019). In the near term, concrete priorities to address the SDG 6.1 funding gap are to realise operational and financial efficiencies and to increase revenues from user payments by improving service outcomes and raising tariffs in an equitable manner (Goksu et al., 2017).

User payments have been linked to sustainability of rural handpump and piped water services (Cronk and Bartram, 2017, 2018, Evans, 1992, Foster, 2013, World Water Council, 2004) and are widely relied upon in cost recovery policies across Africa (African Development Bank, 2010a, African Development Bank, 2010b) and the world (Dole, 2006, Inter-American Development Bank, 2013). Despite this emphasis and the relative importance of tariffs in the water sector's overall funding mix, only one in twenty African countries report an ability to cover most of their recurring rural water supply costs with revenue from user payments (World Health Organization, 2019). McNicholl et al. (2020) quantify the average amount of this shortfall across services provided by five agencies operating in four African countries at roughly $0.69 per person per year. In rural areas predominantly served by poorly regulated, shared waterpoints, it is not feasible to cover such tariff deficits with supply- or demand-side subsidies such as are pervasive in urban settings (Andres et al., 2019). Subsidies are therefore seldomly delivered where they are most needed (ibid.). Consequently, the combination of inadequate cash-on-hand and inability to access capital hinders construction, expansion, and repair of water infrastructure and has created a substantial deferred maintenance problem, increasing the likelihood of failures and service outages (Milman et al., 2021).

Numerous interrelated factors work to counteract the sufficiency of rural water user payments. Historically, governments have set tariff levels below what is needed to cover basic operation and maintenance because cost recovery goals exist in tension with political agendas and tariff strategies that are intended to protect poor populations (Andres et al., 2021, Leigland et al., 2016). As discussed in the previous section, institutional responsibilities are often ambiguous and unsupportive, leading to a paucity of incentives to adhere to established policies involving life-cycle cost analysis, tariff setting, and payment collection (Harvey, 2007). Weak enforcement is exacerbated by the fact that rural community-based management entities, who are often unpaid volunteers, frequently lack the professional skills to administer appropriate payment rules (World Bank, 1999). Service areas are also geographically dispersed, which increases costs associated with payment collection and hinders accountability and transparency. In addition, monitoring systems are inadequate to enable effective regulation of tariff setting and payment collection. Benchmarking of rural service providers in a similar manner as urban utilities (Banerjee and Morella, 2011, Danilenko et al., 2014) has not been feasible because high-quality longitudinal records are rare (Andres et al., 2019). The combination of poor coordination, operational inefficiencies, and inadequate services lead to low user satisfaction and competition with free waterpoints, which in turn diminishes willingness to pay (Koehler et al., 2015). The collective result is that service providers and users alike are disincentivised to engage in payment collection, and fewer than three in ten rural African households pay for water (Afrobarometer, 2022, Foster and Hope, 2017).

The most common approaches for collecting payments for rural community managed handpumps in sub-Saharan Africa are reactive contributions, fixed weekly, monthly, or annual fees, and volumetric pay-as-you-fetch (PAYF) fees (Foster and Hope, 2017). Across the spectrum from common pool resource management to privately managed waterpoints, the institutional rules and technical controls of these conventional approaches carry varying degrees of excludability (Koehler et al., 2015) which affects revenue generation, operational performance, and social inclusion. Notably, Foster and Hope (2017) provide evidence from Kenya where the PAYF approach facilitates more revenue and less waterpoint downtime than fixed fees but is also associated with higher rates of unimproved water source use. Although these approaches are generally compatible across the spectrum of rural water supply infrastructure and service delivery models, expansion of piped services into rural communities and households is often accompanied by an interest in payment modalities that are perceived as more robust.

Prepaid credit systems have been used to collect user payments for water services provided by African utilities since the 1990s (Heymans et al., 2014), and are becoming commonplace in deliberations regarding rural piped water expansion in low- and middle-income countries. In theory, the approach can address many of the aforementioned challenges by reducing or eliminating manual cash transactions. The technology allows users to purchase electronic or physical credit on mobile devices, from vendors, or at automated credit dispensing stations, and redeem at a preferred waterpoint and time. Compared to conventional approaches, systems that employ mobile-based payments and automation have potential to enhance revenue collection efficiency while minimising labour costs by reducing the need for standpipe attendants and payment collection activities (ibid.). The approach can also foster non-cash benefits such as reduced loss to unregulated third-party vendors, enhanced operational data collection, and better targeting of vulnerable populations for welfare support programmes (Hope et al., 2012, Thomas, 2018).

Several drawbacks of prepaid credit payments have been observed in Kenya (Guma and Wiig, 2022) and Tanzania (Komakech et al., 2020). The hardware and software can be unreliable, and limited accessibility of and capacity to utilise the digital data can negate any planning benefits. Even when the additional hardware and data transfer costs associated with the approach are anticipated, the burden of recurring costs borne by intermediate vendors and users such as mobile money fees and purchasing physical cards or tokens can be underestimated or overlooked. Financial returns afforded by anticipated labour and revenue collection efficiencies must be weighed against these hard costs and any social equity risk due to limited access to and affordability of the credit-based payment modality. In general, rigorous evaluation and transferrable evidence of the prepaid credit approach is rare, and financial models that compare prepaid credit and conventional payment systems for deployment in rural water services rely on unsubstantiated assumptions regarding demand response, collection efficiency, and hardware durability.

2.4. Domestic Water Demand

Water services are characterised by attributes that influence the sources users choose, how much water they collect and pay for, and ultimately how much revenue is generated. Rural households in low and middle-income countries often have access to multiple water sources with varying levels of quantity, quality, accessibility, reliability, and price (Hoque and Hope, 2018, Thomson et al., 2018), and optimising between them for different uses can yield time and money savings and resiliency against climate shocks (Elliott et al., 2019, Kohlitz et al., 2020, van Koppen et al., 2020). When seeking to anticipate and enhance user payments in this context, it is most vital to understand the determinants of the source choices households make (Nauges and Whittington, 2009). Due to methodological challenges particular to the setting (Nauges and Whittington, 2009, Wagner et al., 2019), relatively few studies have attempted to develop discrete choice models for rural water sources. However, cases drawing on water use data from India (Briscoe et al., 1981), Benin (Gross and Elshiewy, 2019), and Kenya (Mu et al., 1990, Wagner et al., 2019) agree that proximity, reliability, aesthetics, and price are important factors in the source choices of rural households.

A related body of research is interested in understanding how service attributes influence payment preferences and behaviours of rural water users. Service delivery arrangements that are perceived as more reliable have been positively associated with user payments (Hope, 2015, Hutchings et al., 2017, Koehler et al., 2015, Koehler et al., 2018). Collective payment behaviour for community managed handpumps influences that of individual households, and it appears that stable revenue streams can be achieved when a critical mass of around 60 percent of households contribute regularly (Foster, 2017). Koehler et al. (2015) provides evidence that rural households are less likely to pay for water the further the source is from their residence, especially when alternative water sources are nearby. Low maintenance response time (Hope, 2015) and water quality aesthetics (Foster and Hope, 2016), have also been found to enhance payments. However, Hope and Ballon (2019, 2021) find that demand for proximity, reliability, and water quality can vary across education, wealth, and gender classes, and users are at times willing to make trade-offs for lower prices. Notably, with the exception of the work documented by Hutchings et al. (2017), the evidence of rural water user payment behaviours reviewed here is based entirely on research conducted in two counties in Kenya.

For rural households collecting water off premises, distance to the source is commonly thought to be an important determinant for quantity of water collected, at least to a point within a 30 minute round-trip (Cairncross and Feachem, 2018). This paradigm has been widely adopted and operationalised in practice, even to the point of influencing the global drinking water agenda (UNICEF and World Health Organization, 2021). However, a recent systematic review suggests the strength and effects of the relationship should be further investigated due to inconsistency in study outcomes (Cassivi et al., 2019). Few studies have analysed the effects of household level connections on quantity of domestic water used, hygiene behaviour, and use of multiple water sources (Overbo et al., 2016), reflecting a consequential knowledge gap. Without empirical grounding, rural water infrastructure investments can be planned and financed based on inflated assumptions about the relative demand for service level improvements (Davis et al., 2001).

The influence of rural water infrastructure and pricing decisions on demand and revenue from user payments can be evaluated via water demand studies (Nauges and Whittington, 2009). Estimates of own-price elasticity of demand for drinking water services in cities and small towns (ibid.) and rural communities (Gross and Elshiewy, 2019, Wagner et al., 2019) globally, which range from -0.3 to -0.6 and can vary on an intra- and inter-annual basis (Grafton et al., 2011), have been used to anticipate demand responses to tariff increases. This range indicates, in theory, that it is at times possible to increase localised revenues by raising tariff levels. Although tempered by evidence that hypothetical responses differ from actual payment behaviours (Griffin et al., 1995), there is also a growing body of literature on households' stated preferences of willingness to pay for improvements in water access in low- and middle-income countries, with estimates ranging from USD $3 to as high as $30 per month across a wide variety of contexts (Van Houtven et al., 2017). Despite this evidence, uncertainty around whether users can afford tariffs priced to cover recurring costs persists, particularly in rural areas (UNICEF et al., 2021).

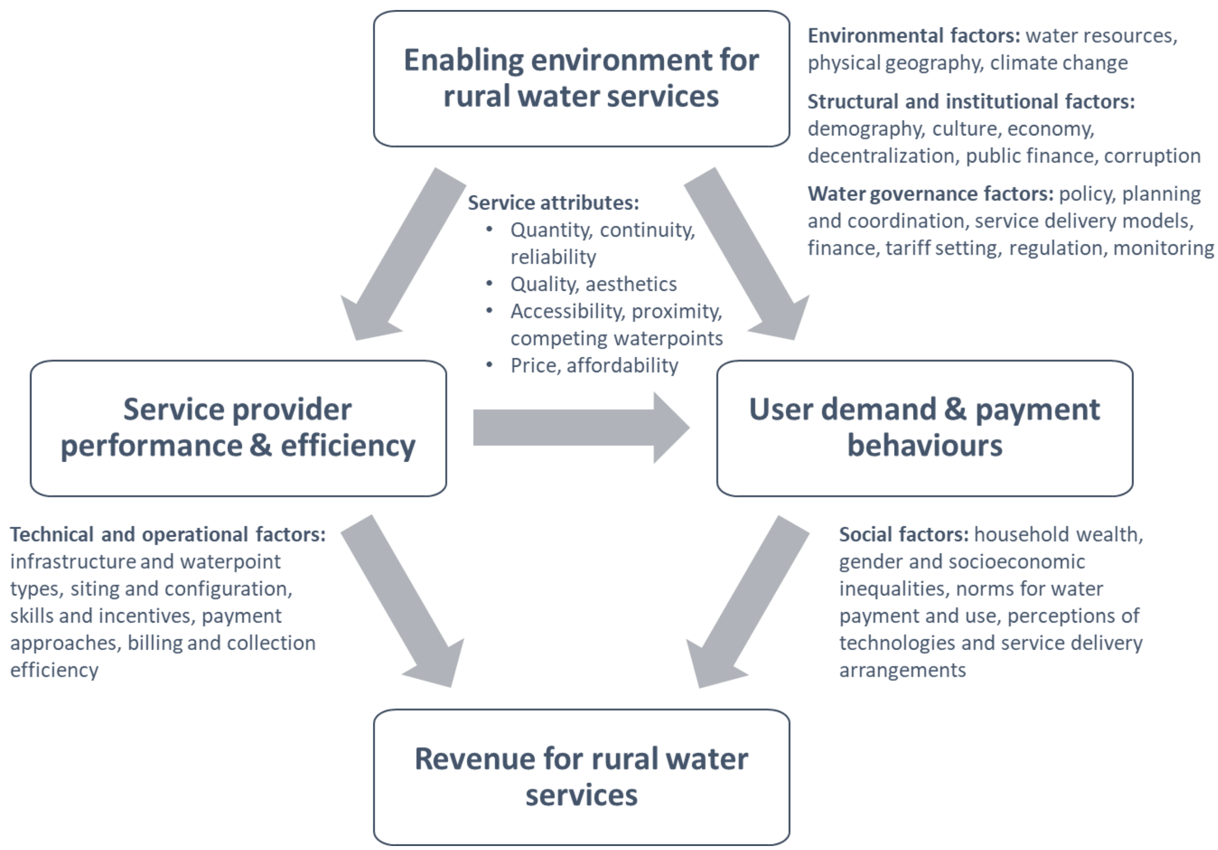
The availability of many types of rural water sources is influenced by seasonal rainfall. During wet periods, harvested rainwater and rain-fed surface and shallow groundwater sources may be more convenient and affordable than other water services. Higher concentrations of contaminants are also likely during the wet season in sources impacted by surface runoff (Kostyla et al., 2015). Seasonal variability in water source quantity and quality can affect domestic source choices on a cyclical basis, which in turn influences demand and revenue for professional water services. Studies that investigate seasonal dynamics commonly draw on cross-sectional datasets and utilise a binary, often subjective wet/dry classification. This hides presumably important nuances about onset, duration, and intensity of dry and rainy periods (Wainwright et al., 2021). Relatively few analyses have combined longitudinal data to explore the inverse relationship between rainfall and use of rural waterpoints (Kulinkina et al., 2016, Thomas et al., 2019, Thomas et al., 2021, Thomson et al., 2019). Of these, two studies evaluate water demand dynamics on an intra-seasonal basis, finding that handpump use increases by 23 percent in weeks following weeks when no rainfall occurs (Thomas et al., 2019) and decreases by 68 percent on days immediately following a heavy rainfall event (Thomson et al., 2019). Reduced handpump usage during wet seasons has been associated with lower user payments in several sub-Saharan countries (Foster and Hope, 2016, 2017, Kelly et al., 2018), but the extent of the relationship in the context of piped water in rural Africa, although widely acknowledged in practice, is an emerging subject for academic research and is not well understood.

2.5. Knowledge Gaps

While exploring the challenge of delivering financially viable piped water services in rural Africa at a scope and scale inspired by SDG 6.1, this chapter has highlighted the criticality of enhancing revenues generated from user payments. It has also identified gaps in knowledge of how rural piped water revenues are influenced by environmental, institutional, technical, and social factors. The works that have been cited suggest numerous characteristics of the enabling environment for rural water services, the public and private agencies providing the services, and the populations served affect how rural water services are delivered, accessed, and paid for. Figure 2.1 illustrates conceptual path dependence between categories of factors which the student has assessed as being most critical regarding revenue generation for rural water services. This framework is revisited in the discussion of the project’s data sources and analytical approach in chapter 3.

Although the relationships depicted in Figure 2.1 are supported by the literature, few studies have analysed revenue from user payments in the niche rural piped water domain and none have attempted to do so across multiple sub-Saharan countries. There is a general urban bias in the water supply literature, especially regarding performance benchmarking and water demand and source choice studies. Reflecting the predominant paradigm in Africa toward the turn of the century, rural water research from the past three decades has focused on handpumps while piped services, particularly those delivered on household premises, have been understudied. Furthermore, multi-country analyses across spatial and seasonal dimensions are needed to advance beyond current local narratives.

Figure 2.1. Factors that influence revenue for rural water services (student's assessment)



These evidence and knowledge gaps have allowed assumptions which prioritise ineffective approaches to endure despite perpetuating low revenues and poor service outcomes. Multiple water source use, including that which involves seasonal rain-fed sources, is particularly misunderstood and is neglected in planning cycles. The rainfall-related threat to rural piped water revenue has not been explored in the literature. A key knowledge gap is whether reliable piped water services provided on household premises, which are at least as convenient as rain-fed sources during the wet season, can stabilise willingness to pay for the primary service and reduce seasonal revenue variability relative to off-site waterpoints. Limited and poor-quality data poses methodological challenges, but the emergence of professionalised service delivery models has yielded new operational and financial information flows which can be exploited to address these gaps. Clearer understanding of the relationship between service attributes and the demand and revenue patterns of piped water services can address gaps in evidence and knowledge and inform viable and resilient infrastructure investments in rural Africa.

Chapter 3: Aims and Methods

3.1. Research Aims

The aims of this project have evolved in response to the knowledge gaps articulated in section 2.5 and assessment of the analytical power of the project's dataset. The steps that have been taken to define and address these aims are described in the following sections of this chapter.

Ultimately, this project has aimed to answer the research question: How do seasonal patterns of domestic water use and payments affect revenue from piped water services in rural Africa? This aim has been addressed through the pursuit of three key questions:

KQ1: *How do interactions between operational factors and seasonal rainfall affect water usage from rural piped schemes in East and Southern Africa?*

KQ2: *How does intra-seasonal rainfall affect revenue patterns of piped water services in rural Ghana, Rwanda, and Uganda?*

KQ3: *How do different piped water infrastructure types and payment approaches affect revenue patterns across service area archetypes in rural Ghana, Rwanda, and Uganda?*

3.2. Methodology

Drawing on the student's decade of prior field experience and professional network in the rural water sector, a mixed methods approach has been adopted to clarify and address the research aims. Empirical datasets have been identified, combined, and cleaned through iterative stakeholder interviews. The full dataset has been analysed to identify patterns which have been examined at depth via the key research questions in three studies. Table 3.1 summarises the methodology and how elements have evolved over the course of the project. The methods employed for data collection and analysis and logic followed to define the research questions are described in sections 3.3 and 3.4.

Table 3.1. Elements of the Methodology

Element	Description and Methodological Implications	Timeframe
1. Prior professional experience	The student's professional network in the rural water sector has provided access to key actors and awareness of data availability in multiple geographies across Africa, Asia, and Latin America.	2008 to 2019
2. Stakeholder interviews	Iterative discussions with piped scheme operators have informed and honed the research questions, clarified the scope of data availability, and informed the data validation and cleaning methods.	January 2020 to December 2021
3. Database design	The database design has established an enabling structure and format for panel data collection and analysis.	January 2020 to March 2020
4. Operational data collection	Bilateral data use agreements have facilitated operational data collection and provided an empirical basis for the project.	March 2020 to October 2020
5. Preliminary data analysis	Preliminary examination of descriptive statistics and variances has informed data validation, cleaning, and regression methods and revealed geographies, variables, and patterns of interest.	April 2020 to December 2020
6. Research questions	Articulation of primary and key research questions based on literature review, stakeholder interviews, and preliminary data analysis has directed subsequent analyses.	May 2020 to January 2021
7. Rainfall data collection	Collaboration with colleagues in the school of Geography and the Environment to access global rainfall datasets has enhanced the project's empirical basis.	July 2020 to October 2020
8. Rainfall data analysis	Exploration of inter- and intra-seasonal rainfall patterns of interest over various timescales has informed the analytical approaches taken in the first and second papers.	July 2020 to November 2021
9. Regression analysis	Several regression approaches have been explored and employed to determine associations between explanatory and outcome variables of interest while controlling for covariates.	February 2021 to October 2021
10. Study-specific analyses	Distinct analytical pathways have been developed to address the key questions. These include specification and construction of single and clustered variables, statistical analyses, and data visualisation.	July 2020 to November 2021

The original scope of the project tentatively included fieldwork to verify and explore the operational context of the dataset. However, as the project evolved during the COVID-19 pandemic, fieldwork became less critical and more impractical. Hence, no fieldwork has been conducted as part of the project. The implications of this are discussed as limitations of the research in section 3.6.

3.3. Data Collection

This section details the data collection methods employed throughout the project. The first sub-section describes the sources and types of data that have been utilised. The second sub-section summarises how the data have been managed during the project as well as expectations regarding future data storage and availability.

Data Sources

As a preliminary step in the data exploration process and in consultation with the piped scheme operators who would eventually provide data for the project, the student has assessed the availability of secondary datasets in public and proprietary repositories which might be utilised to explore relationships between the factors of interest illustrated in Figure 2.1. Although relevant indicators for many of the identified factors are available at the national level, the exercise has focused on disaggregated, localised datasets that might support analysis of causal linkages with revenue generated in geographically defined piped water service areas. The results of this assessment are summarised in Table 3.2. In general, operational datasets maintained by individual service providers in distinct locales pose the greatest analytical potential. The student is aware of reliable and homogenised data corresponding to these locations for only a few additional factors of interest. Specifically, satellite-based geospatial estimates of rainfall and population densities are readily available across most of sub-Saharan Africa. Subsequent data collection efforts have focused on these data sources.

Table 3.2. Availability of localised, secondary data related to factors that influence piped water revenue in rural Africa

Categories of factors[1]	Data Availability	Notes
Enabling environment – Environmental	○	Geospatial rainfall estimates are readily available but groundwater and physical geography data are sporadic and additional models are needed to estimate surface water resources
Enabling environment – Structural and institutional	○	Geospatial population density and urban proximity estimates are readily available but data regarding culture, public policy, and economy are sporadic
Enabling environment – Water governance	○	Water policy documents can be accessed but data regarding planning, coordination, service delivery, regulation, and monitoring in practice are sporadic
Service provider performance – Technical and operational	●	Reliable operational records are available from several service providers in distinct locales
Service attributes	○	Tariff data are available alongside service provider data but sub-national monitoring data are sporadic
User demand and payments – Social	○	Water usage data are available alongside service provider data but data regarding household socioeconomics, norms, and preferences are sporadic

[1]Conceptual relationships between these categories of factors are illustrated in Figure 2.1.

●: Reliable data are available in several countries for most factors in the category

○: Reliable data are available in several countries for a few factors in the category

The project dataset has been primarily compiled from secondary, longitudinal data maintained by six agencies that operate piped water services in rural areas of ten countries. Three of the agencies are international nongovernmental organisations that operate as social enterprises. The remaining three agencies are private companies that offer a range of engineering, construction, and management services. These agencies represent an emerging model of professionalised rural water management characterised by contractual arrangements with water users and government authorities under which sanctions are invoked when substandard services are delivered.

The full dataset covers roughly 5,500 waterpoints and represents services provided to more than half a million people spanning the years 2016 to 2020. In general, the dataset consists of the following:

- Service area characteristics (geolocations and jurisdictions, planning and implementation approach, installation dates)
- Financials (monthly revenues, tariff rates, payment modalities)
- Service levels (monthly waterpoint types and counts, volumes, scheme configuration details)

Furthermore, the data adhere to the following criteria:

1. Services cover rural or a mixture of rural and peri-urban areas
2. Infrastructure consists of small to medium-sized piped schemes covering one or multiple villages with metered on and off premises connections
3. Users make regular financial contributions
4. At least 12 concurrent monthly revenue and water volume records are available

The project also relies on two publicly available third-party datasets. Daily geospatial rainfall estimates from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) dataset (Funk et al., 2014) corresponding to individual piped water service areas over the range of dates present in the operator data (2016-2019) are utilised for seasonal classifications in the first and second papers. Estimates of the number of people residing in 1-arc-second-by-1-arc-second grid cells in 2019, available from the Humanitarian Data Exchange (Facebook Connectivity Lab and Center for International Earth Science Information Network (CIESIN) at Columbia University, 2016), are used to assess population density and degree of rurality of piped water service areas in the third paper.

Data Management

Operational data have been extracted, with permission, from proprietary online and offline electronic databases maintained by the participating piped water operators. Deidentified data have been transferred to a master database where additional transformations and aggregations have been performed. The master database contains separate databases for water service areas, geographic regions, financials, and service levels which are linked with a record identification number corresponding to unique piped water service areas (see field list in Appendix I). All data are documented with metadata that includes data source, access date, assumptions, explanations of naming codes and classifications, relationships between variables, transformations, and missing values. Third-party data have been transferred to additional, separate databases.

All spreadsheets and software files constructed throughout the project are stored in a secure and encrypted OneDrive for Business folder hosted by the University of Oxford's cloud-based Microsoft 365 service, Nexus365. Original data files and participating agency identifier information are stored in a separate folder than the master database and SPSS files, to which only the student has access. Version history of the master database is tracked by Nexus365.

Anonymised summary statistics of the data pertaining to specific analyses have been made available along with published manuscripts in accordance with protocols of respective journals. Otherwise, the research data has not been shared or discussed with any entity other than the student’s co-supervisors. The data will be stored in the locations described for at least three years after the date of publication of the project’s final paper, in accordance with the University of Oxford protocols. Since the assembled dataset holds long-term value to the public, the master database containing anonymised data will be preserved under controlled access in the UK Data Archive[1] and referenced in the University of Oxford's research archive[2]. Metadata describing the purpose, design and context of the project will be made available in a data catalogue. Original data files corresponding to individual participating piped water operators and identifier information will be permanently deleted.

3.4. Analysis

This section explains how data have been analysed over the course of the project's three studies. The first sub-section summarises the overarching analytical pathway that has been taken. It is followed by sub-sections that provide rationale and detail for specific clustering and regression techniques utilised in the second and third papers.

Overarching Analytical Approach

The project is based on the premise that rural piped water revenue can be enhanced with better understanding of the relationships between key factors pertaining to the enabling environment for rural water services, to service provider performance and efficiency, and to rural water user demand and payment behaviours. The data that have been collected to study these relationships are limited and are not experimental. Therefore, an analytical approach governed by fixed hypotheses could have resulted in confirmation bias and compelled the project to take an unproductive or erroneous direction. The research questions have instead been intentionally and sequentially crafted to allow the project to follow an inductive and stepwise analytical pathway.

[1] See https://www.data-archive.ac.uk/

[2] See https://ora.ox.ac.uk/

The assessment of secondary data availability summarised in Table 3.2 reveals that localised data for water usage and revenue can be accessed from piped operators but the potential to examine factors which might influence these outcomes varies by locale. It is neither feasible nor practical to adequately characterise the comprehensive enabling environment for rural water services in any sub-Saharan country with secondary data that are available. Rainfall and population density are the only factors related to the enabling environment that are known to be supported by existing longitudinal and geospatial data. Furthermore, harmonised data related to social norms and water user preferences are generally unavailable. Considering this along with evidence highlighted in the literature review, the most practical and influential lines of inquiry utilising the project's dataset appear to involve temporal rainfall and technical and operational factors associated with service provider performance. This realisation has led to the articulation of the overarching research question and to KQ1. The open-ended analysis of operational factors and rainfall described in paper one (addressing KQ1) has in turn informed more specific lines of inquiry and methods adopted in papers two (addressing KQ2) and three (addressing KQ3).

Subsets of the full dataset have been quantitatively analysed to address the research questions, and a consistent classification and cleaning approach has been utilised. All data have been harmonised to a common typology for infrastructures, tariffs, and payment approaches and unit revenues and tariff levels have been converted to 2019 US dollars at purchasing power parity for private consumption. This methodology is detailed in the respective research papers along with key assumptions and criteria for exclusion of revenue and water usage records. Additional steps pertaining to distinct geospatial, climatological, statistical, and regression analyses conducted in each study and utilisation of third-party datasets are also described in each paper. Esri ArcMap 10.8 has been utilised for all geospatial analyses, and all statistical analyses have been conducted in IBM SPSS Version 27.0.

Since the project has necessarily focused on factors which might be examined with existing data, the project dataset is prone to endogeneity from measurement bias and uncontrolled confounding variables. An attempt has been made to address time-independent heterogeneity through the clustering and regression methods applied in papers two and three. Of note, the analytical approach adopted in paper three accounts for unknown exogenous factors by evaluating revenue patterns across rural piped water service archetypes. These methods are discussed in greater detail in the following sub-section as well as in chapter seven, and limitations of the project arising from the influence of endogeneity are further described in section 3.6.

Archetype Analysis

The analytical approach of paper three, as well as paper two to a lesser extent, is aligned with a method known as archetype analysis in sustainability research. As an alternative to case-based research, this approach has been selected for its ability to collate findings from multiple cases while avoiding overgeneralisation (Sietz et al., 2019). Archetype analysis makes it possible to bridge 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 microscale phenomena to macrolevel processes (Adger et al., 2003). Archetype analysis in sustainability research has been increasing in popularity over the past decade (Oberlack et al., 2019, Sietz et al., 2019) and 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 until this project had not been adapted for rural water supply.

A systematic review of 53 studies by Oberlack et al. (2019) identifies three core features of the archetype analysis approach. The first two are reflected in paper two, and all three are incorporated into the methodology of paper three. First, recurring patterns of a phenomenon of interest are recognised across at least two cases. Individual cases share one or more attributes formulated in language that is sensible for policy and practice, for which configurations across a set of cases are able to describe system dynamics or causal effects. Patterns can be newly observed phenomena across large numbers of empirical cases, diagnostic tools that reflect established knowledge from prior research, or representative scenarios of future concern. Typical methods for pattern identification include meta-analyses, statistical analyses, system dynamics modelling, and participatory scenario development. Second, the phenomenon of interest is explained by multiple models under particular conditions. Rather than seeking to explain the phenomenon in all cases with a single, comprehensive model, archetype analysis identifies a suite of patterns to explain heterogeneity among cases. Third, attributes are abstracted and analysed at intermediate levels. Archetypes may be defined as either causal mechanisms or clusters of cases, and the appropriate degree of abstraction depends on the research purpose and methodology.

Details of how archetype analysis has been partially applied in paper two and fully applied in paper three are described in chapters five, six, and seven. Care has been taken to adhere to four quality criteria for archetype analysis as recognised in the literature (Eisenack et al., 2019). The first criterion is to specify the domain of validity for each archetype. The second criterion is to ensure that multiple archetypes can be combined in different ways to characterise single cases. The third criterion is to explicitly navigate through different levels of abstraction. The fourth criterion is to obtain a balanced fit between configuration of attributes, theory, and empirical evidence when constructing archetypes. In paper three, archetypes that represent cases of conceptual and empirical interest (fourth criterion) have been constructed at macro and micro contextual scales (third criterion) using clusters of piped water service areas with distinct and validated characteristics (first and second criteria). Recurring revenue patterns have been identified from descriptive statistics and regression effects across the archetypes as described in the next sub-section. Outcomes of interest in papers two and three have not been compared between groups because the findings of such an exercise would be limited to the nuanced context of the observed service areas.

Regression Analysis

In the second and third papers, parameter estimates from generalised estimating equations (GEEs) have been used to determine whether connection type and payment approach exhibit an association with revenue-related variables while controlling for tariff level. The GEE method (Zeger et al., 1988) has been selected over other regression approaches for two reasons.

First, the method assumes the effects of unknown and uncontrolled covariates are fixed or averaged across the observed population (Muff et al., 2016). Therefore, care has been taken when clustering data and interpreting results to minimise the influence of covariates. Rather than comparing regression results between groups which are subject to endogeneity, the studies have generally aimed to identify patterns from the regression results that are recurrent across groups of interest. The logic behind this approach is described in greater detail in the previous sub-section which focuses on the archetype analysis methodology.

Second, the monthly records in the project dataset 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. This is irrelevant for the analysis in paper two because regression in the study is conducted at the operator level. However, data are clustered at multiple levels in paper three and operator is therefore defined as a within-subject variable in the regression models to adjust for the effect of correlation between records.

3.5. Ethical Considerations

Approval to conduct expert interviews during the project has been obtained from the School of Geography and Environment's Departmental Research Ethics Committee in November 2019 (SOGE 1A020 – 06). Several steps have been taken over the course of the project to further mitigate risk of harm to the reputations of participating piped water operators that might result from exposure of suboptimal performance. These steps include:

1. All agency data are deidentified in the master database, and original datasets and identifier information are stored in a separate, encrypted folder from the master database.
2. The master database is accessible only by members of the research team.
3. No data files have been emailed between members of the research team. The only files that have been shared virtually are original datasets emailed from participating agencies to the research team.
4. Analyses have been conducted at various levels (geographic region and infrastructure type, for example), but never at the level of the individual agency unless by explicit request by the agency. Operational performance of individual agencies has not been reported, nor have agency names been linked with explicit findings in external publications.
5. All figures and results have been shared with participating agencies prior to publication.

These ethical concerns have been described in a Data Management Plan along with the process that was followed to compile, store, and analyse data and ensure the confidentiality of participating piped water operators. The Data Management Plan has been shared with all operators prior to data collection and formal, bilateral data use agreements have been signed in conjunction with University of Oxford Research Services.

3.6. Limitations

Five limitations are identified and have been considered in the research approach. First, site selection is not random and is determined by collaborators with sufficient and relevant data to support the analyses. This introduces a specific bias towards operators that enforce regular financial contributions from end users and keep high quality records, which is a rarity in sub-Saharan Africa. In a recent global diagnostic of professionalised rural water service providers, less than a quarter of the agencies responding to the voluntary survey report maintaining data systems at a similar level (Nilsson et al., 2021). The agencies that have provided data for this project also operate networked services at relatively large scales for rural Africa. Five of the six collaborating operators each support drinking water services for more than 50,000 people, while many rural water agencies support much smaller service populations (Nilsson et al., 2021). The project's findings are therefore representative only at the scale of operations reflected in the dataset. However, the blend of communal and household piped infrastructure and volumetric payment modalities reflected in the dataset are typical of an emerging professionalised approach to rural water supply (Nilsson et al., 2021). Furthermore, a concerted effort has been made to consider this limitation in the project's narrative. Paper three explicitly endeavours to address contextual limitations of the dataset by applying archetype analysis and articulating findings which can be generalised beyond the cases of individual operators.

Second, the original self-reported data are prone to inadvertent recording errors and manipulation which can lead to imprecise or inaccurate results. 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 in the project's three papers. Additional operator-specific limitations, such as time-bound data gaps or inclusion of arrears in monthly revenue records, have been considered in the analytical approaches and discussions of each paper.

Third, accurate longitudinal data on number of water users are not consistently available. This prevents analysis of variables that enable revenue patterns to be deciphered such as service area penetration and per capita water usage across waterpoint connection types. Demand analysis is limited to aggregate water usage.

Fourth, operational conditions during the analytical window are not fully understood and cannot be controlled via regression. For example, the presence and condition of alternative water supply infrastructure, changes in socioeconomic conditions, and population densities in the service areas are unknown. Furthermore, reliability of scheme performance and water quality are not represented in the dataset. There is an implicit assumption that all schemes deliver a consistent level of service, but it has not been possible to verify this with fieldwork. Exogenous effects such as these are more likely to manifest locally than regionally, introducing biases of unknown magnitude and direction. These biases cannot be eliminated but have been carefully considered during data cleaning and regression analyses.

Fifth, the rainfall data utilised in papers one and two are downscaled from the CHIRPS dataset to align with frequency and geolocation of operator data. Although the satellite-based estimates are validated against rain gauge data, ground truth observations are not available for the study locations.

3.7. Statement on Research Collaboration

Individual contributions to the project and its corresponding papers are summarised in Table 3.3.

Table 3.3. Contributions of Individual Collaborators to the Project

Dimension	Contributor Role[1]	Collaborators					
		AA	RH	JK	CM	ZSH	ED
Overall project and thesis	Conceptualisation	●	○	○			
	Investigation	●					
	Data Curation	●					
	Writing – Original Draft	●					
	Writing – Review & Editing	●	○	○			
	Visualisation	●					
	Supervision		●	○			
	Project Administration	●					
	Funding Acquisition	●	●				
Paper 1	Conceptualisation	●	●		○		
	Methodology	●	●		○		
	Software				●[2]		
	Formal Analysis	●					
	Data Curation	●			●[2]		
	Writing – Original Draft	●					
	Writing – Review & Editing	●	○		○		
	Visualisation	●			●[2]		
Paper 2	Conceptualisation	●	○	○			○
	Methodology	●	○	○			○
	Software	●				○[2]	●[2]
	Formal Analysis	●					
	Data Curation	●					●[2]
	Writing – Original Draft	●					
	Writing – Review & Editing	●	○	○			○
	Visualisation	●					●[2]
Paper 3	Conceptualisation	●	○	○			
	Methodology	●	○	○			
	Software	●					
	Formal Analysis	●					
	Investigation	●					
	Data Curation	●					
	Writing – Original Draft	●					
	Writing – Review & Editing	●	○	○			
	Visualisation	●					

AA: Andrew Armstrong; RH: Rob Hope (co- supervisor); JK: Johanna Koehler (co-supervisor); CM: Callum Munday; ZSH: Zachary Spavins-Hicks; ED: Ellen Dyer; ●: lead; ○: support

[1]See Contributor Roles Taxonomy (CRediT) definitions on the following page
[2]Rainfall data processing and visualisation

Contributor Roles Taxonomy (CRediT) definitions adapted from Brand et al. (2015):

Conceptualisation – Ideas; formulation or evolution of overarching research goals and aims

Methodology – Development or design of methodology; creation of models

Software – Programming; designing computer programs; implementation of the computer code and supporting algorithms

Formal Analysis – Application of statistical, mathematical, computational, or other formal techniques to analyse or synthesize study data

Investigation – Data collection

Data Curation – Management activities to annotate (produce metadata), scrub, and maintain research data (including software code) for initial use and later reuse

Writing - Original Draft – Writing the initial draft

Writing - Review & Editing – Critical review, commentary or revision including pre- and post-publication stages

Visualisation – Preparation of data presentation and creation of key graphics in published work

Supervision – Oversight responsibility for the DPhil project and mentorship to the student

Project Administration – Management and coordination responsibility for the research activity planning and execution

Funding Acquisition – Acquisition of the financial support for the project leading to publications

Chapter 4: Monitoring Socio-climatic Interactions to Prioritise Drinking Water Interventions in Rural Africa (Paper One)

Published in *npj Clean Water*

Armstrong, A., Hope, R., & Munday, C. (2021). Monitoring socio-climatic interactions to prioritise drinking water interventions in rural Africa. npj Clean Water, 4, 10. DOI: 10.1038/s41545-021-00102-9.

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BRIEF COMMUNICATION OPEN

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

Andrew Armstrong[1,2,3✉], Robert Hope[1,2] and Callum Munday[1]

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

npj Clean Water (2021)4:10 ; https://doi.org/10.1038/s41545-021-00102-9

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

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

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

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

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

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

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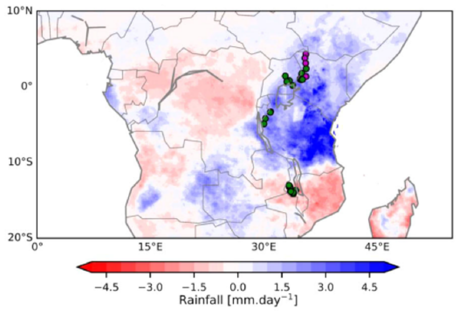

Fig. 1 Analysis of rainfall anomalies during the period from January to April 2020 against 1983–2012 climatology indicates unusually high rainfall in Kenya, Uganda, and Tanzania and low levels of rainfall in Malawi. Green dots indicate locations of piped schemes where the PAYF payment modality is employed.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

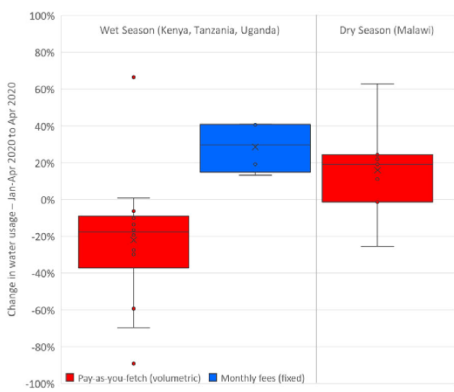

Fig. 2 Changes in water usage by payment modality and season in April 2020 compared to the period mean from January to April 2020. Where the PAYF payment modality is employed, increased rainfall and subsequent availability of alternative surface water sources during the wet season appears to buffer water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

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

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

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

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

METHODS

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

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

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

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

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

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

DATA AVAILABILITY

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

Received: 4 September 2020; Accepted: 13 January 2021;
Published online: 15 February 2021

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ACKNOWLEDGEMENTS

We thank Water Mission for allowing the use of operational data and providing localised insight. This article is an output from the REACH programme, funded by UK Aid from the UK Foreign, Commonwealth and Development Office (FCDO) for the benefit of developing countries (Programme Code 201880). However, the views expressed and information contained in it are not necessarily those of or endorsed by FCDO, which can accept no responsibility for such views or information or for any reliance placed on them.

AUTHOR CONTRIBUTIONS

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

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41545-021-00102-9.

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Supplemental Table 4.1. Water Usage [cubic metres/month]

	2020 Period vs 2020 April					Historic Period vs Historic April					Historic Period vs 2020 Period				
	n	Mean Diff.	Percent Diff.	P^1	p^2	n	Mean Diff.	Percent Diff.	P^1	p^2	n	Mean Diff.	Percent Diff.	P^1	p^2
All sub-Saharan Africa records	25	0.5	-3%	0.967	0.778	**28**	**-32.6**	**-7%**	**0.040**	0.056	26	3.4	16%	0.912	0.889
Kenya	10	10.8	-4%	0.697	0.721	**10**	**-53.9**	**-16%**	**0.029**	**0.017**	10	35.4	35%	0.640	0.575
Malawi	7	30.5	11%	0.175	0.176	9	-46.2	-8%	0.236	0.260	7	22.3	25%	0.508	0.499
Tanzania	**4**	**-29.6**	**-13%**	**0.034**	0.068	**4**	**27.0**	**11%**	**0.032**	0.068	4	-13.5	-1%	0.710	0.465
Uganda	**4**	**-47.1**	**-17%**	**0.033**	0.068	5	-13.5	-1%	0.683	0.893	5	-73.4	-21%	0.152	0.080
Monthly fees	**4**	**89.9**	**20%**	**0.048**	0.068	4	89.9	20%	0.321	0.273	4	126.5	103%	0.434	0.465
Pay-as-you-fetch	21	-16.5	-8%	0.170	0.099	21	-16.5	-8%	0.099	0.123	22	-18.9	<1%	0.469	0.638
Kiosks	2	50.3	-18%	0.736	0.655	2	-36.8	-19%	0.190	0.180	2	158.7	73%	0.608	0.655
Reticulated schemes	23	-3.8	-2%	0.755	0.670	26	-32.3	-6%	0.059	0.101	24	-9.5	11%	0.745	0.954
Medium schemes[3]	20	5.6	-2%	0.723	0.852	**23**	**-40.5**	**-9%**	**0.028**	**0.023**	21	9.0	21%	0.815	0.715
Large schemes[4]	5	-19.8	-10%	0.390	0.500	5	3.6	4%	0.906	0.500	5	-19.8	-4%	0.438	0.345
Schools - use water	20	-9.7	-5%	0.435	0.478	**23**	**-42.3**	**-10%**	**0.021**	**0.026**	21	-14.3	6%	0.665	0.741
Schools - use water & do not pay	7	1.7	-2%	0.940	0.866	9	-60.9	-17%	0.092	0.066	7	34.9	12%	0.404	0.398
Schools - use water & pay	13	-15.8	-6%	0.316	0.382	14	-30.4	-6%	0.143	0.177	14	-38.9	2%	0.394	0.363
No schools	5	41.4	2%	0.392	0.500	5	12.0	10%	0.679	0.893	5	77.8	59%	0.398	0.225
Healthcare facilities - use water	12	-9.7	-6%	0.607	0.209	14	-15.6	-3%	0.308	0.397	13	36.0	32%	0.403	0.650
Healthcare facilities - use water & do not pay	3	-25.6	-8%	0.427	0.285	4	-35.0	-11%	0.232	0.273	3	71.2	29%	0.200	0.109
Healthcare facilities - use water & pay	9	-4.4	-5%	0.854	0.441	10	-7.9	<1%	0.648	0.799	10	25.5	33%	0.644	0.878
No healthcare facilities	13	10.0	-1%	0.607	0.600	14	-49.6	-11%	0.082	0.084	13	-29.2	<1%	0.529	0.753
Increasing rain - Monthly fees	**4**	**89.9**	**20%**	**0.048**	0.068	4	-60.9	-8%	0.321	0.273	4	126.5	103%	0.434	0.465
Increasing rain - Pay-as-you-fetch	**14**	**-39.9**	**-17%**	**0.001**	**0.003**	15	-17.0	-6%	0.241	0.307	15	-38.2	-12%	0.283	0.211
Decreasing rain	7	30.5	11%	0.175	0.176	9	-46.2	-8%	0.236	0.260	7	22.3	25%	0.508	0.499

[1]Paired sample T-test significance (α=0.05)
[2]Wilcoxon signed ranks significance (α=0.05)
[3]Estimated service population 500-5,000 people
[4]Estimated service population >5,000 people

Chapter 5: Intra-seasonal Rainfall and Piped Water Revenue Variability in Rural Africa (Paper Two)

Published in *Global Environmental Change*

Armstrong, A., Dyer, E., Koehler, J., & Hope, R. (2022). Intra-seasonal rainfall and piped water revenue variability in rural Africa. Global Environmental Change, 76: 102592. DOI: 10.1016/j.gloenvcha.2022.102592.

Global Environmental Change 76 (2022) 102592

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Intra-seasonal rainfall and piped water revenue variability in rural Africa

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ARTICLE INFO

Keywords:
Rural water supply
Seasonality
Financial sustainability
Africa

ABSTRACT

Rainfall patterns influence water usage and revenue from user payments in rural Africa. We explore these dynamics by examining monthly rainfall against 4,888 records of rural piped water revenue in Ghana, Rwanda, and Uganda and quantifying revenue changes over 635 transitions between dry and wet seasons.

Results show operators experience revenue variability at regional and intra-seasonal scales. Revenues fall by an average of 30 percent during the wettest months of the year in climate regimes with consistent wet season rainfall. However, seasonally stable revenues are observed in areas where consecutive dry days are common during the wet season, potentially reflecting a dependency on reliable services. We also find changes in tariff level, waterpoint connection type, and payment approach do not consistently prevent or increase seasonal revenue variability.

Local revenue generation underpins delivery of drinking water services. Where rainfall patterns remain consistent, piped water operators can expect to encounter seasonal revenue reductions regardless of whether services are provided on or off premises and of how services are paid for. Revenue projections that assume consistent volumetric demand year-round may lead to shortfalls that threaten sustainability and undermine the case for future investment. Intra-seasonal rainfall analysis can enhance rural piped water revenue planning by offering localised insight into demand dynamics and revealing where climate variability may increase dependency on reliable services.

1. Introduction

Current climate models predict increases in frequency and intensity of drought and heavy rainfall events and decreases in mean precipitation almost everywhere in Africa, with medium to high confidence (Gutiérrez et al., 2021). However, local rainfall trends and socio-climatic interactions are likely to manifest in mixed patterns (Conway and Schipper, 2011), and the converging impacts of climate change will vary across the continent. In rural areas, rainfall patterns influence water usage and threaten the stability of revenue generation. Remote and *in situ* monitoring systems can generate warning signals (Armstrong et al., 2021), but improved understanding is needed to inform resilient water investments in rural Africa. We analyse seasonal revenue dynamics of six small-scale piped water operators in rural Ghana, Rwanda, and Uganda over a four-year period to address three research questions. First, how does seasonal rainfall influence revenue from user payments for rural piped water services? Second, which rainfall metrics are useful for characterising seasonal revenue variability? Third, do tariff level, connection type, and payment approach influence seasonal revenue patterns?

2. Rainfall and rural water services

2.1. Seasonal revenue variability

For more than a century, piped water services in the Global South have been planned and financed under an urban paradigm transferred from the Global North (Braadbaart, 2012). A core assumption of this model is that a household connected to a piped network will collect and use consistent volumes of water from that connection each month of the year, with infrastructure and tariffs designed accordingly. Yet evidence from across sub-Saharan Africa shows rural households have access to and use multiple water sources of varying service levels for different domestic and productive activities, some of which they pay for and some they do not, and they change the sources they use throughout the year depending on availability of seasonal surface or rainwater (Elliott et al.,

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https://doi.org/10.1016/j.gloenvcha.2022.102592
Received 29 April 2022; Received in revised form 1 August 2022; Accepted 22 September 2022
Available online 30 September 2022

2019, Hoque and Hope, 2018, Smits et al., 2008, Thompson et al., 2001). Rain-fed sources such as domestically harvested rainwater can be more convenient and reliable than primary water supplies during wet seasons and are often accessible without payment or at a lower price point after an initial capital investment is recovered. Households that utilise rain-fed sources can therefore spend less time and money on water collection during wet seasons (Kelly et al., 2018) and may even experience enhanced resiliency to supply shocks (Elliott et al., 2019, Kohlitz et al., 2020).

However, seasonal demand dynamics can threaten financial and operational viability of rural water services. Several studies conducted in Africa and Asia suggest domestic use of rural handpumps and piped schemes alike can fall by 20 to 30 percent during wet periods (Armstrong et al., 2021, Elliott et al., 2019, Kulinkina et al., 2016, Thomson et al., 2019). When payments for professional water services are based on volumetric usage, seasonal reductions in water use means revenues are more irregular with implications for operational sustainability. Seasonal revenue variability for handpump services has been documented in several sub-Saharan countries (Foster and Hope, 2016, 2017, Kelly et al., 2018), but its severity and extent related to piped water services across the continent is not well understood.

2.2. *Rainfall dynamics*

Despite the growing body of evidence demonstrating seasonal use of multiple water sources, little is published about how rural households respond to spatial and temporal variations in seasonal rainfall and how this demand response poses a revenue threat to water services within different climate regimes. Except for a few studies that combine longitudinal rainfall and water use data (Armstrong et al., 2021, Kulinkina et al., 2016, Thomas et al., 2019, Thomas et al., 2021, Thomson et al., 2019), most analyses draw on cross-sectional household surveys and utilise a binary, often subjective wet/dry monthly classification which hides presumably important intra-seasonal nuances about onset, duration, and intensity of dry and rainy periods (Wainwright et al., 2021). Water demand and revenue dynamics are likely driven by localised, weekly or even daily changes rather than whether a given month falls in a wet or dry season according to conventional definitions or is wetter or dryer than historical averages. This poses several questions pertaining to our study. In wetter climates, does a more consistent year-round prevalence of rainwater use lead to attenuated seasonal dynamics? Considering evidence that domestic withdrawals from boreholes decrease within a few days of heavy rainfall events (Thomas et al., 2019, Thomson et al., 2019), will less frequent but more intense rainfall lead to higher annual averages but more dramatic instantaneous falls in demand and revenue? Are households less likely to use seasonal sources as rainfall becomes more irregular and unreliable, particularly during rainy seasons (Kendon et al., 2019)? Will the revenue threat to rural water services increase or decrease as household use of rain-fed sources occurs over condensed time periods? Billions are spent on efforts to increase access and maintain drinking water services based on simple demand assumptions stemming from this knowledge gap. The revenue models upon which infrastructure investment decisions are made could be enhanced with improved understanding of how rainfall patterns influence water use and payment behaviours. This is a necessary precursor to assessing and addressing seasonal and climatic revenue threats to rural water services at local, regional, and global scales and to prioritising investments that maximise sustainability and equitability of outcomes.

2.3. *Behavioural determinants*

Rural piped water service providers that are losing market share to alternative sources such as seasonal rainwater may seek to understand what aspects of their service households prefer, and what it would take to incentivise consistent year-round use. Improved understanding of how various determinants modify seasonal water source choice and payment behaviours of rural households can strengthen strategies for addressing the rainfall-related revenue threat. The importance of price, proximity, reliability, and water quality on rural households' decisions to choose one rural water source over another have been highlighted in the literature (Briscoe et al., 1981, Gross and Elshiewy, 2019, Mu et al., 1990, Wagner et al., 2019). Similar factors appear to affect payments for the services that operate and maintain water sources. Rural households are less likely to use and pay for water the further the source is from their residence, especially when alternative water sources are nearby (Koehler et al., 2015, Kulinkina et al., 2016). Faster maintenance response time (Hope (2015), Hope and Ballon, 2019, 2021), favourable and dependable service delivery arrangements (Hope (2015), Hutchings et al., 2017, Koehler et al., 2015, Koehler et al., 2018), and perceived water quality (Foster and Hope, 2016, Hope and Ballon, 2019, 2021) may increase user payments. An important interaction effect is that households often use water from seasonal sources that are lower in quality and cost for purposes other than drinking and cooking (Hoque and Hope, 2020, Pearson et al., 2016, Thomson et al., 2019, Tucker et al., 2014). Payment approach is also an important modifier of rural water user payments and revenues. Pay-as-you-fetch (PAYF) payments collected on a volumetric basis may generate more revenue overall and per volume than flat fees collected periodically (Foster and Hope, 2017). However, PAYF payments are also linked to higher rates of seasonal multiple water source use than flat fees across all socioeconomic classes (ibid.) and may be less resilient to seasonal variability (Armstrong et al., 2021).

The limited evidence that is available suggests rural demand for payment-based water services is prone to being exchanged for seasonal rainwater if the rainwater is less expensive, more convenient, more reliable, and an acceptable quality for non-consumptive uses. A key knowledge gap is whether reliable piped water services provided on household premises, which are at least as convenient as rain-fed sources during the wet season, can stabilise willingness to pay for the primary service and reduce seasonal revenue variability. We explore this question through an analysis of a multi-decadal operational dataset while also considering the potential modifying effects of tariff level and payment approach.

3. Methods

3.1. *Quantifying seasonal revenue variability*

Our empirical analysis draws on operational data from six rural piped water operators in Ghana, Rwanda, and Uganda. After extraction and cleaning, a total of 4,888 records of monthly revenue from user payments corresponding to geographic service areas of individual piped schemes spanning the years 2016 to 2019 are analysed. We exclude records from the analysis if fewer than twelve months are available for any service area. This approach ensures the analysis spans at least one annual rainfall cycle in each service area. We convert all monthly revenue records from local currency to 2019 US dollars per waterpoint by applying deflator factors and currency conversion rates at purchasing power parity for private consumption obtained from the World Bank Development Indicators database (World Bank, 2020) and dividing by the number of functional waterpoints in the service area for the corresponding month. This enables our analysis to consider the effect of temporal demand fluctuations on revenue. We assess seasonal revenue variability as percent change in the rate of monthly revenue per waterpoint between chronological dry and wet seasons, rather than in absolute magnitudes, to account for variation in scheme size and service population across the dataset.

Our seasonal classification utilises Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data (Funk et al., 2014) and adapts the methodology described by Liebmann et al. (2012). Recognising the implications of intra-seasonal rainfall dynamics for our research questions, our approach diverges from typical climatological analysis by classifying individual months as wet or dry relative to annual rainfall means instead of identifying onset and cessation of prominent wet and dry seasons and referencing long-term, multi-year means. Daily geospatial rainfall data corresponding to each service area over the range of dates present in the operational dataset (2016–2019) are extracted from the CHIRPS data. Rainfall levels are summed monthly to align with revenue records. For each service area and month, the monthly rainfall anomaly is calculated by subtracting the monthly average rainfall corresponding to the annual mean from the total rainfall for that month. We classify each month as wet or dry relative to the annual mean such that negative anomaly values represent dry months and positive anomaly values represent wet months. We then group records corresponding to consecutive dry or wet months together as seasons. This approach accommodates intra-seasonal rises and falls in rainfall which might have a critical influence on water use, but also allows erratic shifts which can distort revenue patterns. To compensate for this, we assume a threshold requirement that monthly rainfall is a defined percentage more or less than its local annual average for transitions between seasons to occur. We test the sensitivity of this threshold and find values of five percent or less apply to fewer than one month per year for the average service area and yield nearly the same seasonal patterns as when no threshold is applied, while threshold values of 15 percent or more apply to three months per year for the average per service area and conceal the intra-seasonal dynamics we hope to incorporate. We therefore adopt a moderate seasonal transition threshold requirement of ten percent of the local annual average rainfall in our methodology. Finally, we calculate the percent change in the average revenue generation rate from each dry season to the chronological wet season.

We identify anomalies in the data that appear to result from operational factors such as extended periods of service disruption, administrative changes to billing procedures or failure to collect user payments, inclusion of arrears in monthly revenue records, data recording errors, and infrastructure upgrades. Where possible, data are corrected based on discussion with operators. To further account for exogenous factors which exert an unknown effect on revenue, single months with no recorded revenue are assumed to represent true drops in demand while two or more consecutive months with no recorded revenue are assumed to reflect operational factors that should be controlled or minimised in the analysis and are excluded. The excluded monthly records are evenly distributed across dry and wet seasons and ultimately do not exert a directional effect on our results. We also identify extreme outliers in calculated seasonal percent change in revenue generation rate. Values greater than three standard deviations from the absolute value of the mean for each country are identified and considered for exclusion. This methodology only identifies exceptionally large increases in wet season revenue because revenues cannot decrease by more than 100 percent. These extreme outliers, which are found to be nonrecurring in individual service areas and therefore likely reflect operational factors rather than increased wet season water demand, are excluded. In total, we exclude 242 monthly records of no revenue and 45 chronological season transition pairs from the analysis. From the remaining dataset, we calculate mean percent change in monthly revenue per waterpoint between chronological dry and wet seasons across all service areas as well as those supported by each operator. Differences in means is evaluated via one-way ANOVA and homogeneous subsets are identified via Tukey's HSD.

3.2. *Evaluating rainfall dynamics*

We again utilise the CHIRPS dataset to evaluate several rainfall metrics in the geolocations of the observed piped water service areas which have potential to reveal intra-seasonal patterns in water demand and revenue. Daily rainfall estimates from 2016 to 2019 covering separate rectangular grids spanning the minimum and maximum latitudes and longitudes of the service areas in Ghana, Rwanda, and Uganda are extracted and manipulated for this purpose. We first generate plots of average monthly precipitation ("*monthly precipitation*") for each service area to compare the overall intensity and seasonal dynamics of the respective rainfall profiles. Following the methodology described by Liebmann et al. (2012) and advanced by Dunning et al. (2016) we use daily rainfall to calculate and plot the average annual dry season duration ("*dry season duration*") for geographic grids corresponding to the observed service areas by identifying and subtracting the average dry season completion date from the average onset date. When two dry seasons are prevalent in the typical year, we generate separate plots for each. When no clear patterns emerge from observation of these two metrics that are based on monthly rainfall and seasonal timing, we calculate the cumulative number of instances of three, seven, and fourteen consecutive days with no precipitation during the main wet season ("*instances of dry days*") for each location. Although consecutive dry day metrics are more commonly used as indicators of drought intensity and frequency, recent climate models suggest future increases in dry period duration during the wet season over parts of Africa (Kendon et al., 2019). We apply these metrics to the three-month period of the main wet season in each country to illustrate intra-seasonal rainfall variability in the service areas. Durations of three, seven, and fourteen days are chosen to align with assumed household water storage practices. Rural African households that collect seasonal rainwater likely store and use it over several days. Dry periods of three consecutive days during the wet season are unlikely to disrupt this behaviour, but dry periods of a week or more may inhibit rainwater use. We quantify *instances of dry days* for each of these durations in 0.05-degree grids, assign values to a colour scale, and generate plots covering the geographic regions of the service areas. These plots are overlaid with markers indicating service area locations that experience "variable" or "stable" seasonal revenue based on a threshold of five percent, and we examine the plots for alignment or notable patterns.

3.3. *Analysing behavioural determinants*

Our data classification is aligned with previous work (Armstrong et al., 2022) which makes it possible to analyse the effects of tariff level, waterpoint connection type, and payment approach on seasonal revenue variability. The tariffs observed across the dataset are based on a volumetric water usage charge for all consumption levels, either per container or cubic metre, and do not contain a recurring fixed service charge. We convert all tariff levels to 2019 US dollars per cubic metre from local currency at purchasing power parity for private consumption. All records are further classified by waterpoint connection type: standpipes and kiosks are designated as off-premises connections and taps located in private homes or yards or dedicated for use at educational, religious, or healthcare facilities are designated as on-premises connections. Records corresponding to 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. Payments across the observed service areas 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 prepurchase 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.

Parameters from generalised estimating equations (GEEs) are estimated to evaluate the isolated effects of these factors on seasonal revenue variability. The GEE method (Zeger et al., 1988) is chosen over other linear regression approaches because monthly records are clustered by operator which violates the independence assumption. The method also fits well into our approach because it estimates population-averaged effects when covariates are unknown or unable to be controlled (Muff et al., 2016). We run separate GEE models for all records as well as clusters corresponding to individual operators and groups of interest. All modelling is conducted in IBM SPSS (IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY: IBM Corp) with chronological season transition pairs as repeated measures, service areas as subjects, and operator as a within-subject variable to adjust for clustering. We construct a continuous response variable from change in monthly waterpoint revenue between chronological dry and wet seasons (percent) and utilise tariff level, connection type, and payment approach as explanatory variables. Tariff levels (2019 $/m3 at PPP) are centred on the mean for all records included in each model 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 because all service areas that utilise pay-as-you-fetch payments contain off-premises connections and all service areas that utilise monthly billing contain on-premises connections. Therefore, we include a transformed binary variable based on utilisation of prepaid credit (conventional payments; prepaid credit payments) 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 be the best fit.

4. Results

Here we describe our most salient findings based on observation of seasonal revenue, evaluation of rainfall metrics, and analysis of selected behavioural determinants.

4.1. Seasonal revenue

The box plots in Fig. 1 illustrate dispersion of the average percent change in monthly revenue per waterpoint between a total of 635 chronological dry and wet seasons observed across all service areas as well as clustered by operator. Full descriptive statistics disaggregated by waterpoint connection type and payment approach are reported in Supplemental Table 1.

We observe a wide range of seasonal revenue change across the dataset (IQR 50 percent), with all operators experiencing wet season revenue falls in at least some service areas. Operator A in Rwanda and Operator B in Ghana experience overall negligible seasonal revenue variability, but Operator C in Ghana and operators D, E, and F in Uganda experience an aggregated average 30 percent reduction in revenue during wet seasons (IQR 27 percent). One-way ANOVA indicates all operator means are significantly different from each other ($p < .05$), but post-hoc tests reveal service areas supported by operators C, D, E, and F are in a homogeneous subset. Seasonal change in revenue is also statistically greater ($p < .05$) for Operator E than any of the other operators.

4.2. Rainfall

Plots illustrating *monthly precipitation* and *dry season duration* across the service areas in Ghana, Uganda, and Rwanda are provided in supplemental figures. These metrics do not reveal a clear explanation for the observed differences in seasonal revenue variability between service areas and operators. The *monthly precipitation* profiles in all three countries are similar yet the service areas in those countries see differing degrees of seasonal revenue variability. The service areas in Ghana and Rwanda that experience negligible seasonal revenue variability and therefore might be expected to align with muted rainfall dynamics are instead characterised by pronounced wet and dry seasons. Furthermore, we do not find evidence that *dry season duration* might correlate with falls in revenue during the wet season. Service areas in Ghana experience similar *dry season durations* but drastically different seasonal revenue variability, and service areas in Rwanda see a gradient of *dry season durations* yet all experience relatively stable seasonal revenues. Whether a region experiences relatively wetter or drier seasons, greater differences in mean rainfall between seasons, or longer dry seasons does not appear to influence the degree of observed seasonal revenue variability.

We do, however, find a notable stratification when *instances of dry days* during the main wet season are examined at the level of individual service areas (Fig. 2). Piped water service areas that typically experience revenue falls during wet seasons (red dots) appear to be in climate regimes characterised by consistently rainy wet seasons. In climate

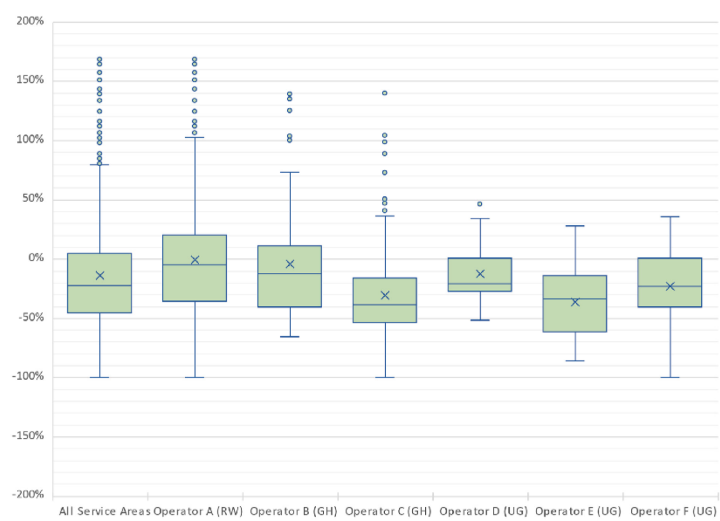

Fig. 1. Average percent change in monthly revenue per waterpoint in individual service areas between chronological dry and wet seasons. Box plot elements: mean markers, median centre lines, upper and lower quartile box limits, whiskers for minimum and maximum values within 1.5x IQR, and outlier markers.

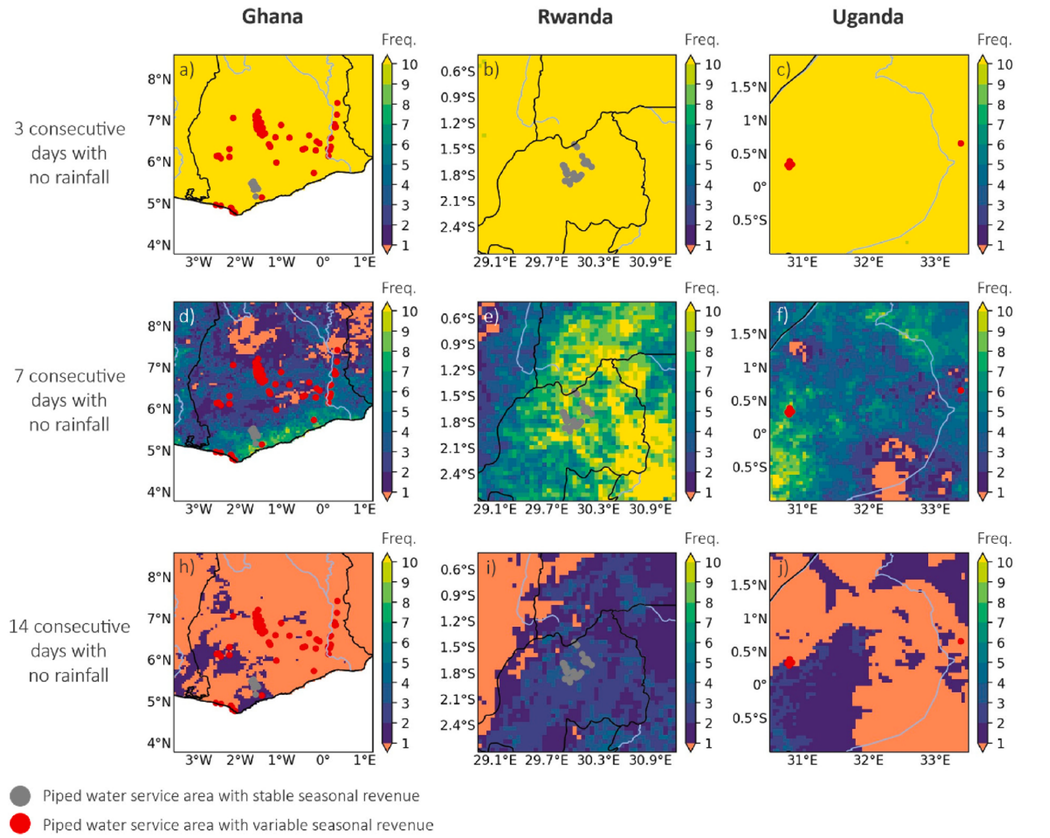

Fig. 2. Instances of consecutive days with no rainfall during main wet season in Ghana, Rwanda, and Uganda (2016–2019 cumulative). Grey markers indicate piped water service areas where average revenue variability of less than five percent is experienced between dry and wet seasons. Red markers indicate service areas where average seasonal revenue variability of greater than five percent is experienced. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

regimes where instances of 7 and 14 consecutive dry days during the wet season are more frequent, such as southern Ghana (panels d and h) and Rwanda (panels e and i), service areas appear to experience more stable revenue streams year-round (grey dots). This is especially notable when longer dry intervals occur during wet seasons (panels h and i).

4.3. Tariff Level, waterpoint connection Type, and user payment approach

Regression results corresponding to separate GEE models for service area clusters of interest are summarised in Table 1. Consistently better goodness-of-fit is observed when correlation across time-adjacent records is represented with an autoregressive correlation matrix. Reference cases correspond to service areas where only off-premises connections and conventional payment approaches are employed with tariff levels held constant at the mean value for the cluster. The models are constructed such that β values indicate the incremental effect of each parameter in relation to the reference case on percent change in monthly revenue per waterpoint between chronological dry and wet seasons. Tariff level increase is modelled as a main effect. The effects of on-premises connections and prepaid credit are modelled as interactions with mean-centred tariff level to control for the fact that the parameters are typically associated with higher user fees. Since Operator B does not utilise conventional payment methods, the reference case in Model 4 is based on off-premises connections where mean tariff levels are charged and paid for with prepaid credit. The isolated effect of prepaid credit is not able to be estimated in models 3 or 4 because prepaid credit payments are not utilised in the service areas supported by Operator A and conventional payments are not utilised in the service areas supported by Operator B.

The estimated effects of the reference cases follow a similar pattern as the descriptive statistics. When all service areas are pooled together (Model 1), the reference case sees a 13.0 percent seasonal reduction in revenue ($p < .001$). However, seasonal revenue variability is not significant ($p \geq 0.05$) for operators A and B (models 3 and 4, respectively), and operators C, D, E, and F (models 5, 6, 7, and 8, respectively) each experience significant reductions in revenue during wet seasons ($p \leq 0.006$). When service areas supported by the latter group of operators are clustered together (Model 2), the reference case sees a 30.2 percent decrease in revenue during wet periods ($p < .001$).

Descriptive statistics for tariff levels associated with each operator are summarised in Supplemental Table 2. Tariff level increases significantly influence seasonal revenue ($p \leq 0.001$) for the three operators in Uganda (models 6, 7, and 8), further reducing revenue during the wet

Table 1
Modelled effects of tariff level increase, on-premises connections, and prepaid credit on percent change in monthly revenue per waterpoint between chronological dry and wet seasons [percent].

			95 Percent Confidence Interval		
	β	SE	Lower	Upper	p
Model 1: All Service Areas (n 635)					
Reference case (intercept)[1]	**−13.0**	**2.0**	**−17.0**	**−9.1**	**<0.001**
Tariff level increase[2]	2.5	3.3	9.0	4.1	0.463
On-premises connections[3]	1.0	5.5	−9.7	11.8	0.853
Prepaid credit[3]	6.2	4.7	3.1	15.4	0.190
Model 2: Operators C (GH), D, E, and F (UG) (n = 272)					
Reference case (intercept)[1]	**−30.2**	**2.5**	**−35.1**	**−25.3**	**<0.001**
Tariff level increase[2]	0.5	3.5	6.3	7.3	0.883
On-premises connections[3]	**−13.1**	**5.8**	**−24.5**	**−1.6**	**0.025**
Prepaid credit[3]	8.6	5.6	19.5	2.3	0.121
Model 3: Operator A (RW) (n = 328)					
Reference case (intercept)[1]	−0.4	2.7	−5.7	4.8	0.874
Tariff level increase[2]	3.6	3.4	10.2	3.0	0.282
On-premises connections[3]	2.4	4.9	−7.3	12.0	0.631
Prepaid credit[3]	–	–	–	–	–
Model 4: Operator B (GH) (n = 35)					
Reference case (intercept)[1]	−5.2	5.5	−16.1	5.6	0.343
Tariff level increase[2]	46.4	31.6	15.5	108.3	0.142
On-premises connections[3]	−234.8	292.9	−808.8	339.2	0.423
Prepaid credit[3]	–	–	–	–	–
Model 5: Operator C (GH) (n = 189)					
Reference case (intercept)[1]	**−28.4**	**3.2**	**−34.8**	**−22.1**	**<0.001**
Tariff level increase[2]	1.6	6.1	13.6	10.5	0.796
On-premises connections[3]	−20.9	12.5	−45.4	3.5	0.094
Prepaid credit[3]	1.1	18.5	−35.2	37.4	0.952
Model 6: Operator D (UG) (n = 10)					
Reference case (intercept)[1]	**−7.1**	**0.0**	**−7.1**	**7.1**	**<0.001**
Tariff level increase[2]	**−24.6**	**0.0**	**−24.6**	**−24.6**	**<0.001**
On-premises connections[3]	**54.0**	**0.0**	**54.0**	**54.0**	**<0.001**
Prepaid credit[3]	**32.2**	**0.0**	**32.2**	**32.3**	**<0.001**
Model 7: Operator E (UG) (n = 56)					
Reference case (intercept)[1]	**−39.5**	**3.9**	**−47.2**	**−31.8**	**<0.001**
Tariff level increase[2]	**−10.2**	**2.5**	**−15.1**	**−5.2**	**<0.001**
On-premises connections[3]	5.4	6.2	−6.8	17.5	0.387
Prepaid credit[3]	2.5	4.4	−6.1	11.2	0.565
Model 8: Operator F (UG) (n = 17)					
Reference case (intercept)[1]	**−38.4**	**13.9**	**−65.7**	**−11.1**	**0.006**
Tariff level increase[2]	**−27.7**	**8.1**	**−43.5**	**−11.9**	**0.001**
On-premises connections[3]	**55.3**	**27.0**	**2.4**	**108.1**	**0.040**
Prepaid credit[3]	**11.5**	**1.1**	**9.4**	**13.7**	**<0.001**

[1] Reference cases correspond to service areas where only off-premises connections and conventional payment approaches are employed with tariff levels held constant at the mean value for the cluster.
[2] Tariff level increase is modelled as a main effect.
[3] On-premises connections and prepaid credit parameters are modelled as interactions with mean-centred tariff level.

season. On-premises connections and prepaid credit payments are associated with significant revenue increases ($p < .05$) during the wet season for operators D and F (models 6 and 8, respectively). However, these results should be regarded with caution because the effects in each model are based on less than five percent of the service areas and seasonal transition records that comprise the full study dataset. When all records for the operators that experience seasonal revenue variability are clustered together (Model 2), tariff level increases and prepaid credit payments do not exhibit significant effects on seasonal revenue and on-premises connections are associated with a 13 percent revenue reduction during wet seasons ($p = .025$). We conclude from these results that tariff level adjustments, on-premises connections, and prepaid credit payments do not consistently mitigate seasonal revenue variability for the operators that experience it.

5. Discussion

Our findings underscore three implications for piped water revenue planning which can enhance the resiliency of infrastructure investments in rural Africa. First, piped water operators can expect to experience localised seasonal revenue reductions in areas characterised by consistent wet seasons. Second, seasonal revenue variability should be anticipated in these climate regimes regardless of whether waterpoint connections are located on or off premises and of how services are paid for. Third, intra-seasonal rainfall variability may lead to greater dependence on reliable, professional services in some sub-Saharan regions. We expand on these points here and address the limitations of our study.

Our first research question asks how seasonal rainfall influences revenue from user payments for rural piped water services. The results we present demonstrate seasonal shifts in rural piped water demand and quantify its impact on revenue generation in multiple sub-Saharan countries. We find operators that experience seasonal revenue variability collect on average 30 percent less revenue as demand falls during wet periods, the magnitude and direction of which agrees with seasonal water consumption patterns of rural households reported in the literature. Revenue projections that broadly assume consistent volumetric demand year-round may lead to shortfalls that threaten sustainability. To put the impact of this recurring deficit into perspective, the average annual financial loss due to nonrevenue water across sub-Saharan utilities is reportedly 34 percent (IBNET, 2020) which leads to substantial economic repercussions in the water supply sector (Liemberger and Wyatt, 2018). Furthermore, overestimating the ability of rural piped water services to generate revenue ultimately undermines the case for future investment. This study contributes to a more nuanced and accurate understanding of rural piped water demand and revenue dynamics relative to geospatial rainfall patterns, which can aid in effective resource allocation.

This study also informs approaches which might be adopted to address seasonal revenue variability. We pose a research question regarding the influence of several behavioural determinants on seasonal revenue patterns, including tariff level, connection type, and payment approach. While controlling for tariff level, we find on-premises connections are associated with similar levels of seasonal revenue variability as off-premises connections. This implies that upgrading rural piped water access from off-site to on-site, though potentially resulting in higher unit revenues (Armstrong et al., 2022), may not lead to more seasonally stable cash flows. Furthermore, we observe seasonal revenue reductions across all payment approaches included in our study and find prepaid credit payments are not consistently associated with less seasonal revenue variability than conventional payments. The tariffs in the study are based on volumetric water usage rather than fixed fees, which prevents examination of whether fixed fee payments stabilise seasonal revenue as prior evidence suggests (Armstrong et al., 2021). Revenue dynamics in this study are therefore expected to track with seasonal water demand with the most noticeable effect of payment approach being a temporal offset based on whether payments occur prior to, at the point of, or at some delayed frequency from water collection. It is plausible that users adjust seasonal water collection behaviours based on the frequency and way payments for services are collected, especially if they prepay days or weeks in advance of rainfall events. Furthermore, operators may make seasonal adjustments to their billing and payment collection practices depending on the modality by which users pay for services. Any of these payment and collection behaviours might intensify or mitigate seasonal revenue reductions. However, we do not find evidence to suggest the observed payment approaches have a predictable effect on seasonal revenue.

There may be a socioeconomic explanation for these inconsistent effects, which our dataset does not permit us to explore and is an area for future research. The seasonal water usage and payment behaviours of rural households in the observed piped water service areas may be influenced by a variety of factors such as cultural norms, education level, spending power and priorities, and perceptions of affordability. These factors likely interact with each other, and their influence may evolve over time. Yet even without thorough understanding of the underlying behavioural determinants of seasonal revenue variability, our findings motivate a close examination of the revenue assumptions that underpin widescale, capital-heavy investments in rural, piped on-premises connections and prepaid credit systems.

Our analysis indicates broad interventions aimed at incentivising water demand to reduce or eliminate the seasonal revenue threat to rural piped services may prove unsuccessful. Alternatively, ensuring availability of adequate financial resources throughout periods of reduced demand may the most effective way to mitigate the impact of seasonal revenue variability. We briefly highlight several promising approaches to this end, including cash flow planning, maintaining cash reserves, adjusting tariff rates on a seasonal basis, pooling financial risk, administering supply-side subsidies, and offering flexible loan repayment terms.

Cash flow planning is a logical and fundamental approach. Unlike financial shocks resulting from asset failures or natural disasters which are infrequent and somewhat unexpected, seasonal revenue variability occurs at a regular frequency and can be characterised. Planning can cushion shocks caused by interannual variability, and bulky expenditures such as capital maintenance projects or hiring new staff can be prioritised and sequenced to align with anticipated financial constraints.

Cash reserves are also generally recommended to compensate for revenue volatility of municipal water services (AWWA, 2018). However, the feasibility of rural African operators building and maintaining a reserve fund is low given the challenging economics (Hope et al., 2020) and recognised cost recovery constraints (McNicholl et al., 2019).

Seasonal tariff rate adjustments may be an effective financial management strategy recognising tariff margins during dry seasons can compensate for reduced demand during wet seasons (Andres et al., 2021). Although tariff level increases correlate with greater seasonal revenue falls for some operators in this study, our results do not present conclusive evidence that tariff variations consistently intensify or mitigate seasonal revenue variability. We therefore recommend tariff modifications be considered with caution.

Financial risk-sharing mechanisms such as insurance and derivatives are also sometimes adopted by water utilities in high-income countries to mitigate weather-related revenue threats (Alliance for Water Efficiency, 2014) and are gaining interest in rural areas of low- and middle-income countries (Koehler et al., 2018). Rainfall index-based crop insurance, which is conceptually similar and utilises a blended finance approach to mitigate climate risk for smallholder farmers, has also been applied in various forms across sub-Saharan Africa (Miranda and Mulangu (2016)). We observe revenue variability in some service areas but not in others suggesting financial risk may be pooled and reduced in an investment portfolio at some geographic scale. Although seasonal revenue variability is not eliminated when all observed service areas are combined (Model 1), there is less overall reduction in average revenue during wet seasons (13 percent overall revenue reduction compared to up to 40 percent experienced by individual operators).

Supply-side subsidies provided directly to service providers on a flexible or seasonal basis can provide a buffer against seasonal revenue shocks as well. Our results suggest this may be more effective at stabilising seasonal revenue than demand-side subsidies which aim to increase household connections or reduce the price users pay for water.

Finally, flexible loan terms, where repayments are based on percentage of water sales and therefore adjust to seasonal variations, can allow operators to avoid default during periods of reduced demand. This approach has been adopted with apparent success by the Cambodia Revenue Finance Facility (The Stone Family Foundation, 2018).

Our final research question asks which rainfall metrics are useful for characterising seasonal revenue variability. We find evidence that rural piped water revenue, hence demand for services, is relatively stable where *instances of dry days* during the wet season are more common. This type of intra-seasonal variability is a pronounced and localised rainfall feature across Africa (Kendon et al., 2019, Wainwright et al., 2021). Hydrologic instability is traditionally recognised as a threat to water security because it complicates the ability of water managers to ensure availability of adequate resources to all populations (Grey and Sadoff, 2007). Our findings further link rainfall patterns to water use and sustainability outcomes and demonstrate the importance of considering such patterns at local scales. The piped water operations observed in this study, particularly in southern Ghana and Rwanda, appear to exemplify a virtuous feedback loop of dependable services leading to consistent demand and revenue from user payments. However, such cases are rare in rural Africa and poor functionality with periods of downtime lasting for weeks is more the norm than the exception (Tincani et al., 2015). Where availability of seasonal rain-fed water sources are unpredictable, rural water users are not able to buffer daily water consumption from a secondary rain-fed source and are likely dependent on professional services. In an increasingly uncertain global climate, it is thus imperative that rural water services remain functionally reliable, financially viable, and affordable for all.

We identify several limitations to our study. The first is that our analysis is representative only at the scale of operations reflected in the multi-country dataset. Furthermore, the operational conditions of the individual piped water service areas and operators are not fully understood and therefore cannot be controlled via regression. Important covariates such as reliability of scheme performance, presence and condition of alternative water supply infrastructure, and changes in social and economic conditions are unknown. Such exogenous effects are more likely to manifest locally than regionally, introducing biases of unknown magnitude and direction. We therefore cannot rule out the possibility that observed differences in seasonal revenue variability across service areas are a result of contextual factors or operator-specific efficiencies. The original data are also prone to inadvertent recording errors and manipulation which can lead to imprecise or inaccurate results. This has been addressed through a systematic internal data validation and cleaning process involving dispersion and outlier analysis as described in the methodology. Lastly, the rainfall data are downscaled from the CHIRPS dataset to align with frequency and geolocation of operator data. Although the satellite-based estimates are validated against rain gauge data, ground truth observations are not available for the exact study locations.

6. Conclusion

Local revenue generation underpins delivery of drinking water services in rural Africa yet is threatened by seasonal rainfall and water usage patterns. We present evidence that intra-seasonal rainfall analysis can enhance rural piped water revenue planning by offering localised insight into water demand dynamics and revealing where climate variability may increase dependence on reliable services. The observed seasonal threat to rural piped water revenue in Ghana, Rwanda, and Uganda varies geospatially and appears to decrease with frequency of dry intervals during the wet season, which is a metric of rainfall variability. Our findings suggest piped water operators in rural Africa can expect to experience seasonal revenue reductions, an average of 30 percent across our dataset, in climate regimes where wet season rainfall is consistent. However, seasonal piped water revenue and hence demand for services appears stable where rainfall patterns are more erratic. On-premises connections do not consistently prevent falling demand and revenue during wet months when compared to off-premises connections at equivalent tariff levels. Likewise, we observe similar seasonal revenue falls among services that are paid for with traditional pay-as-you-fetch and monthly billing approaches as with prepaid credit.

Further research is needed to understand the contextual and behavioural determinants that influence rainfall-related revenue variability beyond those which were evaluated in this study, as well as how and why the phenomenon evolves over time. Future studies should explore rainfall and revenue variability at intra-seasonal scales, recognising climate impacts are likely to result from nuanced shifts in rainfall patterns as well as extreme weather events.

CRediT authorship contribution statement

Andrew Armstrong: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ellen Dyer:** Data curation, Software, Visualization, Writing – review & editing. **Johanna Koehler:** Supervision, Writing – review & editing. **Rob Hope:** Funding acquisition, Supervision, 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.

Acknowledgements

We thank the agencies that granted access to operational data and provided localised insight for this study, including: Ayateke Star; Biguli Traders Association; Mid-Western Umbrella of Water and Sanitation Authority, Uganda; Power Technical Services; Safe Water Network; Water4; Water For People; Water Mission. We also thank Callum Munday and Zachary Spavins-Hicks (School of Geography and Environment, University of Oxford) for their advice and contributions towards collecting and analysing rainfall data. This article is an output from the REACH programme, funded by UK Aid from the UK Foreign, Commonwealth and Development Office (FCDO) for the benefit of developing countries (Programme Code 201880). However, the views expressed and information contained in it are not necessarily those of or endorsed by FCDO, which can accept no responsibility for such views or information or for any reliance placed on them.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2022.102592.

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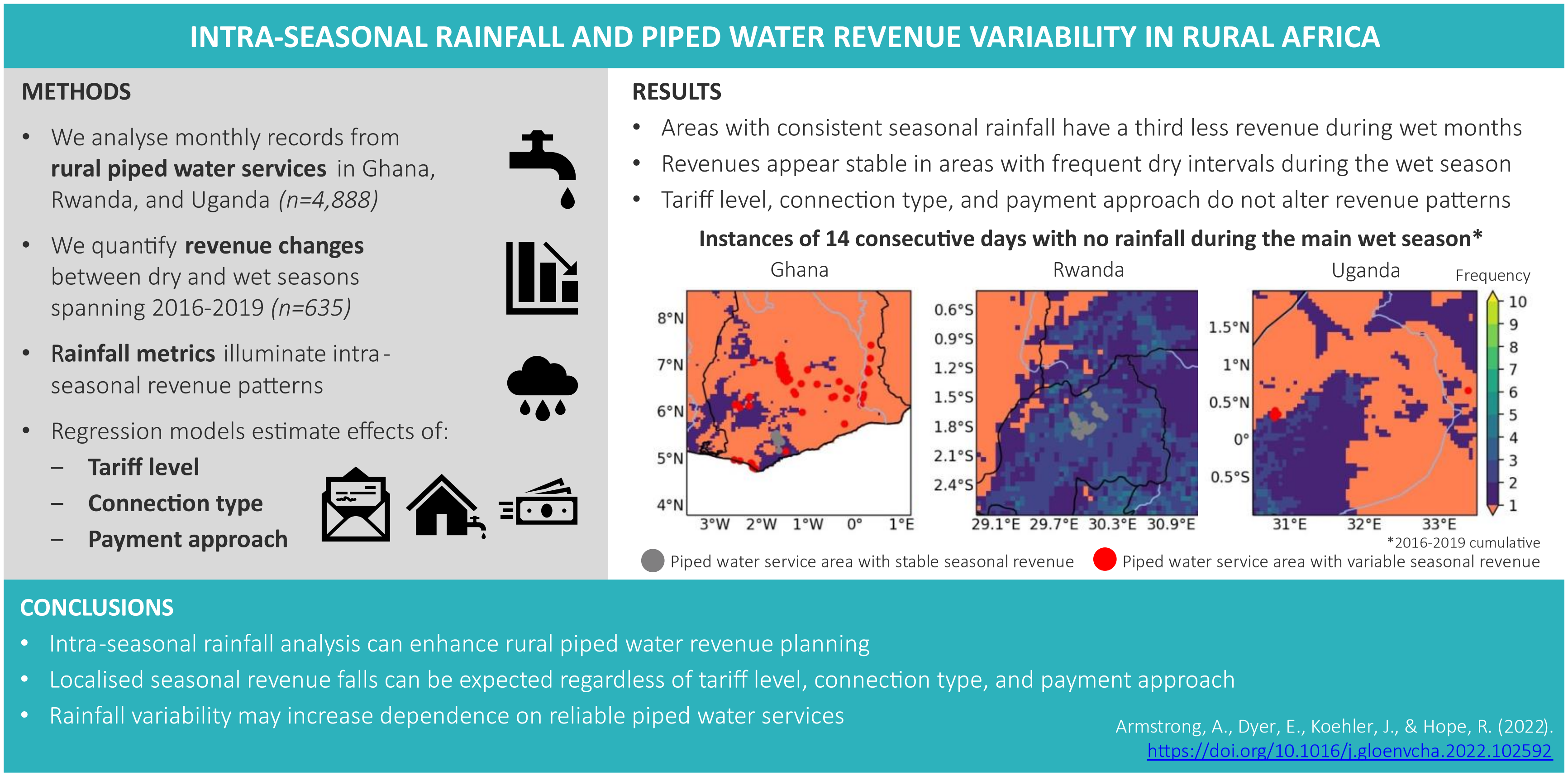


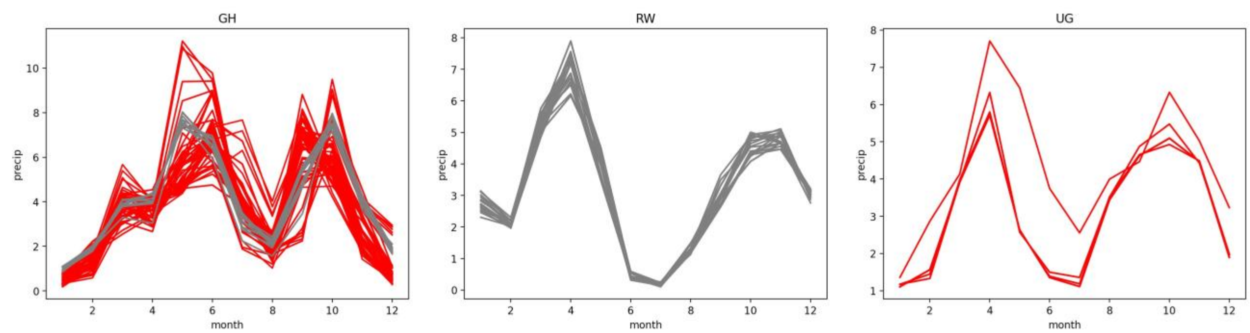
Figure 5.3. Graphical abstract: Intra-seasonal rainfall and piped water revenue variability in rural Africa.

Supplemental Table 5.1. Observed percent change in monthly revenue per waterpoint between chronological dry and wet seasons

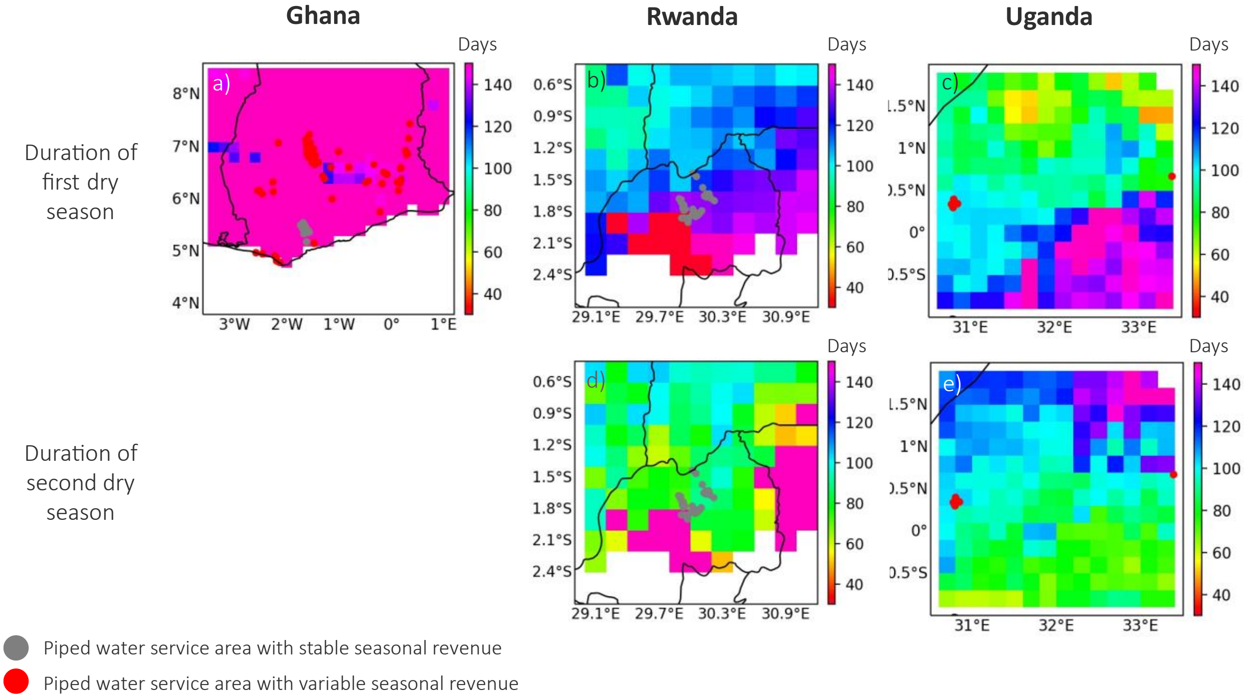
Cluster		Service Areas	Season Transitions	Mean	Med	IQR	SD
All Service Areas	All service areas	225	635	-15%	-21%	44%	48%
	Off premises	106	302	-23%	-27%	39%	45%
	Pay-as-you-fetch	88	244	-25%	-28%	39%	45%
	Prepaid credit	22	58	-19%	-24%	33%	43%
	On premises	119	333	-8%	-16%	43%	51%
	Monthly billing	89	268	-8%	-14%	40%	51%
	Prepaid credit	39	65	-7%	-21%	53%	50%
Operator A (RW)	All service areas	87	328	1%	-5%	32%	51%
	Off premises	30	125	5%	-5%	33%	49%
	Pay-as-you-fetch	30	125	5%	-5%	33%	49%
	Prepaid credit	-	-	-	-	-	-
	On premises	57	203	-1%	-3%	30%	52%
	Monthly billing	57	203	-1%	-3%	30%	52%
	Prepaid credit	-	-	-	-	-	-
Operator B (GH)	All service areas	13	35	0%	-3%	37%	60%
	Off premises	10	30	-12%	-7%	33%	50%
	Pay-as-you-fetch	-	-	-	-	-	-
	Prepaid credit	10	30	-12%	-7%	33%	50%
	On premises	3	5	65%	113%	94%	86%
	Monthly billing	-	-	-	-	-	-
	Prepaid credit	3	5	65%	113%	94%	86%
Operator C (GH)	All service areas	102	189	-29%	-34%	28%	39%
	Off premises	58	114	-40%	-42%	23%	27%
	Pay-as-you-fetch	53	100	-42%	-44%	21%	26%
	Prepaid credit	8	14	-25%	-31%	27%	30%
	On premises	44	75	-14%	-23%	46%	47%
	Monthly billing	19	21	-12%	-21%	72%	57%
	Prepaid credit	34	54	-12%	-20%	49%	42%
Operator D (UG)	All service areas	2	10	-16%	-16%	11%	23%
	Off premises	1	8	-10%	-10%	0%	26%
	Pay-as-you-fetch	1	6	-11%	-11%	0%	29%
	Prepaid credit	1	2	-8%	-8%	0%	2%
	On premises	1	2	-22%	-22%	0%	1%
	Monthly billing	-	-	-	-	-	-
	Prepaid credit	1	2	-22%	-22%	0%	1%
Operator E (UG)	All service areas	15	56	-38%	-38%	12%	29%
	Off premises	55	20	-35%	-36%	7%	30%
	Pay-as-you-fetch	3	12	-33%	-36%	6%	27%
	Prepaid credit	2	8	-37%	-37%	11%	33%
	On premises	10	36	-39%	-39%	17%	28%
	Monthly billing	9	32	-39%	-39%	17%	28%
	Prepaid credit	1	4	-41%	-41%	0%	29%

Supplemental Table 5.1 (continued). Observed percent change in monthly revenue per waterpoint between chronological dry and wet seasons

Cluster		Service Areas	Season Transitions	Mean	Med	IQR	SD
Operator F (UG)	All service areas	6	17	-22%	-18%	7%	34%
	Off premises	22	5	-7%	-7%	33%	37%
	Pay-as-you-fetch	1	1	9%	9%	0%	0%
	Prepaid credit	1	4	-23%	-23%	0%	39%
	On premises	4	12	-29%	-18%	24%	32%
	Monthly billing	4	12	-29%	-18%	24%	32%
	Prepaid credit	-	-	-	-	-	-



Supplemental Figure 5.1. Average monthly precipitation of geospatial grids covering individual service areas in Ghana, Rwanda, and Uganda (2016-2019). Grey lines indicate piped water service areas where average revenue variability of less than five percent is experienced between dry and wet seasons. Red lines indicate service areas where average seasonal revenue variability of greater than five percent is experienced.



Supplemental Figure 5.2. Average dry season duration in Ghana, Rwanda, and Uganda (2016-2019). Grey markers indicate piped water service areas where average revenue variability of less than five percent is experienced between dry and wet seasons. Red markers indicate service areas where average seasonal revenue variability of greater than five percent is experienced.

Supplemental Table 5.2. Tariff level statistics [2019 \$/m^3 at PPP]

	Mean	Median	Maximum	Minimum	IQR	SD
All Service Areas	2.42	2.49	5.84	0.65	1.01	1.27
Operator A (RW)	1.62	1.28	3.26	0.65	1.12	0.92
Operator B (GH)	5.69	5.69	5.84	5.52	0.24	0.25
Operator C (GH)	2.61	2.49	4.97	1.66	0.00	0.49
Operator D (UG)	2.59	2.59	2.73	2.44	0.30	0.50
Operator E (UG)	2.94	3.43	4.13	1.76	1.73	1.35
Operator F (UG)	2.37	2.84	3.19	0.81	1.69	0.97

Chapter 6: Piped Water Revenue and Investment Strategies in Rural Africa (Paper Three)

Published in *Environmental Research: Infrastructure Sustainability*

Armstrong, A., Hope, R., & Kohler, J. (2022). Piped water revenue and investment strategies in rural Africa. *Environmental Research: Infrastructure Sustainability*, 2, 035003. DOI: 10.1088/2634-4505/ac61f8.

IOP Publishing   *Environ. Res.: Infrastruct. Sustain.* **2** (2022) 035003   https://doi.org/10.1088/2634-4505/ac61f8

ENVIRONMENTAL RESEARCH
INFRASTRUCTURE AND SUSTAINABILITY

PAPER

RECEIVED
8 December 2021

REVISED
14 March 2022

ACCEPTED FOR PUBLICATION
29 March 2022

PUBLISHED
28 June 2022

Piped water revenue and investment strategies in rural Africa

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Keywords: piped water, user payments, sustainable development goals, archetype analysis, Africa

Supplementary material for this article is available online

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

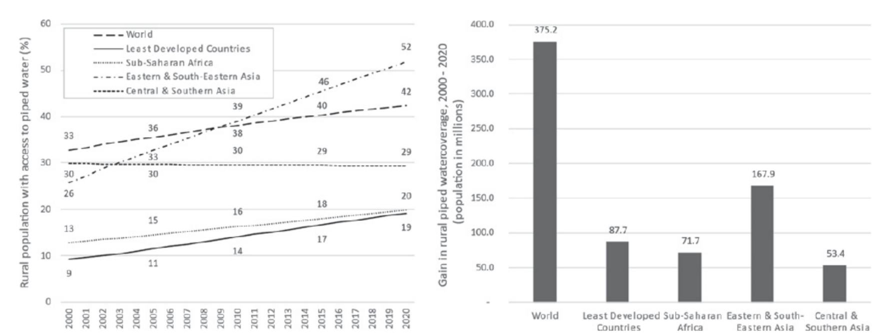

Figure 1. Gains in rural piped water coverage in selected regions, 2000–2020 (UNICEF and World Health Organization 2021).

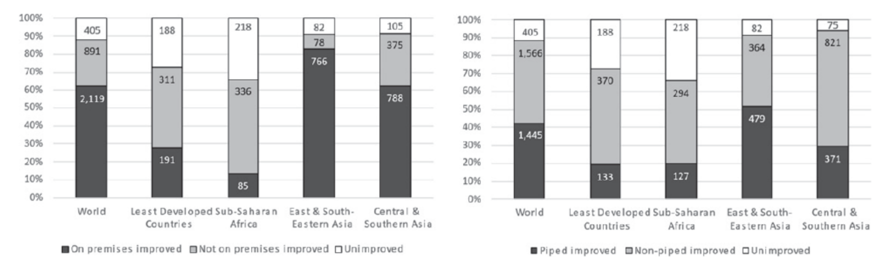

Figure 2. Rural drinking water accessibility and piped coverage in selected regions, 2020 estimates in millions. Improved drinking water sources are those which, by nature of their design and construction, have the potential to deliver safe water. Unimproved drinking water sources include unprotected 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

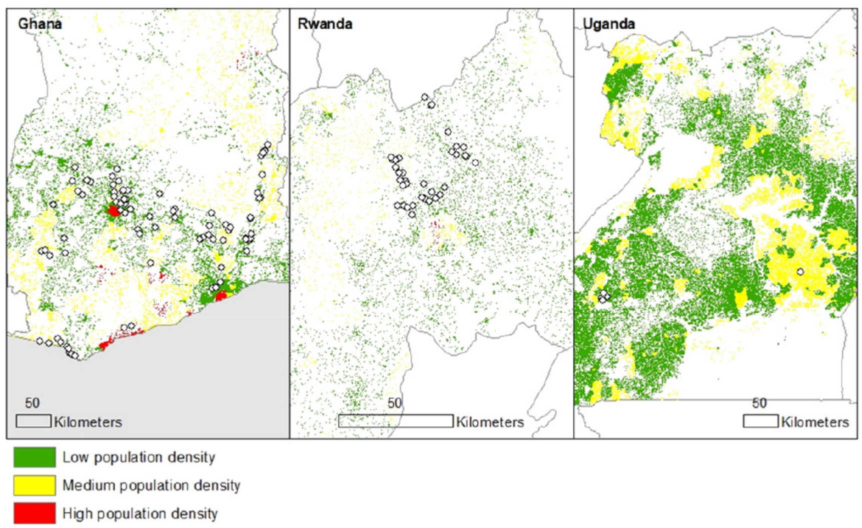

Figure 3. The average estimated population density of the observed service areas in Ghana, Rwanda, and Uganda is 474, 530, and 366 people per square kilometre, respectively. These locations, which are depicted as white dots in the figure, appear to be in areas of low to medium population density relative 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

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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 α 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.

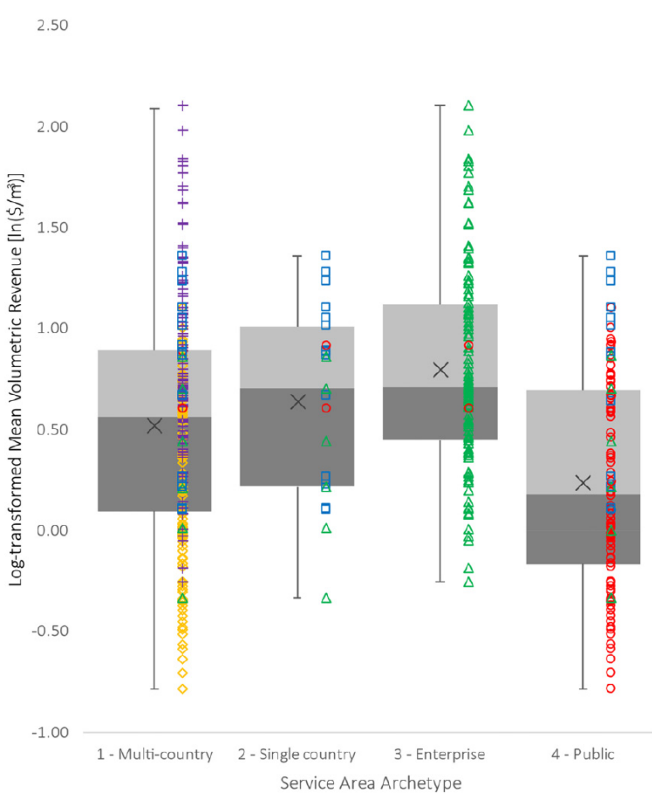

Figure 4. Log-transformed mean revenue rates appear weighted across operators in archetypes 1, 2 and 4 but are normally distributed across service areas within each archetype. Box plot elements: markers correspond to log-transformed mean volumetric revenue for service areas used to construct archetypes; 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		Attribute	Months	Mean	Med	IQR	SD
			Total[b]	Avg. service area						
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

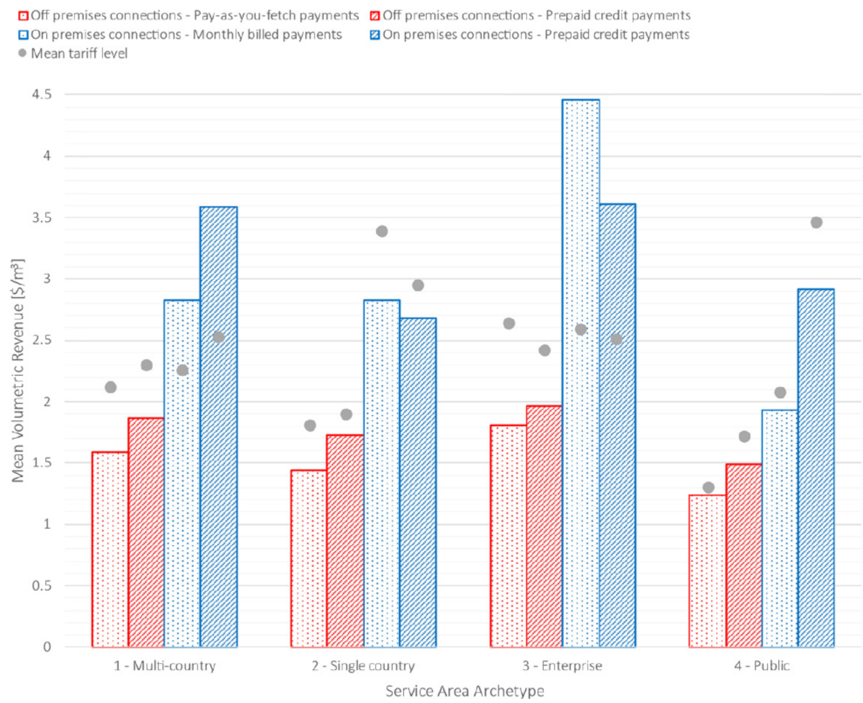

Figure 5. On premises connections generate higher volumetric revenue than off premises connections in all archetypes. Revenue rates appear to correlate with tariff levels and are higher than tariff levels for on premises connections in archetypes 1 and 3 due to the inclusion of arrears payments in monthly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

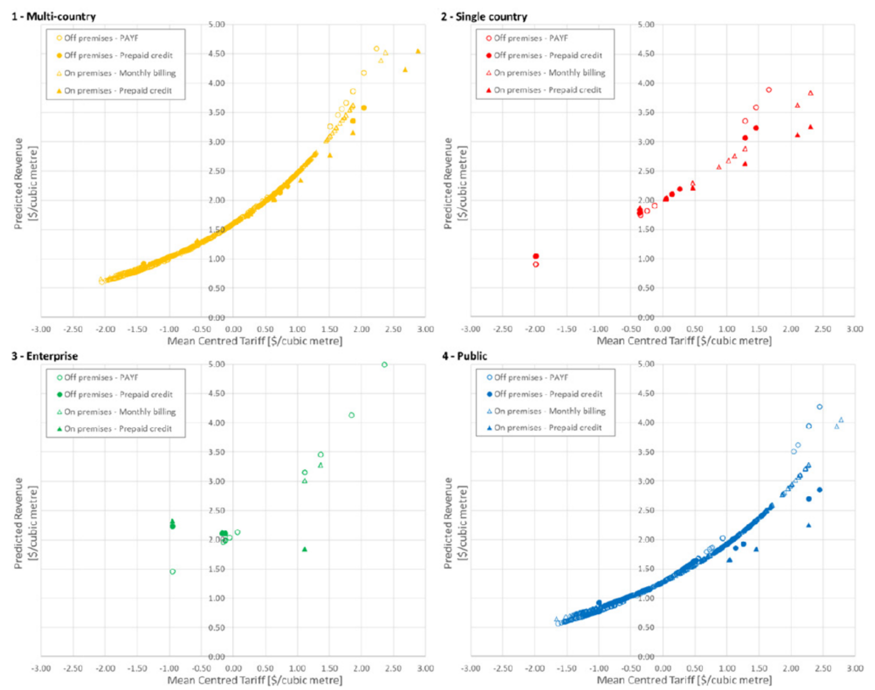

Figure 6. Model-predicted volumetric revenue by tariff level, connection type, and payment approach for service area archetypes: 1. Multi-country, 2. Single country, 3. Enterprise, and 4. Public.

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.

Acknowledgments

We thank the agencies that granted access to operational data and provided localised insight for this study, including Ayateke Star, Biguli Traders Association, Mid-Western Umbrella of Water and Sanitation Authority (Uganda), Power Technical Services, Safe Water Network, Water For People, and Water Mission. We are also grateful to Paola Ballon at the Smith School of Enterprise and the Environment at the University of Oxford for reviewing our methodology. This article is an output from the REACH programme, funded by UK Aid from the UK Foreign, Commonwealth and Development Office (FCDO) for the benefit of developing countries (Programme Code 201880). However, the views expressed and information contained in it are not necessarily those of or endorsed by FCDO, which can accept no responsibility for such views or information or for any reliance placed on them.

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.

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Supplemental Table 6.1. Results of leave-one-out analysis – Modelled effects on volumetric revenue [ln($/m3)]

Service Area Archetype		β	SE	95% CI Lower	95% CI Upper	p
1 - Multi-country	**Reference case (intercept)**	**0.474**	**0.0201**	**0.435**	**0.514**	**<.001**
	Tariff level	**0.470**	**0.0319**	**0.407**	**0.532**	**<.001**
	On premises connections	-0.034	0.0429	-0.118	0.050	.429
	Prepaid credit	-0.075	0.0691	-0.210	0.061	.279
(Operator 1 excluded)	**Reference case (intercept)**	**0.588**	**0.0383**	**0.513**	**0.663**	**<.001**
	Tariff level	**0.291**	**0.0401**	**0.212**	**0.369**	**<.001**
	On premises connections	0.030	0.0536	-0.075	0.135	.572
	Prepaid credit	0.039	0.0741	-0.106	0.185	.595
(Operator 2 excluded)	**Reference case (intercept)**	**0.423**	**0.0234**	**0.377**	**0.469**	**<.001**
	Tariff level	**0.477**	**0.0359**	**0.407**	**0.547**	**<.001**
	On premises connections	-0.068	0.0451	-0.156	-0.021	.134
	Prepaid credit	**-0.152**	**0.0457**	**-0.242**	**-0.063**	**.001**
(Operator 3 excluded)	**Reference case (intercept)**	**0.476**	**0.0204**	**0.436**	**0.515**	**<.001**
	Tariff level	**0.478**	**0.0319**	**0.415**	**0.540**	**<.001**
	On premises connections	-0.041	0.0428	-0.125	0.043	.334
	Prepaid credit	-0.086	0.0677	-0.219	0.047	.205
(Operator 4 excluded)	**Reference case (intercept)**	**0.479**	**0.0225**	**0.435**	**0.523**	**<.001**
	Tariff level	**0.487**	**0.0354**	**0.417**	**0.556**	**<.001**
	On premises connections	-0.021	0.0496	-0.118	0.076	.673
	Prepaid credit	0.079	0.1177	-0.152	0.310	.501
(Operator 5 excluded)	**Reference case (intercept)**	**0.480**	**0.0206**	**0.440**	**0.520**	**<.001**
	Tariff level	**0.470**	**0.0325**	**0.406**	**0.534**	**<.001**
	On premises connections	-0.028	0.0437	-0.114	0.058	.521
	Prepaid credit	-0.089	0.0747	-0.236	0.057	.233
(2016 data excluded)	**Reference case (intercept)**	**0.478**	**0.0202**	**0.438**	**0.517**	**<.001**
	Tariff level	**0.478**	**0.0320**	**0.415**	**0.540**	**<.001**
	On premises connections	-0.042	0.0429	-0.126	0.043	.334
	Prepaid credit	-0.080	0.0687	-0.215	0.054	.241
(2017 data excluded)	**Reference case (intercept)**	**0.505**	**0.0209**	**0.463**	**0.546**	**<.001**
	Tariff level	**0.472**	**0.0371**	**0.399**	**0.545**	**<.001**
	On premises connections	-0.023	0.0431	-0.107	0.062	.595
	Prepaid credit	-0.088	0.0688	-0.223	0.047	.201
(2018 data excluded)	**Reference case (intercept)**	**0.463**	**0.0250**	**0.414**	**0.512**	**<.001**
	Tariff level	**0.462**	**0.0364**	**0.390**	**0.533**	**<.001**
	On premises connections	-0.005	0.0540	-0.111	0.101	.927
	Prepaid credit	0.026	0.0803	-0.132	0.183	.748
(2019 data excluded)	**Reference case (intercept)**	**0.429**	**0.0282**	**0.373**	**0.484**	**<.001**
	Tariff level	**0.468**	**0.0333**	**0.403**	**0.533**	**<.001**
	On premises connections	-0.072	0.0451	-0.161	0.016	.109
	Prepaid credit	**-0.207**	**0.0489**	**-0.302**	**-0.111**	**<.001**

Supplemental Table 6.1 (continued). Results of leave-one-out analysis – Modelled effects on volumetric revenue [ln($/m3)]

Service Area Archetype		β	SE	95% CI Lower	95% CI Upper	p
2 - Single country	**Reference case (intercept)**	**0.698**	**0.0523**	**0.598**	**0.801**	**<.001**
	Tariff level	**0.399**	**0.0503**	**0.301**	**0.498**	**<.001**
	On premises connections	-0.119	0.0803	-0.276	0.038	.139
	Prepaid credit	-0.071	0.0591	-0.187	0.044	.227
(Operator 3 excluded)	**Reference case (intercept)**	**0.702**	**0.0589**	**0.586**	**0.817**	**<.001**
	Tariff level	**0.426**	**0.0498**	**0.329**	**0.524**	**<.001**
	On premises connections	-0.143	0.0839	-0.307	0.022	.089
	Prepaid credit	-0.078	0.0579	-0.192	0.035	.178
(Operator 4 excluded)	**Reference case (intercept)**	**0.545**	**0.0850**	**0.379**	**0.712**	**<.001**
	Tariff level	**0.308**	**0.1100**	**0.902**	**0.524**	**.005**
	On premises connections	0.208	0.2083	-0.200	0.616	.318
	Prepaid credit	-0.080	0.1070	-0.290	0.130	.453
(Operator 5 excluded)	**Reference case (intercept)**	**0.746**	**0.0571**	**0.634**	**0.858**	**<.001**
	Tariff level	**0.397**	**0.0498**	**0.300**	**0.495**	**<.001**
	On premises connections	-0.147	0.0795	-0.303	0.009	.065
	Prepaid credit	-0.080	0.0633	-0.204	0.045	.209
(2016 data excluded)	**Reference case (intercept)**	**0.723**	**0.0531**	**0.619**	**0.828**	**<.001**
	Tariff level	**0.435**	**0.0494**	**0.338**	**0.532**	**<.001**
	On premises connections	**-0.165**	**0.0792**	**-0.320**	**-0.010**	**.038**
	Prepaid credit	-0.091	-0.0576	-0.204	0.022	.115
(2017 data excluded)	**Reference case (intercept)**	**0.695**	**0.0578**	**0.582**	**0.809**	**<.001**
	Tariff level	**0.389**	**0.0509**	**0.289**	**0.489**	**<.001**
	On premises connections	-0.116	0.0840	-0.281	0.048	.166
	Prepaid credit	-0.057	0.0546	-0.164	0.050	.299
(2018 data excluded)	**Reference case (intercept)**	**0.770**	**0.0670**	**0.639**	**0.901**	**<.001**
	Tariff level	**0.472**	**0.0534**	**0.367**	**0.576**	**<.001**
	On premises connections	**-0.261**	**0.0910**	**-0.439**	**-0.082**	**.004**
	Prepaid credit	-0.036	0.0622	-0.158	0.086	.564
(2019 data excluded)	**Reference case (intercept)**	**0.646**	**0.0531**	**0.542**	**0.750**	**<.001**
	Tariff level	**0.344**	**0.0620**	**0.233**	**0.466**	**<.001**
	On premises connections	-0.032	0.0881	-0.204	0.141	.721
	Prepaid credit	-0.116	0.0817	-0.276	0.044	.157

Supplemental Table 6.1 (continued). Results of leave-one-out analysis – Modelled effects on volumetric revenue [ln($/m3)]

Service Area Archetype		β	SE	95% CI Lower	95% CI Upper	p
3 – Enterprise	**Reference case (intercept)**	**0.735**	**0.0392**	**0.659**	**0.812**	**<.001**
	Tariff level	**0.371**	**0.0724**	**0.229**	**0.512**	**<.001**
	On premises connections	-0.040	0.1738	-0.380	0.301	.820
	Prepaid credit	-0.442	0.2602	-0.952	0.068	.089
(Operator 2 excluded)	**Reference case (intercept)**	**0.487**	**0.0008**	**0.485**	**0.489**	**<.001**
	Tariff level	**0.020**	**0.0003**	**0.020**	**0.021**	**<.001**
	On premises connections	**-0.100**	**0.0005**	**-0.101**	**-0.099**	**<.001**
	Prepaid credit	**-2.269**	**0.0044**	**-2.278**	**-2.261**	**<.001**
(Operator 3 excluded)	**Reference case (intercept)**	**0.740**	**0.0400**	**0.662**	**0.819**	**<.001**
	Tariff level	**0.426**	**0.0785**	**0.272**	**0.580**	**<.001**
	On premises connections	-0.092	0.1690	-0.423	0.239	.586
	Prepaid credit	-0.441	0.2545	-0.940	0.058	.083
(2016 data excluded)	**Reference case (intercept)**	**0.741**	**0.0389**	**0.665**	**0.817**	**<.001**
	Tariff level	**0.427**	**0.0786**	**0.273**	**0.581**	**<.001**
	On premises connections	-0.089	0.1683	-0.419	0.241	.599
	Prepaid credit	-0.455	0.2544	-0.953	0.044	.074
(2017 data excluded)	**Reference case (intercept)**	**0.737**	**0.0393**	**0.660**	**0.814**	**<.001**
	Tariff level	**0.370**	**0.0730**	**0.227**	**0.513**	**<.001**
	On premises connections	-0.040	0.1737	-0.380	0.301	.819
	Prepaid credit	-0.440	0.2599	-0.949	0.070	.091
(2018 data excluded)	**Reference case (intercept)**	**0.736**	**0.0395**	**0.658**	**0.813**	**<.001**
	Tariff level	**0.370**	**0.0729**	**0.277**	**0.513**	**<.001**
	On premises connections	-0.040	0.1738	-0.380	0.301	.820
	Prepaid credit	-0.439	0.2602	-0.949	0.071	.091
(2019 data excluded)	**Reference case (intercept)**	**0.485**	**0.000**	**0.485**	**0.485**	**<.001**
	Tariff level	**0.028**	**0.000**	**0.028**	**0.028**	**<.001**
	On premises connections	**-0.403**	**0.000**	**-0.403**	**-0.403**	**<.001**
	Prepaid credit	**-2.186**	**0.000**	**-2.186**	**-2.186**	**<.001**
4 - Public	**Reference case (intercept)**	**0.249**	**0.0240**	**0.202**	**0.296**	**<.001**
	Tariff level	**0.493**	**0.0464**	**0.402**	**0.584**	**<.001**
	On premises connections	-0.080	0.0551	-0.188	0.028	.148
	Prepaid credit	**-0.166**	**0.0418**	**-0.248**	**-0.084**	**<.001**
(Operator 1 excluded)	**Reference case (intercept)**	**0.313**	**0.0572**	**0.201**	**0.425**	**<.001**
	Tariff level	**0.377**	**0.0453**	**0.288**	**0.465**	**<.001**
	On premises connections	-0.023	0.0620	-0.144	0.099	.712
	Prepaid credit	-0.076	0.0476	-0.170	0.017	.108
(Operator 4 excluded)	**Reference case (intercept)**	**0.248**	**0.0265**	**0.196**	**0.300**	**<.001**
	Tariff level	**0.525**	**0.0609**	**0.406**	**0.645**	**<.001**
	On premises connections	-0.103	0.0742	-0.248	0.043	.166
	Prepaid credit	-0.050	0.0575	-0.163	0.063	.384
(Operator 5 excluded)	**Reference case (intercept)**	**0.253**	**0.0242**	**0.206**	**0.301**	**<.001**
	Tariff level	**0.494**	**0.0471**	**0.401**	**0.586**	**<.001**
	On premises connections	-0.074	0.0559	-0.184	0.035	.184
	Prepaid credit	**-0.189**	**0.0374**	**-0.263**	**-0.116**	**<.001**
(2017 data excluded)	**Reference case (intercept)**	**0.276**	**0.0242**	**0.229**	**0.324**	**<.001**
	Tariff level	**0.492**	**0.0585**	**0.377**	**0.606**	**<.001**
	On premises connections	-0.057	0.0635	-0.182	0.068	.370
	Prepaid credit	**-0.196**	**0.0549**	**-0.303**	**-0.088**	**<.001**
(2018 data excluded)	**Reference case (intercept)**	**0.200**	**0.0329**	**0.136**	**0.265**	**<.001**
	Tariff level	**0.481**	**0.0556**	**0.372**	**0.590**	**<.001**
	On premises connections	-0.071	0.0705	-0.209	0.067	.314
	Prepaid credit	-0.056	0.0510	-0.156	0.043	.268
(2019 data excluded)	**Reference case (intercept)**	**0.272**	**0.0284**	**0.216**	**0.327**	**<.001**
	Tariff level	**0.519**	**0.0407**	**0.440**	**0.599**	**<.001**
	On premises connections	**-0.127**	**0.0522**	**-0.229**	**-0.025**	**.015**
	Prepaid credit	**-0.220**	**0.0422**	**-0.303**	**-0.137**	**<.001**

Chapter 7: Conclusion

7.1. Contributions

The primary aim of this project has been to understand how seasonal patterns of domestic water use and payments affect revenue from piped water services in rural Africa. A sizable collection of secondary data has been assembled and analysed in an inductive, stepwise manner to generate evidence that explores key research questions and addresses this aim. Three cross-cutting themes that bind the research together have emerged over the course of the project. First, the project has produced new empirical knowledge about rainfall-related demand and revenue dynamics resulting from multiple water source use in rural Africa. Second, the project's methodological approach has evolved in response to inherent limitations of the secondary dataset. Third, the papers are conceptually linked by a practical interest in piped water infrastructure types and user payment approaches which can be sequenced to achieve SDG 6.1 policy goals in rural Africa. The original empirical and methodological contributions of the project across the first two themes are discussed in this section, and recommendations for policy and practice under the third theme are discussed in section 7.2.

Empirical Contributions

A core contribution of the project is its compilation and empirical analysis of monthly rural piped water usage and revenue records cumulatively spanning more than 500 service-years, which is the largest known portfolio on the subject to-date. Piped water services can align with the internationally recognised safely managed standard and will play an increasing role in the coming decades yet have been historically under-studied in rural areas of low- and middle-income countries. The unavoidable selection bias associated with the project's data sources does not disqualify its empirical contributions. Rather, the findings serve as a practical point of reference for seasonal tariff collection and revenue generation associated with an emerging, professionalised approach to piped water services in rural Africa. The descriptive statistics for tariff levels, water usage rates, and unit revenues across different waterpoint connection types and payment approaches presented in paper three hold particular value as contemporary benchmarks for rural water planners.

The empirical findings have also begun to unravel the complex relationship between piped water services, revenue, and rainfall patterns in rural Africa. Seasonal shifts in household water usage from rural handpumps to rain-fed sources, aligned with recurring periods of reduced revenue from user payments, have been previously documented in several sub-Saharan countries (see literature reviewed in section 2.4). This project is the first to examine the phenomenon in the context of rural piped water services. Exploratory analysis of the project dataset described in paper one reveals that seasonal rainfall and payment approach are at least as important as other operational factors in understanding and anticipating seasonal demand patterns. Paper two then quantitatively estimates the seasonal financial threat to rural piped water, finding revenues decrease by an average of 30 percent during wet months in areas characterised by consistent wet season rainfall, regardless of whether waterpoint connections are located on or off premises. Similar seasonal revenue patterns are observed across the volumetric payment approaches adopted by operators in the study domain including PAYF, monthly billing, and prepaid credit. These findings are consistent across multiple countries and operating contexts, suggesting rural piped water revenue projections should consider seasonal rainfall patterns alongside other institutional, technical, and social factors. The policy and practice implications are explored further in section 7.2.

Paper two's investigation of the relationship between the nature and timing of transitions between wet and dry seasons and revenue patterns represents an additional empirical contribution. The study advances beyond a conventional, binary seasonal classification and applies prominent rainfall metrics from climate science. It presents evidence that seasonal piped water revenue and therefore demand for services appears stable where wet season rainfall is more erratic. This approach can offer localised insight into piped water demand dynamics and identify hotspots of climate vulnerability by revealing intra-seasonal nuances and long-term rainfall trends.

Methodological Contributions

The project has drawn on operational data from rural piped water service areas in six countries across the eastern (Kenya, Rwanda, Tanzania, Uganda), western (Ghana), and southern (Malawi) regions of Africa. This geographic distribution has been intentionally maintained throughout the analyses to facilitate translation of the findings across the remaining 40 sub-Saharan countries. Yet valid concerns arising from measurement errors and unrepresented variables inherent in the secondary dataset have also needed to be addressed. As discussed alongside other limitations of the project in section 3.6, operational data are, by nature, bounded and prone to error. Furthermore, the research is interested in complex and interrelated water use and payment behaviours that are moderated by numerous factors, most of which are either not feasible to measure or unknown and cannot be controlled in the analyses. This hinders transferability and can bias the results. The three papers have made systematic conceptual and methodological contributions that acknowledge the unknown influence of unrepresented variables while attempting to generate findings that reach beyond the contextual boundaries of the study domain.

Paper one conceptualises and demonstrates a flexible data and monitoring framework that can be readily applied across sub-Saharan Africa. Since changes in piped water usage are found to align more closely with rainfall patterns than any socio-technical variable in the project dataset, the framework combines routine records of water usage from sentinel schemes with data from global rain gauge and satellite observation systems. The only requisite contextual information is whether payments are made on a fixed or volumetric basis. Despite the unknown influence of omitted variables on domestic water demand and payments, the course signals generated by the framework appear useful for interpreting spatial and temporal threats to piped water sustainability.

Paper two responds to endogeneity by analysing patterns across groups of interest instead of drawing comparisons between groups. The approach assumes idiosyncratic effects are consistent within the groups and focuses on macro-level interpretation. Application of this logic to rural water supply, which is also fundamental to paper three, is a notable contribution of the project because it can help future studies avoid pitfalls when interpreting results and exploring causality. In paper two, service areas are clustered by operator. Descriptive statistics and ANOVA results indicate the operators experience significantly different levels of seasonal revenue variability. If the interpretation had focused on between-operator differences, these results could have been understood to indicate unmeasured service attributes or contextual factors lead operators to experience different levels of seasonal revenue variability. Instead, the paper takes a view across the groups and points out that homogeneous subsets of operators identified during post-hoc testing align with patterns identified in the analysis of rainfall metrics, specifically the instances of consecutive dry days during the wet season. This finding supports an alternative explanation for the between-operator differences involving intra-seasonal rainfall instead of attributing to unknown or omitted factors.

Paper three advances the approach introduced in paper two by observing patterns across groups of records clustered at multiple levels of conceptual interest. This approach, which is reviewed at depth in section 3.4, is known as archetype analysis in sustainability research and has not been previously applied to rural water supply. The redundancy afforded by multi-level clustering strengthens and supports transferability of the paper's findings. In a broader sense, the service area archetypes described in the paper collectively represent a practical analytical framework for controlling the influence of the macroscale enabling environment and local-scale planning and implementation approach when critical techno-institutional variables are unmeasurable or unknown. Instead of comparing service delivery outcomes from country to country or within state- or enterprise-led investments, recurring patterns are identified across all archetypes and assembled into a global narrative. This framework lays a foundation for future water, sanitation, and hygiene research which is further discussed in section 7.3.

7.2. Recommendations

This research challenges conventional assumptions about domestic demand and financial sustainability in relation to rural piped water services as countries strive to achieve SDG 6.1. The observed household-level services exhibit similar seasonal revenue variability as off-site services and are not consistently associated with higher revenue when tariff level is controlled. Furthermore, prepaid credit payments for the observed rural piped services do not consistently improve revenue generation compared to conventional payment approaches. The implications of these findings for revenue planning have been discussed in the research papers. Three recommendations for rural water policy and practice, which can enhance the viability, resiliency, and equitability of future infrastructure investments, are highlighted in this section.

> ***Recommendation 1:*** *Assess rainfall patterns on localised, intra-seasonal scales to characterise the threat of seasonal revenue variability to rural piped water services*

Paper one and paper two present evidence that seasonal piped water usage and revenue patterns vary geospatially and align with regional climate regimes. While the threat of routine revenue deficits is pronounced in areas with consistent wet season rainfall, inconsistent rainfall in other areas may lead to greater dependence on professional and reliable water services. A practical priority arising from these findings is to assess historical rainfall patterns corresponding to rural water service areas on localised, intra-seasonal scales. Geospatial precipitation datasets are publicly available and can be utilised in such exercises. See Beck et al. (2017) for a recent global evaluation. Rainfall reliability, particularly during the wet season, may be a more pertinent metric than average rainfall volume or season duration. In areas where wet season rainfall is consistent, routine revenue threats to service providers can be anticipated and pre-emptively addressed. In areas where seasonal rainfall patterns are erratic, households are likely unable to rely on rain-fed sources to supplement their daily water needs and may be vulnerable to primary service disruptions. Ensuring service reliability in such areas should be a high priority.

Paper one also demonstrates a potential for coupling regional rainfall forecasts with routinely monitored water usage to identify evolving revenue threats. Such signals contribute a nuanced and timely understanding of rural piped water demand and revenue relative to geospatial rainfall patterns, which can aid in prioritising and targeting responses. Environmental information systems are commonly employed to monitor water resource indicators against rule-based plans and trigger timely actions when predetermined thresholds are surpassed. Similar approaches can be applied to rural drinking water services and can inform adaptive policies that respond to changing socio-climatic conditions.

The conclusion that rural piped services can face a seasonal threat to revenue poses an implication for water demand and revenue planning in Africa, where contemporary service delivery and tariff models have evolved from an urban, utility-based paradigm. These models anticipate daily and annual fluctuations in domestic demand due to cyclic water consumption patterns but fail to consider the substantial influence of competing water sources. This oversight can lead to meaningful consequences where households regularly use water from several sources for different domestic and productive purposes. Physical leaks and uncollected or misappropriated user payments, quantified as nonrevenue water, is an underlying driver of poor cost recovery in the water supply sector (Liemberger and Wyatt, 2018). This research reveals how unplanned financial deficits from seasonal revenue variability can compound with nonrevenue water to stress service provision and hinder investment. For the average service area observed in this project that experiences seasonal revenue variability, the annualised deficit due to wet season revenue decline is 15 percent. This sizeable amount is nearly half of the average 34 percent annual financial loss due to nonrevenue water reported by sub-Saharan utilities (IBNET, 2020).

Financial models which fail to account for either of these shortfalls will underperform and struggle to be sustainable. However, unlike nonrevenue water which in theory can be reduced with enhanced operational performance and tariff collection, analysis of the service attributes observed in this project finds little evidence to suggest seasonal revenue variability can be mitigated with interventions that target a short-term demand response.

Rural piped water operators who are losing market share to alternative sources such as seasonal rainwater may seek to understand what aspects of water services households prefer, and what it would take to incentivise consistent year-round use of the piped service. The water demand literature reviewed in section 2.4 suggests rural households in low- and middle-income countries may be prone to exchanging payment-based water services for seasonal rainwater if it is less expensive, more convenient, more reliable, and an acceptable quality for non-consumptive uses. The analytical approach taken in paper two is thus based on a hypothesis that reliable piped water services provided on household premises, which are at least as convenient as rain-fed sources during wet seasons, may stabilise willingness to pay for the primary service and reduce seasonal revenue variability. However, wet season revenue decline across the observed service areas appears consistent regardless of whether waterpoint connections are located on or off premises. Furthermore, seasonal dynamics explored in paper one and paper two do not appear to be consistently influenced by the country where services are located, the type or size of scheme supplying the services, the tariff level, various volumetric payment approaches, or whether schools or healthcare facilities are served by the scheme.

The only service attribute available in the project dataset that seems to dampen seasonal changes in either demand or revenue is fixed fee payments (see paper one). Where fixed payments for accessing primary water sources are made monthly or less frequently, households may be less likely to factor price comparison into their decision to collect from free, rain-fed sources during the wet season (Ingram and Thomson, 2022). In Kenya, fixed fees have been associated with less use of unimproved drinking water sources than volumetric payments, but also with overall lower rates of revenue generation (Foster and Hope, 2017). Furthermore, shifting between fixed and volumetric payments on a seasonal basis poses administrative challenges and could lead to unintended consequences such as even greater demand decline. It may be advantageous to adopt fixed fees on a temporary or permanent basis in cases where piped services struggle to generate revenue year-round, but the approach is not broadly recommended as a measure to relieve seasonal financial stress.

This research has examined an admittedly narrow and opportunistic selection of water service attributes in relation to seasonal revenue variability. Even so, the consistency in its findings suggests interventions that aim to incentivise water user behaviour and reduce or eliminate seasonal threats to revenue in the near-term, such as increasing the number of household connections or adjusting tariff levels on a seasonal basis, may prove unsuccessful. Supply-side measures that ensure adequate financial resources are available throughout periods of reduced demand may be more effective at mitigating seasonal revenue variability. Candidate interventions such as cash flow planning, risk pooling, and smart subsidies are identified and briefly discussed in paper two. An outstanding knowledge gap is how rural household preferences and water source choices evolve in response to changes in service attributes over longer timescales.

> ***Recommendation 2:*** *Leverage complementary revenue patterns of on- and off-premises services at incremental stages of infrastructure investment*

Paper three finds that rural piped water services delivered on and off household premises exhibit complementary revenue patterns. Where users can afford it, on-premises connections paired with higher tariff levels generate more revenue than off premises services and experiencing similar seasonal revenue variability. However, at equivalent tariff levels, off-site kiosks and standpipes facilitate comparable seasonal revenue at lower up-front cost per capita. Piped services provided off premises can hence contribute to overall financial viability in proportion with on-premises connections while providing an equitable lifeline for vulnerable populations.

This evidence helps to clarify the financial implications of infrastructure decisions aimed at extending universal safely managed services into rural Africa. Strategies that balance capital expenditure with ability to recover recurring costs are needed to maximise water service coverage and sustainability throughout the investment lifespan. It is generally prudent to focus initial investments on assets that can generate the most revenue at the lowest up-front cost. Large water schemes with extensive distribution networks that pipe water directly to every household may be economically viable in densely populated rural areas while smaller schemes that utilise kiosks and standpipes might pose certain advantages in other settings. Detailed water demand studies are needed to accurately anticipate the influence of infrastructure and pricing decisions on demand and user payments (Nauges and Whittington, 2009). Yet rural water investment decisions in Africa seldom draw on empirical evidence and instead rely on loose assumptions about which water sources households will choose to use, how much water they will use and pay for, and how much revenue the services will generate. The greatest potential for error lies in how water demand and revenue rates are anticipated from off-site versus household level services, which often deviate by a factor of five or more. Rural water infrastructure investments that are based on unrealistic revenue estimates can result in services that underperform both financially and operationally, derailing subsequent stages and posing social and public health consequences.

This project has intentionally maintained a multi-country scope and therefore has not endeavoured to undertake the type of place-based econometric analysis needed to develop water demand functions and estimate price elasticity. It has also not evaluated life-cycle costs of the observed service delivery alternatives, nor has it been possible to analyse differences in domestic water usage rates between on and off-premises connections (see project limitations discussed in section 3.6). However, the research has generated understanding about how different waterpoint types and tariff levels can be combined at incremental stages of investment to enhance overall revenue from user payments for piped water services in rural Africa. The results suggest it can be advantageous to prioritise limited resources in early stages on constructing piped schemes that provide off-site access, but which can be strategically upgraded in areas where users can afford to pay more when demand is expressed. This logic has traditionally been applied by urban utilities seeking to optimise financial viability and target delivery of subsidies (Andres et al., 2019, Foster and Briceno-Garmendia, 2010, Komives et al., 2005) but has not been widely examined in the rural water subsector.

Infrastructure investment strategies that prioritise off-site services at key stages are not at-odds with the overarching goal of universal safe water access at the household level. Rather, this research demonstrates that blended service levels, potentially even widespread off-premises connections, can serve as a viable and catalytic step in the pathway to establishing universal safely managed services for rural African households. Well-managed piped services provided off household premises can meet the quality and reliability criteria for safely managed service established by SDG 6.1. Investments in off-site water infrastructure afford these incremental benefits to users while overcoming substantive capital and recurring funding gaps that must be addressed for the services to continue being delivered until development goals and holistic returns are realised. Furthermore, untargeted and uncoordinated expansion of household level piped connections into rural areas could pose equity and affordability challenges for users who are unable to pay for incremental up-front or ongoing cash expenses associated with higher service charges. Paper three reports that on-premises connections across the project dataset are associated with an average 17 percent higher tariff level in three of the four constructed service area archetypes. Without careful and informed consideration of the demand response, expansion of services delivered on premises could be met with reduced usage and diminished revenue as users opt to collect lower priced water from informal or unimproved sources. This would effectively reduce positive impacts that might have been achieved by providing affordable off premises services to targeted socioeconomic groups.

> ***Recommendation 3:*** *Exercise caution when considering prepaid credit over conventional payment approaches to prevent unrealistic revenue expectations and perverse outcomes*

Decisions about water supply infrastructure are integrally linked to service delivery and payment collection arrangements. The prepaid credit approach promises to address many of the revenue collection challenges that have troubled the water sector for decades, and investments in hardware to support the approach are often considered simultaneously with piped water expansion into rural areas. Yet, this research has emphasised that more evidence is needed to understand the trade-offs of prepaid credit systems relative to conventional payment collection approaches in the context of rural piped water services.

Paper two and paper three compare revenue patterns from hundreds of rural piped water schemes across Ghana, Rwanda, and Uganda that utilise conventional and prepaid credit payments. The resulting evidence begins to reveal how different payment collection approaches influence financial viability of safely managed water services in rural Africa. Descriptive statistics of revenue records presented in paper three indicate prepaid credit generates higher volumetric revenue rates than conventional payment approaches in many contexts, especially when paired with off-premises connections. However, regression results show revenue rates between the two approaches are similar when tariff levels are controlled. This implies the apparent revenue benefits of prepaid credit payments across the piped water services represented in the project dataset are associated with higher tariffs and not necessarily improved revenue collection efficiency. Furthermore, paper two reports seasonal revenue reductions across all payment approaches observed in the study and finds prepaid credit payments are not consistently associated with less seasonal revenue variability than conventional payments. It seems prepaid credit does not motivate households to forego supplementing water collection from rain-fed sources during the wet season, presumably because they make purchases at relatively high frequencies and in small amounts.

The financial advantages of prepaid credit over conventional payment approaches remain unclear in the context of piped water services in rural Africa. These findings suggest the prepaid credit approach should be carefully adopted with realistic revenue expectations and a holistic consideration of the social and economic implications to prevent perverse outcomes for vulnerable user groups. If tariffs must be set at a higher level to generate more revenue when deploying prepaid credit systems, the adverse social impact may negate any other intended benefits. Likewise, if prepaid credit does not increase or at least stabilise seasonal revenue, the capital-heavy investment might not justify the non-cash benefits. When these financial implications are considered alongside mounting evidence that prepaid credit technologies utilised by water service providers are often unreliable, poorly managed, and can lead to perverse economic and social consequences (Guma and Wiig, 2022, Heymans et al., 2014, Komakech et al., 2020), it becomes difficult to make a case for promoting the approach.

In contrast, the research has demonstrated that conventional payment collection approaches, such as PAYF and post-use volumetric billing, can generate substantial revenue when paired with appropriate service delivery models while experiencing similar seasonal variation as prepaid credit methods. The analyses are not able to distinguish whether comparability of revenue rates between the two payment approaches are more reflective of true efficiency and effectiveness rather than a common susceptibility to revenue mishandling. Nonetheless, the evidence supports an assertion that institutional arrangements are at least as important as technical measures in enforcing payments for rural services (Koehler et al., 2015) and should be a focal point for future research.

7.3. Future Research

The rural drinking water paradigm in Africa is transitioning from community managed handpumps to professionally managed piped services. As exemplified by the piped water operators observed in this project, there is potential for this shift to lead to higher service levels that incentivise user payments, enhance revenues, and reduce the chronic financial threat to the sector. However, piped water is not a panacea for the underlying environmental, institutional, social, and financial challenges that threaten the sustainability of rural water supply in Africa. Although these challenges are well-rehearsed in the literature, the influence of and on piped water particularly regarding cost recovery is critically understudied and therefore not well understood. The recommendations made in section 7.2 demonstrate how this project has begun to elucidate some of the important relationships between rural piped water technologies and the institutions that manage them. However, the research has also generated additional questions. Perhaps the most salient motivation for future research arising from the project is to support rural water policy makers and practitioners in navigating between the commendable goal of extending and sustaining universal household services and the often-misaligned reality of domestic willingness and ability to pay.

Further research is recommended in four areas based on these reflections as well as the cumulative analyses, findings, and implications described in this thesis. First, the research can be strengthened through analysis of wider, deeper, and experimental datasets. Although care has been taken during the project to generate findings which apply broadly across sub-Saharan Africa, they should be validated in different countries and service delivery contexts. Limited data availability, which is a persistent impediment to social science research in the rural water sector, has also constrained the analytical approach of this project. For example, accurate and reliable service population estimates would have enabled demand to be analysed per capita in paper one and paper three in addition to per unit volume. Furthermore, the dataset does not enable social and institutional explanations to be explored.

Socioeconomic factors such as cultural norms, education level, spending power and priorities, and perceptions of affordability, which likely influence the seasonal water usage and payment behaviours of rural households in the observed piped water service areas, are not reflected in the dataset. Analysis of representative data for these and other factors could reveal important multidirectional relationships and patterns beyond those which have been evaluated in the project. These factors are also likely to interact with each other, and their influence on domestic water demand and payments could evolve over months, years, or even decades. Although the project data are longitudinal, they may not span enough time for these interactions to occur. Experimental research is needed to observe such effects in targeted treatment and control populations.

Second, the service area archetypes presented in paper three are broadly applicable within the rural water and sanitation domain and can be enhanced and leveraged to study additional lines of inquiry. In particular, there is potential to improve the treatment of institutional arrangements within the multi-level archetypal framework by applying cultural theory of risk and building on the "rural waterpoint management cultures" conceptualised by Koehler et al. (2018). A key opportunity for future research relates to the unit of analysis. The data in the project has been structured around distinct service areas, defined as the operational area of a single piped water operator with temporal resolution of financial data and one or multiple waterpoints of common scheme type and access mode. Application of the cultural theory of risk would involve categorisation of each service area according to the primary management culture involved in collection of user fees. Although such classification exercises have historically required extensive ethnography, the theory has been applied on a global scale in recent years using secondary survey data to classify individuals across the group-grid spectrum (Castilla-Rho et al., 2017, 2019, Chuang et al., 2020). A valuable additional level of characterisation would be to distinguish whether additional market, community, bureaucratic, and fatalist management cultural perspectives are represented in the service delivery arrangement.

Third, more research is needed to understand how the project findings relate to revenue collection efficiency. Paper two and paper three have chosen to prioritise examination of the relationship between revenue generation and concrete explanatory variables: waterpoint type, payment approach, and tariff level. The papers consider how these variables influence domestic water use and payments, and hence revenue. However, their modifying effects on the operators' ability to collect revenue have not been fully explored. Prepaid credit approaches are touted for their ability to ensure cash transactions are fully accountable and therefore less prone to mishandling. Likewise, it is hypothetically simpler to restrict water access and enforce user payments with on-premises connections compared to off-premises standpipes and kiosks. Yet, the project's results suggest the financial benefits of prepaid credit systems and on-premises connections in practice may be minimal at equivalent tariff levels. Furthermore, the management culture involved in collecting user fees will undoubtedly have an effect on collection efficiency, and arrangements with strict rules and enforcement may experience similar outcomes as technology-based approaches such as prepaid credit. Additional research questions along these lines could be investigated with the existing project dataset.

Fourth and finally, the costs and benefits of integrated socio-climatic monitoring processes and systems that build on the concepts explored in paper one and paper two could be explored and refined. This research has emphasised that climate change will not only influence sub-Saharan water resources and infrastructure, but also the financial viability of drinking water services on which rural populations across the subcontinent depend. Furthermore, impacts are likely to result from extreme weather events, which are fairly easily recognised, as well as nuanced shifts in rainfall patterns, which can be more difficult to identify. Multisectoral monitoring systems with the geospatial and temporal sensitivity to detect such nuances are needed. This will require interdisciplinary coordination among practitioners and academics across climate and water management fields. Such an endeavour is challenging, expensive, and impractical without strong leadership and commitment from governments. Better understanding of the advantages will aid in efforts to advocate for and justify investments in socio-climatic monitoring.

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Appendix I: Master Database Field List

Database	Field Name	Field Type	Notes	Num. Records
DB1_service_areas	service_area_id	int	All waterpoints in a service area have common scheme & waterpoint type. Some service areas are located in geographically overlapping areas	390
DB1_service_areas	service_area_name	varchar		
DB1_service_areas	service_provider_id	int	Service provider names linked to IDs in a separate database	
DB1_service_areas	region_id	int		
DB1_service_areas	service_area_lat	decimal	Schemes with off & on premises connections separated into coincidental service areas	
DB1_service_areas	service_area_lon	decimal	Schemes with off & on premises connections separated into coincidental service areas	
DB1_service_areas	management_bureaucratic	binary	(1=yes, 0=no) Charcterised by some element of public service provision **SUBJECTIVE & UNVALIDATED CLASSIFICATION**	
DB1_service_areas	management_community	binary	(1=yes, 0=no) Charcterised by some element of community based service provision **SUBJECTIVE & UNVALIDATED CLASSIFICATION**	
DB1_service_areas	management_market	binary	(1=yes, 0=no) Characterised by some element of private service provision **SUBJECTIVE & UNVALIDATED CLASSIFICATION**	
DB1_service_areas	support_entity	public, CSO, private, unsupported		
DB1_service_areas	installation_date	date		
DB1_service_areas	installation_origin	new, existing		

Database	Field Name	Field Type	Notes	Num. Records
DB2_regions	region_id	int	Sub-national administrative unit equivalent to district (e.g. county in KE, department in HN, region in ID)	61
DB2_regions	region_name	varchar		
DB2_regions	country_name	varchar		
DB2_regions	global_area	SSA, LAC, SEA, SA		
DB2_regions	gdp_deflator_2016	decimal	World Bank GDP deflator factors	
DB2_regions	gdp_deflator_2017	decimal	World Bank GDP deflator factors	
DB2_regions	gdp_deflator_2018	decimal	World Bank GDP deflator factors	
DB2_regions	gdp_deflator_2019	decimal	World Bank GDP deflator factors forecasted from historic values	
DB2_regions	ppp_conversion	decimal	World Bank 2019 PPP conversion factors, private consumption	
DB2_regions	dollar_conversion_2016	decimal	Conversion from historic local currency to 2019 international dollars at PPP	
DB2_regions	dollar_conversion_2017	decimal	Conversion from historic local currency to 2019 international dollars at PPP	
DB2_regions	dollar_conversion_2018	decimal	Conversion from historic local currency to 2019 international dollars at PPP	
DB2_regions	dollar_conversion_2019	decimal	Conversion from historic local currency to 2019 international dollars at PPP using forecasted GDP deflators	

Database	Field Name	Field Type	Notes	Num. Records
DB3_financials	financials_id	int		6,074
DB3_financials	service_area_id	int		
DB3_financials	month	int	All records sum monthly and correspond with a specific month of the year	
DB3_financials	quarter	int		
DB3_financials	year	int		
DB3_financials	local_revenue_total	decimal		
DB3_financials	local_revenue_fee	decimal	Total monthly revenue from flat fees	
DB3_financials	local_revenue_sale	decimal	Total monthly revenue from water sales	
DB3_financials	local_revenue_other	decimal	Total monthly revenue from other sources	
DB3_financials	tariff_collection	prepaid_meter, PAYF, monthly, annually, other		
DB3_financials	tariff_structure	fixed, volumetric	All volumetric tariffs are based on a flat rate (not increasing or decreasing blocks)	
DB3_financials	local_tariff_level	decimal		
DB3_financials	local_currency	varchar		

Database	Field Name	Field Type	Notes	Num. Records
DB3_financials	local_tariff_unit	household_month, 20L		
DB3_financials	dollar_revenue_total	decimal	Total revenue converted at 2019 PPP	
DB3_financials	dollar_revenue_cubic_meter	decimal	Total volumetric revenue converted at 2019 PPP	
DB3_financials	dollar_revenue_waterpoint	decimal	Total waterpoint revenue converted at 2019 PPP	
DB3_financials	dollar_tariff_level	decimal	Tariff level converted at 2019 PPP	
DB3_financials	dollar_tariff_unit	household_month, cubic_meter		
DB3_financials	dollar_NRW	decimal	calculation only available for volumetric tariffs	
DB3_financials	infrastructure_age	int	age in months	
DB4_service_levels	levels_id	int		7,023
DB4_service_levels	service_area_id	int		
DB4_service_levels	month	int	All records sum monthly and correspond with a specific month of the year	
DB4_service_levels	quarter	int		
DB4_service_levels	year	int		

Database	Field Name	Field Type	Notes	Num. Records
DB4_service_levels	volume_produced	int	All records represent metered readings	
DB4_service_levels	volume_produced_confidence	automated, manual, estimated		
DB4_service_levels	waterpoint_type	on premises, off premises	off premises connections include kiosks and standpipes, on premises connections include on and off plot connections	
DB4_service_levels	waterpoint_total	int	Total number of waterpoints in service area	
DB4_service_levels	gravity_schemes	int	Source of power for supply line, not distribution line	
DB4_service_levels	motorised_schemes_grid	int		
DB4_service_levels	motorised_schemes_diesel	int		
DB4_service_levels	motorised_schemes_solar	int		
DB4_service_levels	motorised_schemes_hybrid	int	Primary power source is solar with AC or diesel genset backup	
DB4_service_levels	water_source_type	ground, surface		
DB4_service_levels	water_source	borehole, canal, dug well, river, lake, spring		
DB4_service_levels	institutions_served	int		

Appendix II: Executed Data Use Agreements

Note: The executed agreement with Water For People covers data provided by Ayateke Star, Biguli Traders Association, Mid-Western Umbrella of Water and Sanitation Authority (Uganda), and Power Technical Services. Water Mission and Water4 declined to sign a formal data use agreement.

Water For People

UNIVERSITY OF
OXFORD

THE CHANCELLOR MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD

and

WATER FOR PEOPLE, a Colorado not-for-profit charitable organization

DATA USE AGREEMENT

THIS AGREEMENT dated 27/3/2020 2020 is made **BETWEEN:**

(1) **THE CHANCELLOR MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD** whose administrative offices are at University Offices, Wellington Square, Oxford OX1 2JD, England (the "University"); and

(2) **WATER FOR PEOPLE** a Colorado not-for-profit organization whose registered address is 100 East Tennessee Avenue, Denver, Colorado 80209 (the "Provider").

WHEREAS:

(A) The Student, as part of his DPhil in Geography and the Environment at the University, is undertaking a research project on "Financing Piped Water Services in Rural Africa and Asia", which aims to examine the drivers for revenue generation and risks to social equity associated with user payments for piped water services in order to addresses the gap in funding and financing necessary to achieve SDG 6.1 (the "**Project**"); and

(B) The Provider has certain Data relevant to the Project and is willing to provide a copy of such Data to the University to enable the Student to undertake the Project as part of his DPhil studies at the University (the "Purpose") on the terms set out in this Agreement; and

(C) The Parties acknowledge that the Student is undertaking the Project to submit a related thesis for examination in accordance with the University's regulations governing post-graduate study in fulfilment of the requirements of a higher degree of the University. The Parties further acknowledge that the Project is also intended to lead to academic publications relating to the results of the Project in furtherance of the Student's career.

NOW IT IS AGREED as follows:

1. Definitions

Unless defined elsewhere in this Agreement the following terms have the following meanings:

1.1 "**Data**" means the data more particularly described in the Schedule to this Agreement which is disclosed by the Provider to the University;

1.2 "**Student**" means Andrew Armstrong

2. The Data

2.1 The Data shall remain at all times the property of the Provider. Except as permitted expressly by the terms of this Agreement, the University shall not disclose the Data to any third party.

2.2 The University shall not acquire any rights to the Data disclosed to it under this Agreement, and shall not use it for any purpose other than in connection with the Purpose without the prior written consent of the Provider.

2.3 The University shall not in any way reproduce or commercially exploit the Data for its own benefit, or for the benefit of another, without the prior written consent of the Provider.

2.4 The University shall use the same degree of care as it uses to protect its own confidential information, but no less than reasonable care, to prevent the unauthorised use, dissemination or publication of the Data.

2.5 The University shall disclose or otherwise make available the Data only to those employees of the University, external examiners, external lecturers and the Student who need access to the Data for the performance of their work with respect to the Purpose, and who have been notified that the Data is confidential.

2.6 The Data disclosed under this Agreement will be delivered "AS IS"; and the Provider makes no warranty of any kind with respect to the accuracy of the Data which it discloses, or with respect to the suitability of such Data for the Purpose or for any other particular use.

3. The University's Rights

3.1 Nothing contained in this Agreement shall in any way restrict or impair the University's right to use, disclose or otherwise deal with any portion of the Data which:

3.1.1 was known to the University before receipt from the Provider, and was not received by the University under an obligation of confidentiality owed by the University to the Provider;

3.1.2 is or becomes publicly known without the fault of the University;

3.1.3 is obtained by the University from a third party in circumstances where the University has no reason to believe that there has been a breach by the provider of the information of an obligation of confidentiality owed to the Provider;

3.1.4 the University can establish by reasonable proof was substantially and independently developed by officers, employees or students of the University who had no knowledge of the Provider's Data;

3.1.5 is approved for release in writing by an authorised representative of the Provider; or

3.1.6 the University is specifically required to disclose by law or pursuant to the order of any court of competent jurisdiction provided that, in the case of a disclosure under the Freedom of Information Act, none of the exemptions in that Act applies to the Information.

4. Freedom of Information Act 2000

If the University receives a request under the Freedom of Information Act to disclose any Data, it will notify and consult with the Provider. The Provider will respond within five days after receiving notice if the notice requests assistance in determining whether or not an exemption in the Act applies.

5. Individuals

5.1 Each party to this Agreement undertakes to make no claim in connection with this Agreement or its subject matter against any employee, student (including the Student), agent or appointee of the other (except for claims in relation to fraud or wilful misconduct). This undertaking is intended to give protection to individuals: it does not prejudice any right which a party might have to claim against the other. The benefit conferred by this clause is intended to be enforceable by the persons referred to in it.

6. Liabilities

6.1 The Provider warrants that it has the right to disclose the Data to the University and that to the best of the Provider's knowledge the Data disclosed does not infringe any third party intellectual property rights.

6.2 The liability of either party to the other for any breach of this Agreement, for any negligence or arising in any other way out of the subject matter of this Agreement will not extend to any indirect damages or losses, or to any loss of profits, loss of revenue, loss of business, loss of data, loss of contracts or opportunity, whether direct or indirect.

6.3 In any event, and in order to conserve the assets of the University for application to its charitable purposes the maximum liability of the University to the Provider under or otherwise in connection with this Agreement or its subject matter shall not exceed £100,000.

6.4 Nothing in this Agreement limits or excludes either Party's liability for: (a) death or personal injury resulting from its negligence; (b) any fraud, or (c) any other liability which, by law, cannot be limited or excluded.

7. Publications

7.1 The University and Student may publish the results of the Project in accordance with standard academic practice.

7.2 The University and Student will acknowledge the Provider's contribution of the Data in any publication based on the Data in accordance with reasonable current practice consistent with the nature of the Data and of the publication in question.

7.3 Nothing in this Agreement shall prevent or hinder the Student from submitting for a degree of the University a thesis, dissertation or comparable work completed by him with the aid of the Data, the examination of such a thesis, dissertation or comparable work by any examiners appointed by the University or the deposit of such a thesis, dissertation or comparable work in any library of the University in accordance with the relevant procedures of the University. Upon the reasonable request of the Provider, the Student may seek to make seek to make such thesis, dissertation or comparable work subject to the University's policies of restricted access. For the avoidance of doubt the Provider hereby acknowledges that the University cannot guarantee that the thesis, dissertation or comparable work will be placed on restricted access.

8. Termination

8.1 This Agreement may be terminated by either Party for any material or persistent breach of the obligations set out in this Agreement, by giving ninety (90) days' written notice to the other of its intention to terminate. The notice shall include a detailed statement describing the nature of the breach. If the breach is capable of being remedied and is remedied within the ninety-day notice period, then the termination shall not take effect. If the breach is of a nature such that it can be fully remedied but not within the ninety day notice period, then termination shall also not be effective if the party involved begins to remedy the breach within that period, and then continues diligently to remedy the breach until it is remedied fully. If the breach is incapable of remedy, then the termination shall take effect at the end of the ninety day notice period in any event.

9. General

9.1 This Agreement is not transferable, and neither party may purport to assign it (in whole or in part) without the prior written consent of the other.

9.2 No one except a party to this Agreement has any right to prevent the amendment of this Agreement or its termination, and no one except a party may enforce any benefit conferred by this Agreement, unless this Agreement expressly provides otherwise.

9.3 The University's duty to protect the Data shall survive the termination of the Purpose and continue in full force and effect for the period of three years thereafter.

9.4 If the whole or any part of the Data becomes the subject of any further agreement between the parties, then the terms of this Agreement shall be superseded by that further agreement; but only in respect of such part of the Data as is the subject of such further agreement.

9.5 This Agreement shall be governed by English Law, and the parties submit to the exclusive jurisdiction of the English Courts for the resolution of any dispute which may arise out of this Agreement.

9.6 This Agreement may be executed in any number of counterparts, each of which when executed will constitute an original of this Agreement, but all counterparts will together constitute the same agreement. No counterpart will be effective until each Party has executed at least one counterpart.

AS WITNESS the hands of authorised signatories for the parties on the date first mentioned above.

SIGNED for and on behalf of **THE CHANCELLOR MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD**:

Name: Eve Henshaw

Position: Senior Research Contracts Manager

Signature: Eve Henshaw

Date: 27/3/2020

SIGNED for and on behalf of: **WATER FOR PEOPLE**

Name: Stephen Oakley

Position: Chief Legal officer

Signature: S Oakley

Date: 3-18-2020

Acknowledged by the Student

Name: Andrew M. Armstrong

Signature: [signature]

Date: 26 March 2019

Acknowledged by the Student's Supervisor

Name: Professor Rob Hope

Signature: Rob hope

Date: 26 March 2020

Safe Water Network

THE CHANCELLOR MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD

and

SAFE WATER NETWORK

DATA USE AGREEMENT

THIS AGREEMENT dated 27/3/2020 2020 is made **BETWEEN:**

(1) **THE CHANCELLOR MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD** whose administrative offices are at University Offices, Wellington Square, Oxford OX1 2JD, England (the "University"); and

(2) **SAFE WATER NETWORK,** a not-for-profit organization whose registered address is 122 East 42[nd] Street, Suite 2800, New York, N.Y. USA 10168 (the "Provider").

WHEREAS:-

(A) The Student, as part of his DPhil in Geography and the Environment at the University, is undertaking a research project on "Financing Piped Water Services in Rural Africa and Asia", which aims to examine the drivers for revenue generation and risks to social equity associated with user payments for piped water services in order to addresses the gap in funding and financing necessary to achieve SDG 6.1 (the "**Project**"); and

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7.3 Nothing in this Agreement shall prevent or hinder the Student from submitting for a degree of the University a thesis, dissertation or comparable work completed by him with the aid of the Data, the examination of such a thesis, dissertation or comparable work by any examiners appointed by the University or the deposit of such a thesis, dissertation or comparable work in any library of the University in accordance with the relevant procedures of the University. Upon the reasonable request of the Provider, the Student may seek to make seek to make such thesis, dissertation or comparable work subject to the University's policies of restricted access. For the avoidance of doubt the Provider hereby acknowledges that the University cannot guarantee that the thesis, dissertation or comparable work will be placed on restricted access.

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AS WITNESS the hands of authorised signatories for the parties on the date first mentioned above.

SIGNED for and on behalf of **THE CHANCELLOR MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD:**

Name: Eve Henshaw

Position: Senior Research Contracts Manager

Signature: Eve Henshaw

Date: 27/3/2020

SIGNED for and on behalf of: **SAFE WATER NETWORK**

Name: ALLEN K. MERRILL

Position: DIRECTOR, GLOBAL STRATEGIC INITIATIVES

Signature: Allen K Merrill

Date: March 26, 2020

Acknowledged by the Student

Name: Andrew M. Armstrong

Signature: [signature]

Date: 26 March 2019

Acknowledged by the Student's Supervisor

Name: Professor Rob Hope

Signature: Rob hope

Date: 26 March 2020

Schedule

The Data

The dataset will consist of the following:

- Water service area characteristics (geolocation, institutional arrangements, and waterpoints)
- Financials (monthly or quarterly revenues, tariff rates, and payment modalities)
- Service levels (monthly or quarterly access modes, service continuity, and water quality)