Policy design and professional service delivery performance of drinking water services in rural Mali

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Abstract

This thesis examines how contract design and consumer demand affect revenue generation to sustain the professional delivery of drinking water services in rural Mali. The research provides an empirical and conceptual understanding of the role of 1) contract arrangements, 2) service levels, and 3) tariff designs for revenue generation, contributing new insights for rural water sustainability. To this end, contractual changes in service delivery – including upgrading handpumps to solar kiosks and changing payment modalities at handpumps from volumetric to flat fees – are analysed drawing on more than 4,800 months of data from 192 waterpoints.

Guided by contract and consumer demand theories, the findings indicate that any rural water contract is likely to be incomplete due to the inability to guarantee user demand. While contract renegotiation can help navigate uncertainties in operational and financial performance, unpredictable demand variability limits the scope of revenue generation of a commercial contract design to sustain rural water services. The quantitative analyses apply Interrupted Time Series and fixed effects regression models to estimate revenue and volumetric water use changes from upgrading to solar kiosks and changing payment modalities. Notably, users appear more inclined to pay a volumetric tariff at solar kiosks, resulting in improved revenue generation. Additionally, when payment modalities switch from volumetric to monthly flat fees, a handpump registers, on average, more than three times higher monthly revenue, along with a two-fold increase in daily water use. Yet, regardless of infrastructure type and payment modality, demand remains seasonal, leading to fluctuating revenues with peaks biased to the dry season.

Three recommendations are proposed to steer rural water policy and practice towards more sustainable services. First, investments in incremental service level improvements are recommended to meet user demand and enhance revenue generation. Second, continuously collected operational and financial service data can be leveraged to inform investment planning, policy design, and service delivery arrangements. Third, cost-recovery policies should more clearly consider subsidies to sustain the professional delivery of rural drinking water services.

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Chapter 1: Introduction

How can safe drinking water services be effectively delivered to communities in rural Africa? Drinking water supply in rural Africa is characterised by limited operational and financial sustainability. In response to unsatisfactory service outcomes from community-based management approaches, professional service delivery models have emerged for providing safe drinking water to rural populations. However, these models struggle to generate sufficient revenue from user payments to be financially viable. Exploring the recent shift from community management to professional service delivery to improve operational outcomes in rural water, this thesis examines how contract design and consumer demand affect revenue generation to sustain services. Applying quantitative and qualitative methods to a professional service delivery model operating in rural Mali, three interlinking papers assess the extent to which formal contracts constitute an effective mechanism to promote rural water sustainability and evaluate the effects of two specific changes in service attributes on user demand and revenue outcomes.

1.1. Motivation of the research

In rural Africa, more than 500 million people lack safe drinking water services (UNICEF and WHO, 2023). This access challenge is amplified as particular geographical, spatial, socio-political, and economic factors converge to leave approximately 25%-30% of rural waterpoints non-functional at any point in time (Foster, 2013; RWSN, 2010). This means that about $1.5 to 2.5 billion of infrastructure investments go unused after only a short lifespan (Foster et al., 2020). In addition, hand and foot pumps, which are the most common water supply technology in rural Africa, experience frequent breakdowns which can take several weeks or even months to be repaired (Foster and Hope, 2017; Hope, 2015; Smith et al., 2023).

In response to this unsatisfactory performance, and in line with the global policy ambition to deliver safe drinking water services to everyone by 2030 (UNGA, 2015), professional service delivery models have emerged across rural Africa to guarantee the operational sustainability of water supplies (Lockwood et al., 2021; McNicholl et al., 2021; Nilsson et al., 2021). These models use formal contracts in an attempt to promote the operational and financial sustainability of service delivery.

This constitutes a fundamental transformation of the rural water landscape which has traditionally been characterised by informal community-based management with limited accountability for results. For drinking water services, a contract defines a standard of service which the service provider is expected to meet (Charles et al., 2023; McNicholl et al., 2019). In exchange, the contract clarifies the service provider's revenue base, mainly by granting the right to collect tariffs from users (Gia and Fugelsnes, 2010; Janssens, 2011; Kleemeier and Narkevic, 2010; Koehler et al., 2018). This is in line with prevailing policies across sub-Saharan Africa stipulating that operation and maintenance (O&M) costs of rural drinking water services are to be covered through user payments (Foster, 2016, p. 13; Hope et al., 2019, p. 166). Contracts for rural water services thus align operational outcomes with financial objectives of service provision.

Research has now more clearly documented that professional service providers repair failed waterpoints in a few days, whereas communities can take months to complete repairs – if at all (Chintalapati, 2021; Foster et al., 2022; Smith et al., 2023). Despite effectively ensuring improved operational results in accordance with contractual obligations, professional service providers rarely generate sufficient revenue via user payments to be financially viable. Financial data from professional service providers show that user revenue roughly covers a third of the recurring costs of keeping water supply infrastructure reliably working in rural Africa (McNicholl et al., 2021, 2020, 2019). This means that while operational service outcomes are achieved, revenue goals are missed – despite formal contracts that are meant to promote financial sustainability.

This mismatch between contractual expectations and outcomes in implementation speaks to wider issues of contractual incompleteness, a phenomenon well-studied by contract theory (Hart, 2017, 2003; Hart and Moore, 2008, 1988). Hart and Moore (1988) demonstrate that contracts are necessarily incomplete, yet adaptable throughout implementation. An important mechanism for adaptation consists in renegotiation allowing parties to adapt an incomplete contract design to uncertainties regarding anticipated performance. Even though contract theory appears as a salient conceptual tool, it has not yet been applied to rural water services.

Therefore, this thesis draws on contract theory to provide a comprehensive understanding of the prospects and limitations of formal contracts with professional providers for delivering sustainable rural water services. How does contract implementation unfold for the professional delivery of rural water services? What can contract parties do when contractually defined outcomes are not achieved? How can a contract be adapted to uncertainties? What are the implications for performance when changes to a contract are made? This thesis explores these and related questions to generate new evidence on how to deliver rural drinking water services that effectively promote operational and financial sustainability.

1.2. User payments for sustaining services

The limited financial viability of professional service delivery models is a key barrier to achieving rural water sustainability. The collection of user fees is critical for strengthening operational and financial performance (Hope and Rouse, 2013; Thomson and Koehler, 2016). Yet, only one in three households in rural Africa is estimated to pay for its drinking water supply (Foster and Hope, 2017). A better understanding of how to enhance revenue derived from user payments is needed to make progress towards financial sustainability and is thus a core motivation for this research.

Consumer demand theory may provide a helpful lens to understand how rural water user behaviours are related to specific characteristics of a service. As Lancaster (1966a, 1966b) demonstrates, a consumer essentially views a product, be it a good or service, as a bundle of characteristics. Within one single product, there can be the opportunity to adjust characteristics being offered to consumers. Importantly, altering the characteristics of a product can make it more attractive to consumers. Accordingly, drinking water service providers may change specific aspects in the services they deliver to their rural customers in an attempt to increase demand and improve revenue generation.

In the water sector, the Sustainable Development Goal for Water, SDG 6 (UNGA, 2015) identifies attributes of drinking water services in terms of quantity, affordability, proximity, quality, and reliability. These service attributes may provide guidance on key priorities of rural water users to increase demand, unlock payments, and generate revenue more effectively (Hope et al., 2020).

Indeed, there is evidence that specific characteristics of water services do matter for rural users. Studies suggest that rural households are generally willing to pay a reasonable fee for a valuable service (Hope, 2015; Hope and Ballon, 2021, 2019; Mu et al., 1990; Piper and Martin, 1997; Shongwe and Dlamini, 2021; Whittington et al., 1991, 1990) and that tariff design influences water use and payment behaviours (Armstrong et al., 2021; Foster and Hope, 2017, 2016; Koehler et al., 2015; Nauges and Whittington, 2010).

Service improvements are hypothesised to help secure more sustainable revenue streams. Empirical studies supporting this assertion have mostly relied on stated preference methods (Van Houtven et al., 2017). However, factors which influence users' stated preferences are not necessarily those which determine their actual behaviours (de Corte et al., 2021; Griffin et al., 1995). In addition, it is empirically unclear how and to what extent variation in key variables related to service attributes affects actual use of and payments for rural water services (Armstrong, 2022; Nauges and Whittington, 2010). Unpacking the factors that shape demand for professional rural water services is hence a key priority for research and policy to inform propositions that effectively enhance revenue generation to sustain service delivery.

To achieve this, the thesis provides an in-depth study of a professional service delivery model operating in rural Mali. It applies contract and consumer demand theories to examine the contractual performance of and demand for the professional delivery of rural drinking water services in order to identify strategies to strengthen revenue outcomes which may ultimately contribute to enhanced rural water sustainability.

The research has been conducted in collaboration with UDUMA, a professional rural water service delivery company. In Mali, UDUMA has raised private and public capital for government contracts aiming to provide reliable rural water services, subject to user payments. This is one of the first empirical cases in rural Africa where a service provider has deployed long-term contracts to make commercial investments in water supply infrastructure and committed to their subsequent operation and maintenance. UDUMA was willing to engage in a formal research partnership which constituted a unique opportunity to draw on multi-year operational and financial data to generate new knowledge on the aforementioned gaps.

1.3. Structure and overview of the thesis

Adopting an article-based format, this thesis is structured around three interlinking papers detailing a coherent body of research. Chapter 2 reviews the literature to anchor the thesis in existing evidence, develop a conceptual framework, and identify persisting knowledge gaps regarding rural water sustainability. Chapter 3 introduces the case study context and provides an overview of the methodologies used for data collection and analysis. Chapter 4 (Paper 1) explores how renegotiation may address the incompleteness of formal contracts underlying professional rural water service delivery models. Chapter 5 (Paper 2) assesses the effect an upgrade from handpumps to solar-powered water kiosks exerts on revenue generation. Chapter 6 (Paper 3) explores the impact of changing from volumetric to flat fee payments on revenue performance at handpumps. Chapter 7 concludes the thesis.

Chapter 2 defines the scope of the research (section 2.1), explores the increasing relevance of contracts in water policy (section 2.2), and discusses current rural water service delivery paradigms from a contracting perspective (section 2.3). The tenets of contract theory are presented in section 2.4 to understand the limits of formal contracting arrangements. Section 2.5 summarises literature pertaining to drivers affecting demand and revenues for rural water services and identifies knowledge gaps the thesis seeks to address. The review closes by presenting the research's overarching aim and defining the questions guiding the empirical work (section 2.6).

Chapter 3 presents the methodology of the thesis by introducing the research's approach to knowledge generation and motivating the case selection (sections 3.1 and 3.2). The strategies for data collection and the techniques deployed for data analysis are described in sections 3.3 and 3.4, respectively. Specific limitations of this research are outlined in section 3.5, before a statement on research collaboration details the roles and responsibilities of other individuals who contributed to the research (section 3.6).

Chapter 4 (Paper 1) applies contract theory to UDUMA's contractual model to explore how and to what extent an incomplete contract design for professional rural water service delivery can be addressed and discusses how contracted outcomes could be leveraged to support sustainable services. The analysis is based on qualitative evidence from semi-structured interviews, contract documents, and project reports, and provides relevant context to situate Papers 2 and 3. The paper is co-authored with Johanna Koehler (Public Administration and Policy Group, Wageningen University and Research) and Rob Hope (Smith School of Enterprise and Environment, University of Oxford) and has been submitted to *Ecology and Society*.

Chapter 5 (Paper 2) explores how upgrading handpumps to solar-powered water kiosks affects water use and revenues, conditional on seasonal fluctuations. Following an interrupted time series design, a suite of regression models is applied to 452 monthly records of observed payments and metered water usage across a total of 15 waterpoints to estimate the revenue effect of the infrastructure change. The paper is co-authored with Sara Merner (School of Geography and the Environment, University of Oxford), Stefania Innocenti (Smith School of Enterprise and Environment, University of Oxford), Alinta Geling (UDUMA Mali S.A., Mali) and Rob Hope and has been published in *World Development*.

Chapter 6 (Paper 3) analyses 4,413 months of data across a total of 177 handpumps to explore the implications of monthly flat fee contributions and volumetric (pay-as-you-fetch) payments for water use and revenue generation. In particular, the paper seeks to understand how a change in payment modalities affects average daily water use, monthly revenue, and subsidy requirements to sustain services. The paper is co-authored with Johanna Koehler, Mikael Dupuis (UDUMA, France) and Rob Hope and has been published in *npj Clean Water*.

Chapter 7 concludes this thesis by discussing the cross-cutting themes and original contributions of the research. Based on the research's findings (7.1), section 7.2 identifies implications for policy and practice before directions for future research are suggested in section 7.3.

Chapter 2: Literature Review

2.1. Scope of the literature review

The perennial challenge in delivering drinking water services in rural Africa is to effectively provide services that promote operational and financial sustainability. The literature review aims to understand the gaps in current understanding of rural water sustainability in order to define research questions to generate new knowledge that informs policy and practice.

This thesis is shaped by both theory and practice. The latter refers to the recent emergence of professional service delivery models and, in particular, a public-private partnership based on a formal contracting model which has not been applied in such a way before in rural water. In line with policy and practice, the research posits that user revenue, which depends on effective demand, is a necessary condition for sustainable services. The theoretical side explores contract theory and how this intersects with consumer demand theory which has not been applied jointly before for rural water. These theories provide the anchoring for the empirical analyses which examine the interplay of contract design and consumer demand for rural water services.

The chapter is laid out as follows. First, the review briefly introduces the concept of contracts, illustrates their relevance for urban drinking water services and explores whether and how contracts apply to the rural water landscape. It then assesses the prevailing paradigm of community-based management from a contracting perspective and discusses the extent to which formal contracts with professional service providers may facilitate progress towards rural water sustainability. The review goes on to present the foundational tenets of contract theory in order to understand the limitations of formal contracting arrangements with professional service providers. Since the sustainability of rural water services depends on revenue derived from user payments, evidence on contextual conditions and operational factors affecting demand is summarised, before persisting knowledge gaps are identified. The literature review closes by presenting the research's overarching aim and guiding questions.

2.2. Contracts as a means to achieving specific ends

According to North (1990), contracts form part of the human-made strategies for organising and sustaining societal relations and economic performance. In its most basic form, a contract is an arrangement between two or more parties which allocates rights and obligations that can be legally enforced. Such an arrangement involves the exchange of goods or services, or a promise to exchange those at a future date and defines expected outcomes (Hart and Moore, 1988; North, 1990; Williamson, 2002). When signing a contract, parties know how future payoffs will be distributed amongst them, how resources flow, and how risks are allocated. Essentially, contracts act as reference points for behaviours, shaping future performance outcomes by anchoring initial expectations of the contracting parties (Hart and Moore, 2008). The core purpose of a contract is hence to increase the likelihood of achieving specific outcomes by formally clarifying and allocating responsibilities, rights, and risks amongst the parties involved.

Providing a shared understanding of mutual expectations is particularly relevant when exchanges of services or goods involve asset-specific investments, such as infrastructure (Hart and Moore, 1988; North, 1990; Williamson, 2002, 1995). Infrastructure investments are characterised by a lock-in effect where “buyers cannot easily turn to alternative sources of supply, while suppliers can redeploy the specialized assets to their next best use or user only at a loss of productive value” (Williamson, 2002, p. 176). Contracts can help mitigate risks associated with such investments by clarifying mutual expectations over the long term (Athias and Saussier, 2018; Guasch, 2004; Hart, 2003).

These contract principles focusing on performance outcomes and investment facilitation are gaining traction in the water sector. For the provision of drinking water services in urban contexts, contracts are relatively common (ESAWAS, 2022; Marin, 2009; OECD, 2011; World Bank, 2022; WSP, 2014). Here, contractual arrangements between service authorities holding the infrastructure assets and service providers, e.g. public or private utilities, are designed to attract investments and to clarify service delivery obligations through key performance indicators subject to independent regulation and oversight. In addition, urban households are generally being supplied through private connections, governed by individual supply contracts with the utility.

While rural water supply is characterised by a different set of conditions, such as remote, sparsely populated areas, with households generally relying on off-premises drinking water supplies provided through point sources (UNICEF and WHO, 2023), contracts receive increasing policy attention. Similar to motivations underlying contractual arrangements for urban water, the rationale for contracting rural water services is to attract capacity and expertise for operations and maintenance, to bolster efficiency, and to potentially increase capital financing (Gia and Fugelsnes, 2010; Kleemeier and Lockwood, 2012; Kleemeier and Narkevic, 2010; Simone et al., 2016).

In the decentralised rural water sector, local governments hold the formal authority to delegate services delivery to a designated entity (Lockwood and Smits, 2011; REACH and RWSN, 2023). Although the contractual delegation of service delivery functions may vary in scope and in scale, it is a widely established policy principle in rural water. In more than 19 countries in sub-Saharan Africa, service authorities holding the infrastructure assets must delegate service delivery to a provider which can either be a public entity, private enterprise, or a legally recognised community-based organisation. In other countries, the involvement of the private sector in rural water is encouraged but the modalities of such a participation are not further specified (Figure 2-1).

Yet, despite this policy relevance, the conceptual and empirical understanding of the performance and limitations of contracts for rural water services is limited. Two primary reasons exist for the persisting knowledge gap on the role of formal contracts for the provision of drinking water services in rural Africa: 1) there are very few cases where contracts have been used to attract investments for rural drinking services (Kleemeier and Lockwood, 2012), and 2) the prevailing governance modality for rural water largely remains informal community-based management rather than formal contracting arrangements (Carter, 2021; Whaley et al., 2019).

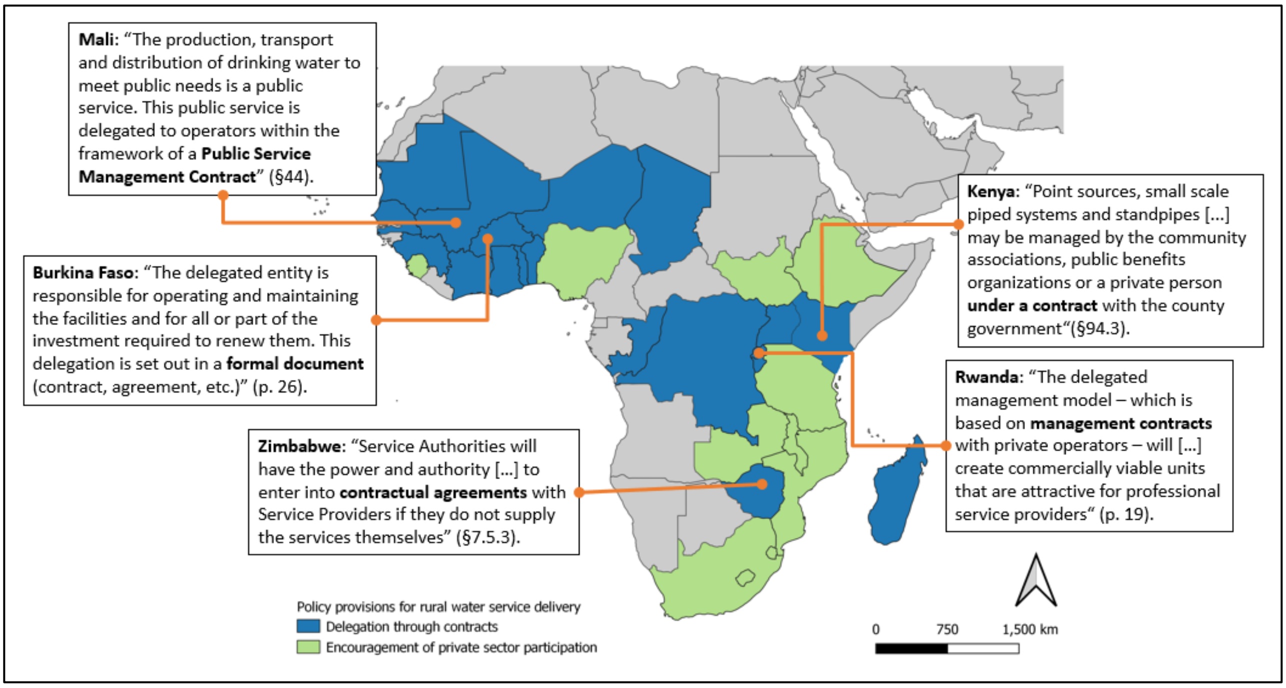

Figure 2-1. Delegation and private sector participation in rural water service delivery. Results of a desk review of national water policies, laws, and regulations. Quotes taken from the following sources: National Strategy for Drinking Water Services in Rural Areas (Ministry of Water and Sanitation of Burkina Faso, 2018), Water Act of Kenya (Republic of Kenya, 2016), Water Act of Mali (Republique du Mali, 2002), National Water Supply Policy (Ministry of Infrastructure of Rwanda, 2016), National Water Policy (Ministry of Water Resources Development and Management of Zimbabwe, 2012). This overview of policy provisions does not draw conclusions about their implementation in practice.

2.3. A contracting perspective on the rural water landscape

To examine this gap further, the following sections explore current policy paradigms for rural water supply from a contracting perspective. First, the institutional approach of community-based management which is still the most common organisational form for providing rural water services is discussed, before the emerging trend of professional service delivery (Nilsson et al., 2021; REACH and RWSN, 2023; REAL-Water, 2023) is reviewed.

2.3.1. Community-based management through a contracting lens

Even though less formal than being stipulated in a legal contract, community management sets out implicit contractual conditions through which governments and donors provide infrastructure with the assumption that this is being managed perpetually through a community-based organisation. These requirements generally pertain to initial investments and subsequent operational and financial management.

Typically, the community-based model ties investments in drinking water supply infrastructure to a set of obligations that a beneficiary community is expected to meet. For instance, to *attract* the initial investment, "communities are often requested to contribute 5 to 15 per cent of initial capital costs" (Harvey and Reed, 2004, p. 98; see as well Carter, 2021). In addition to these direct contributions to capital investments[1], communities are required to form a community-based organisation, most of the time a waterpoint committee, which is responsible for the management and financing of operations and maintenance (O&M) (Briscoe and De Ferranti, 1988; Carter, 2021; Harvey and Reed, 2004). As such, the committee must decide on arrangements for financing O&M activities which includes establishing a revenue collection mechanism and a tariff that users are supposed to pay to cover at least recurring service costs, opening a bank account, and organising procedures for bookkeeping. Furthermore, the committee is presumed to clarify the arrangements for operations by deciding how to maintain and repair the waterpoint[2]. Finally, the community model includes handover documents through which the community receives ownership of and full responsibility for its waterpoint. Even though largely implicit, this illustrates that the initial infrastructure investments are conditional on different requirements that communities must meet.

For ongoing service provision under the community model, the waterpoint committee has the obligation to ensure that water keeps flowing. The users, in return, are expected to pay for the service received (Briscoe and De Ferranti, 1988; Harvey and Reed, 2004, 2007; Harvey, 2007), thereby providing "the fuel for sustainable rural water services" (Carter, 2021, p. 121). This simplified contractual arrangement for managing and funding ongoing O&M effectively allocates all operational and financial risks of service provision to local communities (Hope and Rouse,

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[1] These requirements for the construction of drinking water supply infrastructure range from lump sums per user in Mali (DNH, 2007, p. 45) or Burkina Faso (Ministry of Water and Sanitation of Burkina Faso, 2018, p. 48) to "rural communities [expected to] contribute 5 per cent in cash and 5 per cent in kind" to construction costs in Ethiopia (Federal Democratic Republic of Ethiopia, 2018, p. 112).

[2] Actual O&M activities may be conducted by external pump mechanics or community volunteers, but the waterpoint committee keeps the responsibility for management (Harvey and Reed, 2004, pp. 41; 76).

2013). During the post-construction phase, these implicit contract arrangements receive little follow-up or actual oversight so they are seldomly enforced and properly supported (Harvey and Reed, 2004, 2007; Hutchings et al., 2015; Lockwood and Smits, 2011; RWSN, 2010).

Outcomes in practice generally remain below expected standards, leaving approximately 25%-30% of rural waterpoints non-functional at any point in time (Foster, 2013; Foster et al., 2020; RWSN, 2010). These substandard outcomes suggest that the parties involved in community arrangements are not meeting their respective obligations, pointing to a contractual breakdown. Based on a survey covering 600 sites in rural Ethiopia, Malawi, and Uganda, Whaley et al. (2019) find that maintenance and repair are the prime predictors for handpump functionality and indicate that waterpoint committees, which are generally constituted of volunteers, largely lack the specialised capacity needed to meet these requirements, with severe implications for sustainability.

Studies suggest that rural households are generally willing to pay a reasonable fee for a valuable service (Mu et al., 1990; Shongwe and Dlamini, 2021; Whittington et al., 1991), indicating that users hypothetically agree to comply with their obligation to pay for services. Yet, committees only seldomly provide the level of services required to meet user demand (Hope, 2015; Hope and Ballon, 2021, 2019). Slow repairs and long periods of downtime deteriorate the quality of services, further reducing users' willingness-to-pay (Hope and Rouse, 2013; Thomson and Koehler, 2016). Assuming payments are contingent on service quality, there may be an understandable logic why only 30% of rural households in sub-Saharan Africa pay for their water supply (Foster and Hope, 2017). Besides, users may decide not to fulfil their contractual obligation for reasons related to day-to-day management issues playing out at the community level. There is evidence that the implementation of community arrangements suffers from user funds being misused, little accountability and transparency, and local politics, which limits users' willingness-to-pay (Chowns, 2015; Cleaver et al., 2021; Jones, 2013; van den Broek and Brown, 2015; Whaley et al., 2019).

Given these insights from implementation of the community model, it may be understandable why users do not follow up on their obligation to pay, and why in turn, water supplies fall into disrepair and are abandoned. In particular, this emphasises that a community meeting the initial conditions for receiving investments, "does not necessarily reflect an ability, or willingness, to pay for O&M costs over time" (Harvey and Reed, 2004, p. 107). Hence, the question emerges on how to provide services that meet user demand and promote revenue, and hence rural water sustainability?

2.3.2. Professional service delivery for meeting contracted service outcomes

In response to slow progress to deliver safe drinking water to rural populations, governments across Africa are increasingly exploring contracts with professional service providers as a new institutional arrangement to guarantee service outcomes (McNicholl et al., 2019; Nilsson et al., 2021). This development aligns with wider shifts in political commitments, reflected in global policy frameworks such as the Sustainable Development Agenda (UNGA, 2015).

In comparison to informal community-based management, professional service delivery models[3] are characterised by accountable mandates emerging from contractual arrangements with government authorities and water users, clearly allocating risks and responsibilities for delivering an agreed standard of service (Nilsson et al., 2021). Such service delivery models bundle the management of multiple waterpoints under one maintenance framework (Katuva et al., 2016; van der Wilk, 2019) and pool operational and financial risks at scale to ease the risk burden placed on individual communities (Koehler et al., 2018; Oxford/RFL, 2015). The question is whether formal contracts with professional service providers are a way to strengthen drinking water service outcomes in order to meet user demand and enhance revenue generation.

[3] According to Lockwood, professional service delivery models involve "trained personnel working within clear legal, policy, contractual, and accountability frameworks, who are monitored and evaluated against performance indicators and with agreed financing arrangements and transparent, regulated pricing structures to carry out repairs and support services for rural water infrastructure" (2021, p. 1).

For the professional delivery of rural water services, a contract generally defines an expected level of service through specific outcomes such as volume of water, water quality, or repair time (Charles et al., 2023; McNicholl et al., 2019). In exchange, the contract clarifies the service provider's revenue base, mainly by granting the right to collect tariffs from users (Gia and Fugelsnes, 2010; Janssens, 2011; Kleemeier and Narkevic, 2010; Koehler et al., 2018). This is in line with prevailing policies across sub-Saharan Africa stipulating that O&M costs of rural drinking water services are to be covered through tariffs collected from end users (Foster, 2016, p. 13; Hope et al., 2019, p. 166). Contracts for rural water services thus formally clarify and allocate mutual obligations and rights, thereby aligning operational outcomes with financial objectives of service provision.

Contracts stipulating performance targets need to be backed by reliable and verifiable data to demonstrate operational and financial results. Here, advancements in information and communication technologies can strengthen institutional design, accountability, and service delivery (Hope et al., 2020). Through progress in mobile and satellite network coverage, remote data collection, in-situ sensors, and mobile payment technology (Hope et al., 2012; Nagel et al., 2015; Ndaw, 2015; REAL-Water, 2022a; Thomson et al., 2012; Thomson, 2020; Thomson and Koehler, 2016), operational risks can be managed more rapidly and efficiently through tailored maintenance responses, and delivered results can be monitored and tracked.

Professional service providers mostly aim to repair broken rural water infrastructure in three days or less, offering a step-change compared to communities taking weeks or months to complete repairs (Nilsson et al., 2021). Empirical evidence demonstrates that providers generally deliver services in accordance with contracted indicators (Foster et al., 2022; Smith et al., 2023), indicating that they meet their contractual obligation. Yet, they only rarely generate sufficient revenue via user payments to cover operating costs (McNicholl et al., 2021, 2020; Smith et al., 2023). In other words, while operational service outcomes are guaranteed, revenue goals are missed and this despite formal contracts that are meant to promote financial sustainability are in place. This gap between expected and actual results necessarily leads to interrogate what has been missed in the contract.

2.4. What insights does contract theory offer for rural water sustainability?

Despite formally regulating relationships involving the exchange of goods or services, contracts are often "poorly worded, ambiguous, and leave out important things. They are incomplete" (Hart, 2017, p. 1732). Contract theory highlights that in practice, parties to a contract can neither anticipate nor foresee all relevant contingencies ex-ante, and therefore necessarily end up writing an incomplete contract (Hart, 2017, 2003; Hart and Moore, 2008, 1988).

In addition, the enforceability of legal contracts is likely to vary in a spectrum from conditions of mature contract markets to more informal social contexts. Hence, it may be challenging to introduce formal contracting approaches to rural areas of developing countries where the reach of state authorities is limited and more informal and customary practices are at play (Herbst, 2014; Messick, 2005; North, 1990).

It is only during the implementation stage of a contracting arrangement that issues stemming from an incomplete contract design or limited enforcement become observable to contracting parties (Hart, 2017; Hart and Moore, 1988; OECD, 2011). This realisation is linked to the availability of information about the parties' respective behaviours. As gaps between contractually agreed and actual performance outcomes arise, specific mechanisms internal to the arrangement may be mobilised to address such shortcomings (Ménard, 2004).

One such mechanism to address the inherent flaws of an incomplete contract, as demonstrated by Hart and Moore (1988), is renegotiation. Through renegotiation, contracting parties can adjust contractual terms to the uncertainties and contingent circumstances unfolding during contract execution, thereby adapting an initial contract design to observed performance. This adaptability is particularly relevant for contracts that span long time-horizons and involve specific investments

(Goldberg and Erickson, 1987; Hart, 2017, 2003). Empirical investigations of infrastructure-heavy services find that contract renegotiation is common across country contexts and sectors (Athias and Saussier, 2018, 2007; Beuve and Saussier, 2021). For example, in Latin America, more than 75% of concession contracts in the urban water sector have been renegotiated relatively shortly after their initial award (Guasch, 2004; Guasch et al., 2008).

Any contract design is necessarily informed by assumptions about the parties' expected behaviours that may not reflect what actually occurs in practice. Empirical research suggests that uncertain demand is a central factor in contract distortion which is likely to amplify the inherent incompleteness of contracts (Athias and Saussier, 2018, 2007; Feng et al., 2023; Guasch, 2004; Guasch et al., 2008), reflecting wider challenges related to demand forecasting (Flyvbjerg et al., 2005). This last point constitutes a particular challenge for designing contracts applicable to the delivery of water services in rural Africa where reliable data on water demand is scarce (Cronk et al., 2024; Elliott et al., 2019; Hope et al., 2020; Therkildsen, 1988).

In the case of rural water services, assumed user demand and associated revenue projections are often found to be unrealistic (Armstrong, 2022; Gia and Fugelsnes, 2010). These mismatches between expected and actual outcomes only materialise during contract implementation of which there is limited evidence for rural water. Therefore, this thesis seeks to contribute additional empirical understanding of this nexus for the case of professional rural water service delivery.

Since effective demand, expressed by users through actual use of and payments for a service (Cord et al., 2022; Smith et al., 2023), is a necessary condition for generating revenue to sustain services, the following section summarises existing evidence on drivers affecting rural water demand and identifies persisting knowledge gaps.

2.5. Demand for rural water services and associated revenue implications

Indeed, research demonstrates that multiple factors influence demand for drinking water services in rural Africa. Cord et al. (2022) argue that drivers influencing demand for rural water services can largely be separated in two categories: contextual conditions and operational factors. Contextual conditions are characteristics of the implementation environment, such as the policy setting, environmental drivers, or local social dynamics, and are difficult for service providers to change. Operational factors, on the other hand, are components of the design and implementation of the service delivery arrangement which may be adjusted by service providers. Accordingly, the following sections present existing evidence on the influence of contextual conditions and operational factors on rural water demand and their implications for revenue generation.

2.5.1. Demand in relation to contextual conditions

Generally, rural households in Africa use a variety of water sources with different characteristics, such as price, distance, and quality, turning drinking water into a heterogeneous good (Cronk et al., 2024; Elliott et al., 2019; Gross and Elshiewy, 2019; Hoque and Hope, 2018; Martínez-Santos, 2017; Mu et al., 1990; Nauges and Whittington, 2010; Thompson et al., 2001; White et al., 1972). This challenges the notion, still widely established in water policy, planning, and global surveys, that rural households rely on a singular drinking water source, as common in urban contexts of the Global North (Elliott et al., 2019; Mu et al., 1990).

Since rural households are likely to access a range of alternative sources, it is uncertain whether people will actually use an improved drinking water source which may be managed by a professional service provider. This non-exclusive nature of rural water may not always be considered in policy and practice, leading to flawed assumptions about the role and obligations of water users. It is assumed that users will use and pay for the service as planned, but users may decide differently.

Studies looking to understand the complex source choice decisions rural households face on a daily basis find that proximity, reliability, taste or perceived quality, and price are important factors in their choices (Gross and Elshiewy, 2019; Mu et al., 1990; Wagner et al., 2019). The price of water seems to have a strong influence on user preferences: generally, rural households do prefer sources that are cheaper (Nauges and Whittington, 2010; Wagner et al., 2019), and are thus responsive to relative price changes at water sources (Mu et al., 1990). This aligns with wider empirical evidence suggesting that lower-cost and closer alternatives, and long distances and associated walking times deter people from using improved water sources (Foster and Hope, 2017; Koehler et al., 2015; Martínez-Santos, 2017; Nauges and Whittington, 2010; Thompson et al., 2001; White et al., 1972). In addition, specific characteristics of groundwater quality such as salinity are found to influence user perceptions of taste of water and do in turn affect demand (Foster and Hope, 2017, 2016; Mu et al., 1990; Nauges and Whittington, 2010).

When a drinking water contract links revenue to the quantity of water sold (Janssens, 2011), a related question is: if people choose to rely on an improved drinking water source, how much water will they collect? Already White et al. identified in their seminal study, "Drawers of Water" (1972), the influence that distance between a household and the waterpoint exerts on the quantity of water collected. Household water use is subject to a 'plateau effect', implying that if water must be carried, the quantity brought home varies little for sources between 30 metres and 1000 metres from the household (Thompson et al., 2001; White et al., 1972). In addition, the tariff structure administered at a water source affects use behaviours: a study in rural Kenya found that volumetric tariffs reduce water usage amongst low-income groups (Foster and Hope, 2017).

Furthermore, seasonality has long been recognised as a recurring pattern in rural water supply, impacting both source choices and volumes of water collected. Findings from Ethiopia, Ghana, Kenya, Malawi, Rwanda, Tanzania, and Uganda indicate that climatic conditions, especially seasonal rainfall and temperature, influence user demand (Armstrong et al., 2022, 2021; Foster and Hope, 2016; Hoque and Hope, 2018; Kulinkina et al., 2016; MacAllister et al., 2020; Thomas et al., 2019; Thomson et al., 2019). When surface water availability is reduced, groundwater demand increases. Inversely, days of heavy rain are associated with households choosing to turn away from improved groundwater sources (Hoque and Hope, 2018; Thomson et al., 2019). Summarising findings from various studies conducted across rural Africa, Ingram and Thomson estimate a “general decrease in collection of groundwater over rainy periods of about 20–30 per cent” (2022, p. 140). These insights suggest that demand and revenue for professional rural water services are likely to fluctuate on a cyclical basis, with peaks biased to the dry and troughs to the wet season.

Besides, revenue generation for rural water services is intimately influenced by drivers affecting user payments. Existing evidence indicates that users fail to meet their payment obligations for multiple reasons. Similar to drivers influencing source choices and quantities of water collected, user payments do interact with geographical, environmental, and seasonal factors. For instance, payments are positively associated with proximity: users’ willingness-to-pay increases when situated closer to an improved waterpoint (Calkins et al., 2002; Foster and Hope, 2016; Mu et al., 1990). Furthermore, Koehler et al. (2015) find that handpump clusters in a small geographic area are associated with lower payments, as they create opportunities for free-riding, thereby reducing incentives for payments. In addition, research conducted in rural Uganda shows that payments are influenced by the availability of free alternative water sources (Smith et al., 2023; van den Broek and Brown, 2015), reflecting other studies that have identified cheaper or free alternative sources as a major obstacle to willingness-to-pay (Whittington et al., 2009; World Bank, 1993). Equally, seasonal rainfall is found to influence payments for rural water services (Armstrong et al., 2022; Foster and Hope, 2017, 2016). As the relative value of an improved waterpoint diminishes during wet periods, the inclination of households to pay is reduced. In turn, users are more likely to rely on an improved water source during the dry season, biasing payments and revenues to this period.

Finally, various studies investigate social, economic, cultural, and institutional conditions influencing water user payments. For instance, communities with strong leadership and a high degree of organisation are more likely to set up and sustain payment systems over time (Koehler et al., 2015; van den Broek and Brown, 2015). Furthermore, path-dependency shapes community-level outcomes in funding rural water services. Research from Kenya indicates that adequate revenue streams are more likely to be generated at community handpumps when a critical mass of at least 60% of households regularly pay their fees (Foster, 2017).

As illustrated, water demand is affected by various contextual conditions, leading to relative uncertainty about how much water households will use and pay for, and how much revenue the services will generate. While these contextual conditions are beyond the reach of the design of the delivery arrangement, amplifying contract incompleteness, the service provider may still adjust operational factors to enhance demand.

2.5.2. Demand in relation to operational factors

Consumer demand theory can provide a helpful lens to understand how user demand and operational factors of rural water services may be related. As Lancaster (1966a, 1966b) demonstrates, consumer demand is linked to specific characteristics of a product, be it a good or a service. Consumer demand theory is based on the premise that what consumers are seeking to acquire is not products themselves but the characteristics they contain, and that a consumer essentially views a product as a bundle of characteristics (Lancaster, 1966a). According to consumer demand theory, within one single product, there can be the opportunity to adjust characteristics being offered to consumers. Notably, changing the characteristics of a product can make it more attractive to consumers (Lancaster, 1966a, 1966b).

Applying this rationale to the rural water sector, service providers may change specific aspects in the services they deliver to their customers in the quest to increase demand and enhance revenues. SDG 6.1 identifies attributes of drinking water services in terms of quantity, affordability, proximity, quality, and reliability (UNGA, 2015). Considering drinking water as a composite good, these service attributes may provide guidance on key priorities of users (Hope et al., 2020).

There is evidence that specific characteristics of water services do matter for rural users. Notably, demand and revenues appear to be “sensitive to the scope” of service improvements (Van Houtven et al., 2017, p. 130). Assessments of user responses to hypothetical improvements in drinking water services suggest that user revenue is likely to be higher, more regular, and consistent with households benefiting from piped connections (Mu et al., 1990; Nauges and Whittington, 2010; Van Houtven et al., 2017). While piped supplies are only expanding slowly in rural areas (Armstrong, 2022; WHO et al., 2022), new rural water supply technologies such as solar kiosks or water ATMs are gaining momentum across Africa (REAL-Water, 2022a; World Bank, 2018), offering incremental service level improvements in comparison to handpumps which may better match increasing user aspirations. Yet, user demand is not only contingent on infrastructure and related service levels by design.

Users of community handpumps in Kenya state to particularly value improvements in operational performance, such as short breakdown durations and high-quality repairs, as provided by professional service providers (Hope, 2015; Hope and Ballon, 2021, 2019; Koehler et al., 2018, 2015). Koehler et al. (2015) estimated a fivefold increase in average willingness-to-pay levels after households had experienced a reliable maintenance service in rural Kenya, acknowledging, however, that the real test will be if the stated preferences translate into actual payments.

Furthermore, research indicates that payment approaches matter for demand and revenue generation (Foster and Hope, 2017; Jones, 2013; Koehler et al., 2015; Nauges and Whittington, 2017). Water policies in Africa promote different approaches to generate user revenue to fund recurring service costs, ranging from fixed weekly, monthly, or annual fees and direct pay-as-you-fetch contributions to reactive payments (Harvey and Reed, 2004). However, beyond a study from coastal Kenya (Foster and Hope, 2017), there is limited comparative evidence on how different payment approaches at handpumps perform in terms of water use and revenue outcomes.

2.5.3. Knowledge gaps regarding consumer demand for rural water services

As presented, a growing body of literature suggests that rural households are generally willing to pay a reasonable fee for a valuable service and that tariff design matters for demand and revenue generation. The studies that suggest that there is demand for improvements in rural water services have mostly relied on stated preference methods (Van Houtven et al., 2017). However, factors which influence users' stated preferences are not necessarily those which determine their actual behaviours (de Corte et al., 2021; Griffin et al., 1995).

Only a few studies in Kenya (Koehler et al., 2021) and Uganda (Smith et al., 2023) have focused on revealed use and payment behaviours to ascertain whether better services at handpumps, particularly through rapid response to breakdowns and high-quality repairs, actually and effectively drive user demand and revenue. Both studies find that stated preferences had only limited convergence with actual payments, leading to revenues not covering operating costs, undermining the long-term sustainability of these professional handpump maintenance services. Further evidence is needed to determine whether these patterns hold across contexts.

The question of how users respond to service improvements requires further empirical investigation. As outlined, consumer demand theory suggests that changes to attributes may make a service more attractive for consumers. However, it is empirically unclear how and to what extent variation in key variables related to service attributes affects actual use of and payments for rural water services (Armstrong, 2022; Nauges and Whittington, 2010). Therefore, empirical evidence "using real payments over meaningfully long periods of time" (Smith et al., 2023, p. 13) is needed to determine whether, how, and to what extent changes in service attributes actually affect demand and revenue generation for professional rural water service delivery.

2.6. The role of contract design and consumer demand in sustaining rural water services

In response to the knowledge gaps identified in this literature review, this thesis aims to examine *how contract design and consumer demand affect revenue generation to sustain the professional delivery of rural drinking water services in Africa*. Based on the literature, this research posits that 1) contracts are a means to reduce uncertainty and to attract investments to deliver desirable outcomes, and that 2) service outcomes may increase revenue if service levels meet user requirements. To investigate these propositions, a framework linking contract and consumer demand theories guides the empirical research.

Contract theory suggests incomplete contracts are common requiring renegotiation, particularly in new markets or where information is scarce, which applies to rural water services in Africa. Renegotiation can be a means to adapt the incomplete contract design of a professional service delivery arrangement to uncertainties in operational and financial performance.

Consumer demand theory indicates services have attributes and attribute levels which motivate different behaviours, including payment. Water service providers may alter the contractually agreed attributes of the services they deliver to make them more attractive to their customers and ultimately enhance revenue generation. Here, service attributes pertaining to water quantity, quality, affordability, proximity, and reliability may provide guidance on priorities of water users.

The respective empirical chapters of the thesis are tailored to answering the following guiding questions, collectively contributing to addressing the overarching aim of this research:

- Paper 1: How does contract incompleteness affect the sustainability of professional rural water service delivery, and to what extent might an incomplete contract design be addressed?
- Paper 2: To what extent do solar-powered water kiosks affect water use and revenue generation, conditional on seasonal fluctuations?
- Paper 3: How does a change in payment modalities affect water use, monthly revenues, and collection efficiency at handpumps, and what, if any subsidy, is required to sustain services?

By addressing these questions in the context of Mali, the thesis contributes new knowledge on how contract-based models for professional rural water service delivery are set up and evolve, and how they may be sustained. The research makes a conceptual contribution to the understanding of rural water service contracts and offers empirical evidence on how and why contractual arrangements for rural water service delivery evolve and adapt over time (Paper 1). Furthermore, considering drinking water as a composite good with different attributes, the thesis provides new empirical insights into the relationship between service attributes, user demand, and revenue outcomes for rural water services (Papers 2 and 3).

Chapter 3: Methodology

Chapter 3 describes the background of the research project and outlines the research design by introducing the case study context and motivations for the case selection. It reflects on the thesis' approach to knowledge generation and presents the methods applied for data collection. How the data are used to respond to the research questions is laid out in the section on data analysis. The chapter closes by discussing the limitations of the research and presenting the respective contributions of individual collaborators.

3.1 Background of the research

My doctoral research is embedded in an International Training Network entitled "Next Water Governance – NEWAVE", funded by the European Commission as part of the EU Research and Innovation programme Horizon 2020. NEWAVE approaches current and future water governance challenges from different perspectives and across various geographies to provide insights for research, policy, and practice. Aligned with this policy-oriented research agenda, my thesis seeks to contribute new knowledge on the emerging trend of professional drinking water service delivery in rural Africa.

The pervasive policy challenge of keeping drinking water flowing in rural parts of sub-Saharan Africa was already the focus of my work prior to starting the doctoral research. During 2016 to 2020 I worked on behalf of the German Development Cooperation (GIZ) in Mali, based in Bamako, to support national, regional, and local governments in improving rural water and sanitation supplies. While my 'positionality' transitioned from a policy advisor to a researcher, my interest for this policy puzzle remained, particularly since established policies and related implementation mechanisms did not necessarily achieve their intended results.

Acknowledging these personal motivations underlying my research is crucial to explaining why I chose a pragmatic approach to knowledge generation. As a research paradigm, pragmatism is genuinely interested in learning from implementation and experimentation (Feilzer, 2010; Morgan, 2014). It explicitly recognises that "it is the researcher who […] decides which question is important and what methodology is appropriate, and [that] those choices are certainly influenced by the aspects of sociopolitical location of the researcher, his/her personal history, and his/her belief system" (Kaushik and Walsh, 2019, p. 6).

Furthermore, a pragmatic research philosophy posits that a specific research problem should be investigated using the most suitable methods and data (Feilzer, 2010; Kaushik and Walsh, 2019), emphasising the relevance of mixed-methods research designs (Morgan, 2014, 2007). According to Kaushik and Walsh (2019), a pragmatic stance offers a middle ground between post-positivist and constructivist research paradigms. In line with this more flexible social science research theory, the thesis integrates methodological concepts from post-positivism and constructivism to transcend traditional distinctions between qualitative and quantitative approaches. These principles act as guiding tenets for the proposed research seeking to produce knowledge with relevance for water policy and practice.

The applied nature of this thesis builds on a research partnership with UDUMA, a professional drinking water service delivery company operating in rural Mali. Through the collaborative engagement with UDUMA, which is formalised via a data-sharing agreement between the University of Oxford and UDUMA (Appendix I), access to longitudinal data on user payments and volumetric water use, disaggregated at the waterpoint level, and relevant supporting documentation (including government contracts, project reports, baseline studies, etc.) was gained. These quantitative and qualitative data form an essential part of the research's empirical material and were instrumental in addressing the overarching aim guiding this thesis.

3.2 Research aim and design

The overarching aim of this research is to examine how contract design and consumer demand affect revenue generation to sustain the professional delivery of rural drinking water services in Africa. To achieve this aim, the thesis provides an in-depth study of UDUMA's professional service delivery model operating in rural Mali. The thesis investigates the interaction between contract design and consumer demand by exploring the extent to which renegotiation is a mechanism to adapt formal contracts to uncertainties in operational and financial performance, and how specific service adaptations affect water use and revenue outcomes.

Following the pragmatic anchoring of the research, the thesis advances a mixed methods research design (Johnson et al., 2007; Johnson and Onwuegbuzie, 2004) to collect, analyse, and interpret empirical material to address the research questions. By doing so, the thesis seeks to enhance the validity of its findings and to paint a more holistic picture of the implementation of a contract-based service delivery model and of the effects of specific changes to service attributes on water use and revenue outcomes. Paper 1 examines the initial design and subsequent evolution of UDUMA's contractual model since 2019. It describes the context and unpacks the process of contractual renegotiation, prompting two service adaptations, and illustrates related user responses using insights from interviews. The effects of the service adaptations on water use, payment collections, and revenue outcomes have, in turn, been explored over time and quantified in Papers 2 and 3.

Providing a longitudinal perspective on use and payment patterns is necessary to move beyond known limitations of cross-sectional studies. As discussed in Section 2.5, seasonality influences rural water demand but is often not captured in national and global statistics derived from household surveys that mostly take place in the dry season (Elliott et al., 2019). Here, professional service providers offer new sources of continuously collected operational and financial data with the potential to address critical knowledge gaps.

To investigate observational water use and payment data, the research relies on the concept of revealed preference proposed by Samuelson (1948, 1938). Revealed preference is a way to infer the preferences of individuals given the choices observed. Conceptually, revealed preference links to the assumption underlying consumer demand theory that individual preferences can be defined in terms of the characteristics of purchased goods or services (Lancaster, 1966a; Mark et al., 1981). Observed behaviours are also part of the foundational tenets of contract theory. Renegotiation is likely to occur when parties realise that a contract design is incomplete (Hart and Moore, 1988). Observational data on water use and payments can be such a source of information.

By making use of triangulation and corroboration of multiple sources of evidence, combining primary and secondary quantitative and qualitative data, and deploying complementary analytical approaches to the empirical material, the research investigates UDUMA's contract-based service model, its evolution, and performance, and associated user responses in-depth and over time. The following sections briefly introduce the case study context and motivations for the case selection, before outlining the principles of case study research that guide the thesis.

3.2.1 Justification of case selection

3.2.1.1 Case study context: Mali

Mali is a landlocked country in West Africa, bordering Senegal, Mauritania, Algeria, Niger, Burkina, Côte d'Ivoire, and Guinea. The country is home to a socially diverse population of approximately 20 million people, 65% of whom live in rural areas. With an annual population growth rate of 3%, Mali's total population is expected to double by 2035 (World Bank, 2023). The national poverty threshold is $314 per person per year, with about 44% of the population living below this threshold in 2018 and a higher poverty head count in rural areas of approximately 54% (INSTAT, 2019).

Mali has a tropical climate in the south and west, but climatic conditions become increasingly arid towards the north and east. Mali, as other countries in the Sahel, increasingly faces climate-related vulnerabilities including drought risks (IPCC, 2023), as experienced in the 1970s and 1980s with severe socio-economic consequences, particularly affecting rural populations (Gleitsmann et al., 2007; Heinrigs, 2010; Ikoku, 2022; Jankowska et al., 2012; Lutz et al., 2009).

Similar to other sub-Saharan African countries (UNICEF and WHO, 2022), latest data from the Joint Monitoring Programme indicate that Mali has made limited progress on providing basic drinking water services to rural populations with more than a quarter still lacking access to an improved water source (WHO and UNICEF, 2024). While Mali's population is estimated to grow by 3% annually (World Bank, 2023), investments in new drinking water supply infrastructure only translate into a 1% increase in national coverage (CPS Mali, 2019). Access to basic drinking water services is further constrained by an average functionality rate of around 70% (CPS Mali, 2019; DNH, 2016), similar to functionality estimates from the region (Foster et al., 2020).

To respond to these challenges, Mali initiated decentralisation and sector reforms leading to shifts in institutional mandates and policy frameworks for rural water services (Jaglin et al., 2011; Jones, 2013). Three broader policy trends of rural water service delivery prevalent in sub-Saharan Africa (as described in Chapter 2) can be exemplified in Mali: contractual delegation of service delivery functions, user payments for covering recurrent service costs, and the emerging trend towards professional service delivery. In Mali, local governments, as service authorities, bear the ultimate responsibility for drinking water services on their territory. However, they must delegate service delivery via a formal contract to a provider which can either be a private or public entity or a legally recognised water user association (DNH, 2006; Republique du Mali, 2002). Furthermore, as in other countries in sub-Saharan Africa, user payments for rural water services are mandatory in Mali and are expected to cover at least recurring service costs (DNH, 2006). The National Water Strategy states that payment for water from handpumps should be via a regular tariff or direct payment at the pump according to volume used (DNH, 2007, p. 44). Finally, Mali pursues professionalisation as a means to improve drinking water services in rural areas, mainly to respond to low levels of operational sustainability of infrastructure assets (DNH, 2019). Mali is hence comparable with the wider rural water context described for sub-Saharan Africa (Chapter 2).

According to Mali's latest nation-wide waterpoint inventory conducted in 2016 (DNH, 2016), handpumps are the predominant waterpoint type in rural Sikasso, with a total of 5,216 boreholes equipped with either a India Mark II or Vergnet-Hydro pump. Yet, roughly one in four handpumps was non-functional at the day of the inventory, underlining the issue of operational underperformance (Figure 3-1).

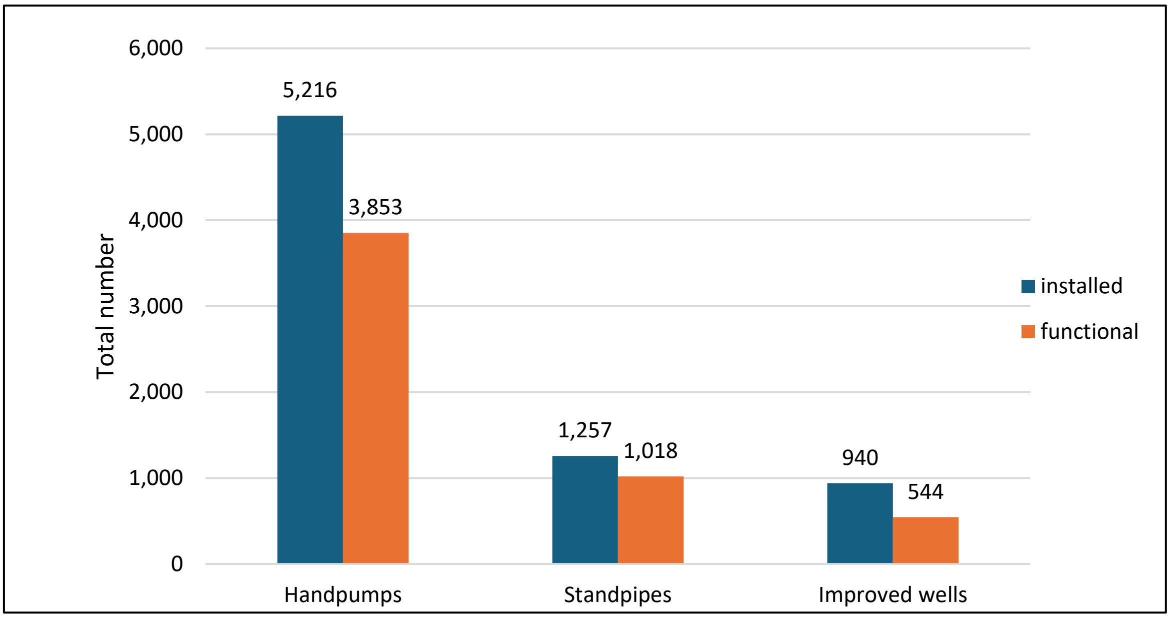

Figure 3-1. Total number of waterpoint types installed in Sikasso. Data sourced from the latest national waterpoint inventory (DNH, 2016).

3.2.1.2 Study case: the UDUMA model

In 2018, 30 local governments in the Region of Sikasso, located in Southern Mali (Figure 3-3), decided to contract UDUMA, a professional service delivery company, to rehabilitate, operate, and maintain up to 1,400 handpumps for a duration of 15 years (van der Wilk, 2019). Since 2019, UDUMA provides a reliable service in line with its contractual obligation, guaranteeing repairs within 72 hours of breakdown, providing a response to the outlined sustainability challenge. The service is subject to user payments, with tariffs regulated by the government. UDUMA had already implemented a similar model in Burkina Faso at a smaller scale, covering about 230 handpumps. This prior experience informed its contractual setup in Mali (UDUMA, 2017).

UDUMA is a for-profit company with a business model based on full cost recovery through user payments. UDUMA's market-based approach is unusual in the African context which is dominated by social enterprises or NGOs providing some or complete subsidies for maintaining rural handpumps. The view of UDUMA is that a commercial approach can be a transition to delivering and sustaining social, health, and economic outcomes.

To cover the capital costs required for rehabilitating handpumps at scale and fund the initial management of rural water services in Mali, UDUMA has leveraged its long-term contracts signed with local governments to secure commercial loans at market rates of a total amount of €2 million. The business model at scale, with a regulated tariff, was meant to allow for reimbursing the initial private capital investment while generating an adequate profit margin (van der Wilk, 2019, p. 5). That a private enterprise commits to carrying significant commercial risks is, to my knowledge, unique for the provision of rural water services in Africa, where "most countries have not demanded significant investments in infrastructure from their private partners" (Kleemeier and Lockwood, 2012, p. 1).

Selecting UDUMA as a study case is therefore an opportunity for generating new knowledge on whether and to what extent commercial contracts with professional service providers are an alternative mechanism to deliver desired rural water outcomes. UDUMA is an example of a wider cohort of professional service providers, providing maintenance services for a portfolio of infrastructure types and collecting user payments to generate revenue (REAL-Water, 2023; RWSN, 2019; Uptime, 2023). Since professional service delivery is part of a wider trend in rural water supply across sub-Saharan Africa (see Chapter 2), empirical insights from this case study may hence be of relevance to other service delivery models operating in different country contexts.

UDUMA's initial business model assumed an average daily water usage of two m^3 per handpump and projected no default in volumetric payments, effectively tying revenue to water demand and payment collection. In its initial project proposal, UDUMA (2017, p. 31) conducted a risk analysis and assessed the risk of insufficient demand leading to "revenues smaller than projected" as "low".

In the first two years of operations, operational and financial data, however, revealed that these assumptions were flawed. Actual daily water usage was only a quarter of the anticipated volume, and users paid only 40% of water collected, resulting in low revenues. In 2021, in light of limited revenue generation, UDUMA states in its progress report to RVO: “several issues were underestimated and some situations not expected. The capacity of the consortium to handle these problems was probably also overrated” (UDUMA, 2021, p. 6).

In hindsight, it appears that UDUMA underestimated revenue risks related to user demand and the collection of volumetric payments at handpumps. While it is unclear whether UDUMA conducted adequate risk management and due diligence procedures before signing the contract and making related investments, the performance observed during contract execution suggests that its initial contract design was incomplete due to the inability to guarantee water demand and enforce volumetric payments.

In response, UDUMA initiated revisions of its long-term contracts, introducing changes in 1) infrastructure by upgrading handpumps to solar-powered water kiosks and in 2) payment modalities at handpumps by shifting from volumetric payments to monthly flat fees. The research exploits these specific changes to the service model generating data for answering the guiding research questions. Figure 3-2 presents an overview of the evolution of UDUMA’s contractual model, associated service delivery changes, and related papers constituting the thesis. A detailed description and analysis of UDUMA’s model is provided in Chapter 4 (Paper 1).

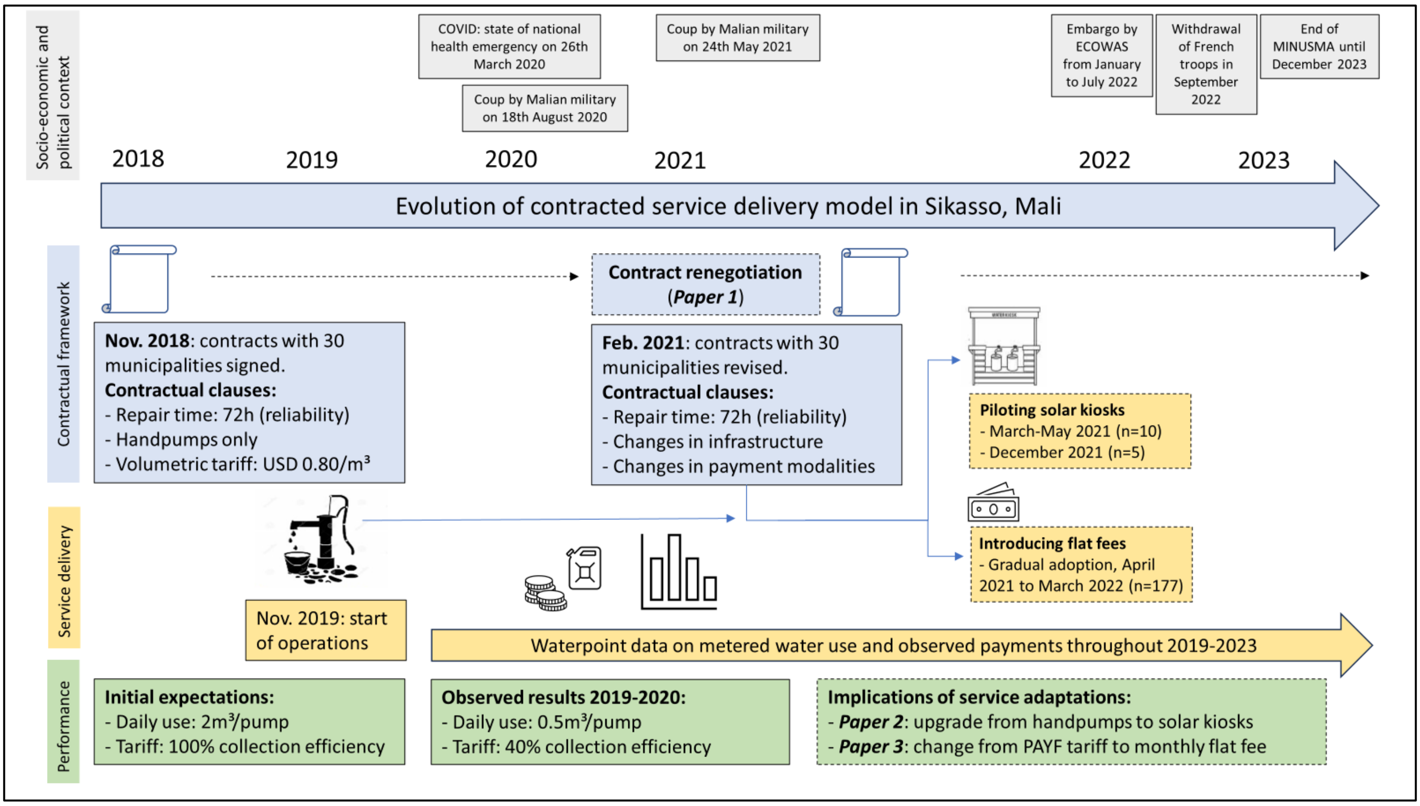

Figure 3-2. Overview of the evolution of UDUMA's contractual model and related papers.

3.2.2 Rationale for case study using mixed methods

Case study research is well positioned to develop concrete, context-dependent knowledge, particularly at stages of exploratory investigation (Flyvbjerg, 2011, 2006; Gerring, 2004; Yin, 2009). Since professionalised service delivery approaches have not yet been widely adopted in the rural water landscape, conducting a case study of UDUMA presents an opportunity to generate new conceptual and empirical evidence on the implications of this institutional transformation.

A study case is generally defined as a specific unit which is spatially bound and typically evolves in time. A single case study design attempts to provide an intensive analysis, characterised by detail, richness, and completeness with the ambition to draw lessons for other contexts and to propose insights on a larger class of (similar) units (Flyvbjerg, 2011; Gerring, 2004). The criterion for external validity of case studies is hence not the formal generalisability of generated knowledge but its potential transferability or applicability to comparable contexts and cases (Flyvbjerg, 2011, 2006; Gerring, 2004; Ruzzene, 2012).

Conducting a single case study can be justified through multiple rationales. Of relevance for the thesis are two aspects pertaining to the "revelatory" and "longitudinal" nature of the case (Yin, 2009, p. 49). As detailed in Chapter 2, our current understanding of the design and performance of professional rural water service delivery models is limited. Particularly, the role of commercial, long-term contracts in the set-up and implementation of such models remains underexplored. Investigating UDUMA's contractual design in Mali's decentralised rural water sector may hence be revelatory for other contexts. Furthermore, "studying the same single case at two or more different points in time" (Yin, 2009, p. 49) allows to analyse how a contract-based service delivery model evolves over time to provide insights on the underlying processes, drivers, and consequences of institutional adaptation and change.

The internal validity of a case study is likely to improve when it combines various data sources and analytical methods to generate complementary insights that substantiate an argument (Flyvbjerg, 2011, 2006; Gerring, 2004; Ragin, 1992). Therefore, through the triangulation of different data sources and analytical techniques, and the corroboration of insights, the thesis seeks to establish coherent evidence for its conclusions. By deploying a sequential process of empirical inquiry where quantitative insights inform subsequent qualitative analysis, the research makes use of the "complementary strengths" of quantitative and qualitative approaches (Johnson and Onwuegbuzie, 2004, p. 22). While quantitative analysis is useful in identifying larger patterns and relationships between variables of interest, qualitative data are critical to contextualise, confirm, and eventually explain the revealed patterns, mainly by suggesting potential mechanisms underlying the observed phenomena (Gerring, 2017).

The following sections detail the research process, depict how the methods for data collection and analysis are connected, and set out how they have been used to answer the research questions.

3.3 Approaches to data collection

The empirical research uses primary and secondary quantitative and qualitative data (Table 3.1) to investigate UDUMA's contract design and evolution, related service adaptations, and associated user responses and revenue implications. The empirical material consists of longitudinal waterpoint data from UDUMA, climatological data, and qualitative data collected through semi-structured interviews conducted with various stakeholders, on-site observations through in-person fieldwork in Mali, and documents.

Table 3.1 Overview of data collected as part of the research

Data Type	Description	Source	Time Range
Social-Quantitative	**Longitudinal waterpoint data** on metered water volumes and observed payments from Sikasso	UDUMA (4,865 monthly records across a total of 192 individual waterpoints)	2019-2023
Biophysical-Quantitative	**Climatological data** (monthly rainfall and temperature estimates)	*TAMSAT* and *Copernicus Climate Change Service*	2019-2023
Social-Qualitative	**Key informant interviews** on rural water services in Mali to situate the UDUMA model in its larger policy context	Semi-structured interviews with sector experts (n = 14) from Mali	2021
Social-Qualitative	**In-person consultations** with stakeholders at the local level to collect data on their perceptions of UDUMA's service	Semi-structured interviews with water users, local governments, and village representatives from nine villages in Sikasso (n = 53)	2022
Biophysical-Qualitative	**Waterpoint mappings** at the local level to collect data on the availability and characteristics of alternative water sources	Identification of a total of 85 water sources in nine villages in Sikasso, with 27 waterpoints managed by UDUMA	2022
Social-Qualitative	**Interviews** and workshops with UDUMA staff to understand the provider's perspective and interviews with funding agencies to clarify their perspective	Semi-structured interviews with UDUMA staff from Mali (n = 3) and France (n = 19) and representatives of relevant funding agencies (n = 2)	2020-2023
Social-Qualitative	**Documents**, such as policy frameworks, laws, contracts incl. annexes, and project reports	Official government records, UDUMA, online sources	2002-2022

The study site comprises the Region of Sikasso, located in the south of Mali (Figure 3-3), where UDUMA provides its reliable service. The area's climate is characterised by an annual dry season from approximately March to June, followed by a wet season from July to October with an average rainfall of 230mm per month, peaking in August, and an off-season from November to February. The average temperature varies between 24°C in January and 35°C in May (World Bank, 2021a; World Food Programme, 2021).

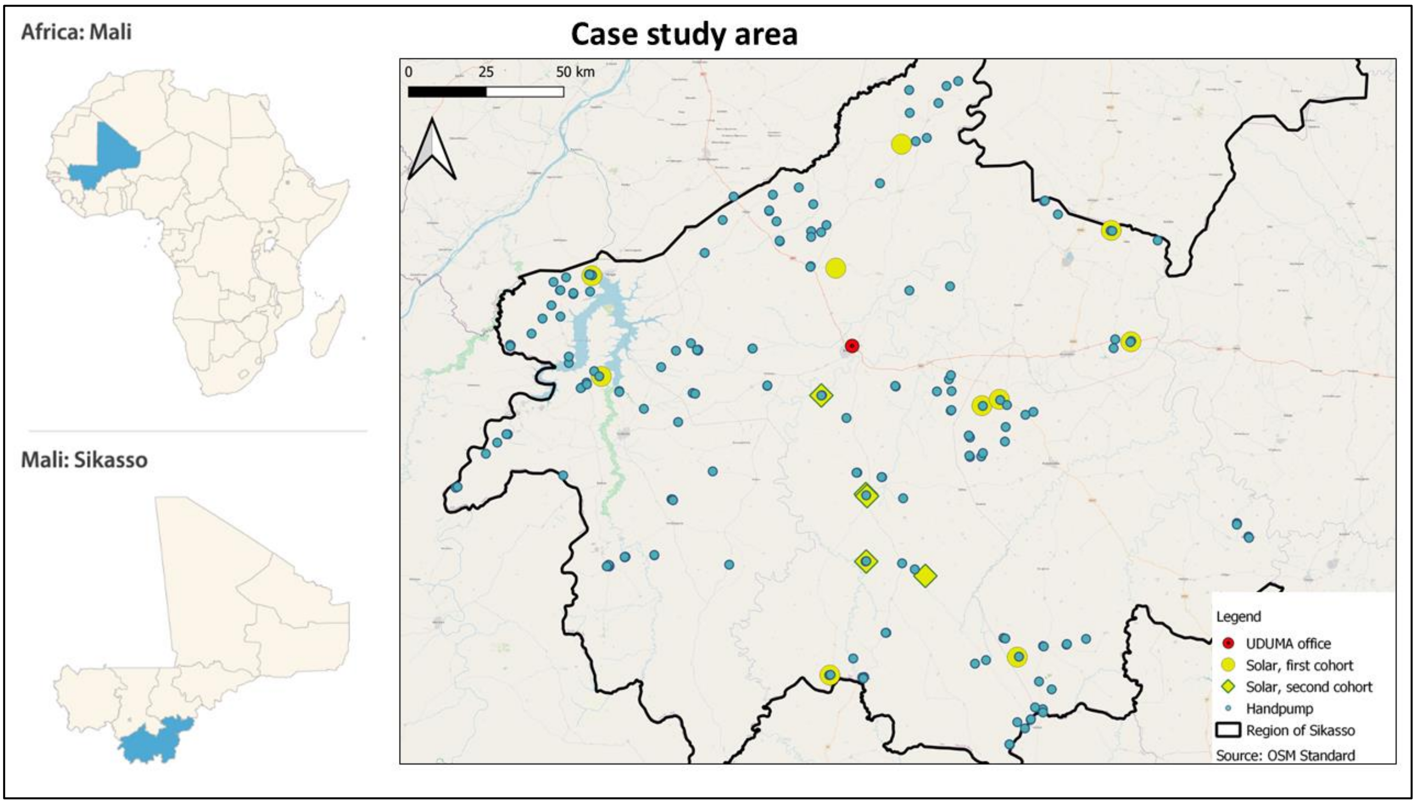

Figure 3-3. Case study area in Sikasso, Mali. Map presenting UDUMA's service area and relevant waterpoints (177 handpumps and 15 solar kiosks). Due to close proximity, some handpumps and solar kiosks are overlapping. For transparency, the full list of the 192 individual waterpoints and their GPS coordinates is provided in the Appendix.

3.3.1 Quantitative data

In its service area, UDUMA installs and maintains rural waterpoints fitted with water meters, making it possible to monitor water consumption and payments. Payment modalities, service levels, and tariffs are formally established in contracts signed between UDUMA and local governments as service authorities (van der Wilk, 2019). Since each waterpoint has a unique identification code, monthly use and payment data can be linked to specific waterpoint characteristics (e.g.: infrastructure type) and information on service attributes:

a) **Data related to infrastructure:**
    a. Location: Municipality, Village, georeferenced location
    b. Type of infrastructure: handpump, solar-powered water kiosk
    c. Date of installation or upgrade of waterpoint

b) **Data related to service attributes:**
    a. Payment modality: volumetric direct payments, monthly flat fees
    b. Tariff structure: 500 FCFA ($0.80)/m³, 15,000 FCFA ($24)/month

c) **Data related to monthly waterpoint performance:**
    a. Metered water volumes
    b. Registered payments

As part of UDUMA's professional management approach, data on water use and payments per individual waterpoint are routinely collected every month. The unit of analysis is the individual waterpoint with repeated monthly measurements building the observational panel data (Frees, 2004). Using the unique waterpoint identification codes, volumetric water usage and observed payment data can be collected, compiled, and tracked. Metered water usage data from point sources are particularly uncommon in rural Africa.

UDUMA uses two types of standardised water meters in Mali (Maddalena at handpumps and Diehl at solar kiosks) to measure volumetric water usage. For the collection of volumetric data, area managers visit the respective waterpoints and conduct meter readings at the end of a month. The meter's index is recorded with a mobile data-collection tool (Kizeo), by scanning the unique QR code of the waterpoint, entering the meter reading, and taking a photo of the meter. These data are time-stamped and stored online. As part of this data collection process, a unique ID-number is generated per meter reading, ensuring that the data can be traced. The functionality of water meters is checked as part of the monthly meter readings. Where issues are detected (meter is broken or malfunctioning), meters are replaced.

The reliability of the metering data is controlled by supervisors based at UDUMA's field office in Bougouni. By comparing the meter reading with the picture and the historical track record of the respective waterpoint, supervisors verify and confirm the accuracy of the reported service data. When inconsistencies are identified (such as unusual water usage compared to the historical mean), an area manager is dispatched to conduct a verification visit at the waterpoint in question.

For the payment data, the area managers collect the cash revenue at each waterpoint as part of the monthly field visit. Under the volumetric payment approach, where users make direct payments to the waterpoint caretaker, the area manager collects the revenue amount from the caretaker. At handpumps operating under a monthly flat fee, the payment amount is collected from the respective waterpoint committee as a pre-payment for the following month (or months in case multiple months are paid in advance). The area managers register the revenue generated at each waterpoint using the mobile data-collection tool used for the meter readings (Kizeo), creating a specific revenue transaction ID, allowing for data to be traced. All cash revenue is sent to a local bank account using a mobile payment system (Orange money) for the transaction.

The data is consolidated in an operating account, compiling the monthly volumetric water usage and payment data per waterpoint, and stored on a cloud-based database. Supervisors subsequently compare revenues collected with the expected revenues based on volumetric water usage to assess the accuracy of the payment data. In cases where unusual patterns in revenue recovery (such as low or high amounts of non-revenue water compared to the historical mean) are identified, additional verification is conducted. On the 10th day of the following month, the operating account is closed, and the final data are stored, using the software solution MyReport. UDUMA subsequently shares these data in EXCEL format (csv or xlsx) according to the existing data-sharing agreement. The inherent limitations of this data generating process underlying the research are discussed in Section 3.5.

Based on these data, two distinct data sets for 177 handpumps and 15 solar-powered water kiosks were compiled. The longitudinal operational and financial performance data covering more than three years of operations between 2019 to 2023 allow to track water use, payment, and revenue patterns, using the following key metrics at the waterpoint level: average daily volume of water used, monthly payment collections, and monthly revenue (Table 3.2).

Table 3.2 Metrics to measure water use, payment behaviours, and revenues

Metric	Measurement	Unit
Daily volume of water	Average volume per day per waterpoint in a month	m^3
Monthly revenue	Total revenue generated per waterpoint in a month	$
Monthly collection efficiency	Ratio of revenue collected to revenue due per waterpoint in a month	%

Finally, total monthly rainfall estimates were retrieved from TAMSAT (Maidment et al., 2017, 2014; Tarnavsky et al., 2014), and monthly average temperature estimates were generated using Copernicus Climate Change Service data (Copernicus Climate Change Service, 2019) for each waterpoint using its geographic location coordinates.

3.3.2 Qualitative data

The qualitative material draws on various sources of primary and secondary evidence, including data collected through a total of 91 semi-structured interviews conducted with a range of local, national, and international stakeholders, on-site observations from fieldwork in Mali, and relevant contract, project, and policy documents. The subsequent sections provide an overview on the data, present the methods used for collecting the qualitative data, explain the respective sampling procedures and their rationales and limitations, describe the techniques used for documenting interactions with participants, and reflect on biases and positionality.

3.3.2.1 Fieldwork in Mali

To contextualise the implementation of UDUMA's contractual model and appreciate the perspectives of the various actors involved, in-person fieldwork was conducted in May 2022 in nine villages to interview local stakeholders and collect ancillary data on UDUMA's service area through waterpoint mappings. The selected field sites (Figure 3-4) were part of UDUMA's pilot cohort of ten villages that had received an infrastructure upgrade from handpump to solar-powered water kiosk in the period between March and May 2021 (more detail in Papers 1 and 2).

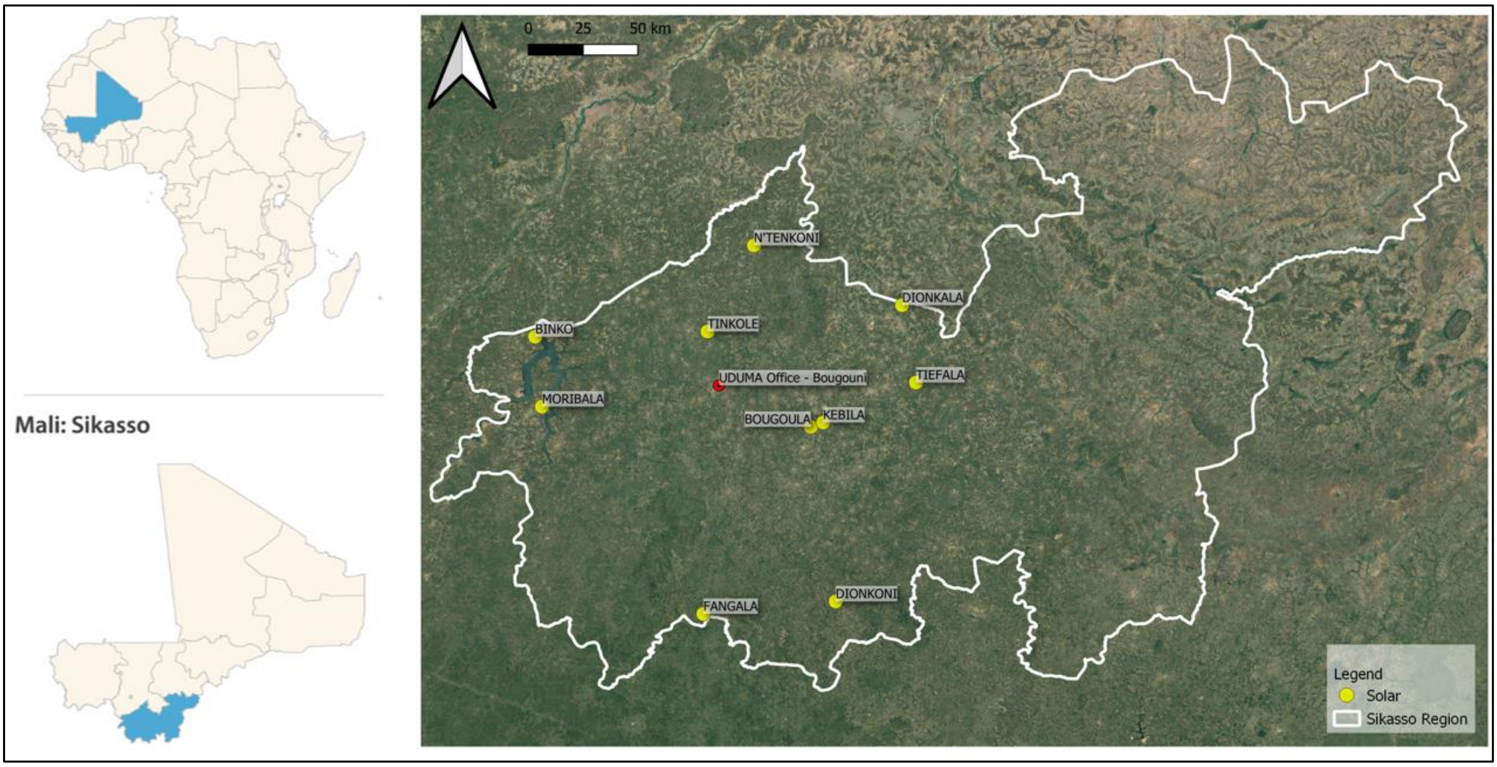

Figure 3-4. Map of fieldwork sites in Sikasso, Mali

Planning and implementation of fieldwork involved close collaboration with UDUMA's field staff and local governments to avoid unintended negative consequences (Wutich and Brewis, 2019). UDUMA facilitated the fieldwork by providing support in terms of logistics (dispatching a car and driver) and acted as a door-opener to the various stakeholders (site visits were conducted together with UDUMA's field officer in charge of community engagement).

Table 3.3 provides the dates at which the handpump management started, when the handpump was upgraded to a solar kiosk, and when the site was visited during fieldwork. Due to security reasons, it was not possible to visit the municipality of Wola and the village of Dionkala, and therefore no qualitative data were collected in these sites.

Table 3.3 Overview of fieldwork sites

Municipality	Village	Start of handpump	Upgrade to solar kiosk	Date of field visit
Fakola	Dionkoni	01/09/2020	25/03/2021	15/05/2022
Kebila	Bougoula	16/12/2019	30/03/2021	14/05/2022
	Kebila	23/01/2020	31/03/2021	13/05/2022
Koumantou	Tiefala	21/10/2019	30/04/2021	12/05/2022
Meridiela	N'tenkoni	25/11/2020	10/05/2021	10/05/2022
Sere Moussa Ani Samou	Moribala	28/02/2020	21/05/2021	18/05/2022
Sibirila	Fangala	17/03/2021	19/05/2021	16/05/2022
Sido	Tinkole	05/06/2020	05/05/2021	09/05/2022
Tagandougou	Binko	09/10/2020	21/05/2021	11/05/2022
Wola*	Dionkala*	08/12/2020	04/05/2021	NA

*Not possible to visit during fieldwork due to security concerns.

- **Interviews at the local level: sampling strategy and main research method**

Key stakeholders interviewed at the local level were water users using and paying for UDUMA's service, representatives from municipalities as contracting authorities, and community representatives. In total, 36 water users, 8 representatives of local governments, and 9 community representatives were interviewed in person during the field stay in Sikasso. The recruitment strategy for the interviews at the local level was informed by purposive sampling, selecting participants who have the potential to provide relevant and diverse data pertinent to the research question (Tong et al., 2007).

The main research method for collecting data on the subjective viewpoints, experiences, and attributed interpretations of respective participants were semi-structured interviews asking open-ended questions (Narayanasamy, 2009; Tong et al., 2007). Documentation of the interviews was undertaken using pen and paper to limit any perceived power imbalances between participants and researcher (Fetterman, 2010; Mannay and Morgan, 2015). Transcripts of the paper-based notes were established on a daily basis for further analysis.

For the user interviews, the participant selection was tailored to people using solar kiosks and handpumps managed by UDUMA (Figure 3-5). Three to five users were interviewed at each site. The interviews covered key themes such as the degree of user satisfaction, practices, motivations, and interpretations regarding UDUMA's service and related service adaptations. The sample is not probabilistic but biased towards UDUMA's customers, therefore providing only limited information on the perspectives of users not relying on UDUMA's service for their drinking water supply. This is a key limitation of the methodology but inherently related to the question of interest underlying the data collection process.

Figure 3-5. Solar-powered water kiosks. Top row: users in Bougoula; bottom row: users in Binko.

Interviews with representatives from local governments were conducted to gather insights on the perspective of the service authorities as a formal contract party. Interview respondents were either the municipality's mayor, Secretary General, or the officer in charge of WASH. The interviews focused on understanding the municipality's rationale for joining the arrangement and its perception of the relationship with UDUMA. Informal discussions with community representatives were designed to unravel collective perceptions of UDUMA's service and to understand the communities' motivations shaping the outcomes of the contract arrangements.

For the interviews with water users and community representatives, translation between French and Bambara was required. UDUMA's field officer translated the guiding questions and respective interviewee responses and facilitated dialogues as necessary. While the UDUMA employee's intimate understanding of the fieldwork setting was crucial for enabling the data collection, this set-up may have created an interviewer bias as the interviewees' opinions may interfere with the relationship existing between them and UDUMA as the target organisation.

- **Waterpoint mapping**

In addition, contextual information on UDUMA's service area was collected through waterpoint mappings (Figure 3-6). For this, with support from village representatives, alternative water sources, such as community wells, handpumps, small piped systems with public standposts, and surface water sources were identified and mapped in each of the sites. The specific characteristics of each source, such as source category, functionality, perceived water quality, and key institutional information pertaining to ownership, and management and payment arrangements were recorded using a custom-built mobile data collection tool (ONA/ODK). In case people were fetching water at alternative sources, short questions were asked to understand their motivations to choose this particular source, to identify the use purposes of the water collected, and to illicit their perceptions of UDUMA's service. In total, 85 water sources were identified across the nine villages out of which 27 waterpoints are managed by UDUMA. These insights are used to illustrate the non-exclusive nature of rural water (Paper 1).

Figure 3-6. Alternative water sources. Examples from Kebila, N'tenkoni, and Moribala (left to right).

- **Positionality during fieldwork**

During fieldwork, interviewees may have reacted differently given my social and cultural background as a French-speaking white male, particularly in Mali's post-colonial context. While I have more than three years of lived experience working in Bamako and am relatively accustomed to local cultural and social practices, I am aware that my position as a foreign researcher necessarily created power imbalances. Moreover, I had to navigate expectations as respondents asked whether the research would result in improvements in their water supplies, which might have influenced user responses. Inevitably, these factors will have produced unquantifiable bias in the reported research.

3.3.2.2 Data on UDUMA's perspective: interviews and project documents

Three interviews with local UDUMA staff in Mali were conducted to collect information on the provider's perspective regarding the implementation of the contract. Particularly, insights on the application of specific contractual clauses, such as payment enforcement, as well as the wider processes of renegotiation were gathered. In addition to the in-person interviews with staff from UDUMA Mali, six in-person workshops and 13 online meetings with staff from UDUMA France have been organised between 2020 to 2023 to understand the service model and stay informed of its implementation and evolution. These spaces for discussion provided opportunities for regular updates from Mali and allowed for sharing research findings and receiving feedback. As part of these exchanges, the provider's perspective on the implementation of the contract and the wider processes of renegotiation was gathered. Besides, semi-structured interviews with representatives of funding agencies (n = 2) involved in UDUMA's model were conducted to clarify their role in the initial arrangement and its evolution. These expert interviews were conducted online in 2023.

In addition, relevant documentation on UDUMA's service delivery model was collected. The formal service delegation contracts (initial version from 2018 and revised in 2021) and related appendices were retrieved from UDUMA (UDUMA, 2018a, 2021a, 2021b). Ménard emphasises the importance of appendices to a contract as these specifications are meant to "make commitments as observable as possible [and] often determine the essence of the agreement" but are frequently ignored in studies on contracts (2004, p. 18). Furthermore, various project documents were compiled, consisting of UDUMA's initial project proposal (UDUMA, 2017), annual progress reports (UDUMA, 2022, 2021c, 2020, 2019, 2018b), a report on UDUMA's strategy change (UDUMA, 2021d), and a report from the Regional Water Directorate (DRH, 2020).

3.3.2.3 Data collection at the national level: expert interviews and documents

Semi-structured expert interviews with representatives (n = 14) from technical and political organisations intervening in the water sector in Mali were conducted online throughout the year 2021 due to COVID-related travel restrictions and Mali's volatile security situation. A combination of purposive sampling (seeking representatives of government, donor agencies, local and international NGOs, and civil society organisations) and snowball sampling was used to identify key informants. The interviews were structured around the role of contracts, infrastructure, and financing for rural drinking water services in Mali. Interviews were conducted in French and lasted on average for one hour. Notes were taken during the interviews and subsequently transcribed for further analysis. Finally, legal and policy documents were compiled based on their relevance for drinking water services in rural Mali (DNH, 2019, 2007, 2006, 2004; Republique du Mali, 2002).

3.3.3 Ethical considerations

Prior to all data collection, the research obtained ethical approval by the School of Geography and Environment's Departmental Research Ethics Committee (SOGE1A2020-195, SOGE 1A2020-210, SOGE1A2021-046). At every stage of research involving human participants, verbal or written consent was secured before data collection. Participants received information on what is being researched, the scope of their involvement, any possible risks and benefits associated with their participation, and how the findings would be disseminated. Participation was voluntary and participants were free to withdraw at any stage of the interview process. All questionnaires guiding the semi-structured interviews with the various stakeholders are provided in the appendices of the thesis (Appendix II A) to E)).

All research data (spreadsheets, documents, interview files, etc.) have been stored in a secure Nexus 365 folder. Raw data files from UDUMA have been stored in a separate folder than the database where additional transformations have been performed to compile the datasets underlying Papers 2 and 3. In accordance with the data policies of the respective journals, anonymised subsets of the quantitative data have been submitted with the relevant manuscripts and will be published as part of the individual papers.

3.4 Data analysis

The quantitative and qualitative data described above have been analysed using complementary approaches. The thesis investigates the interplay between contract design and consumer demand, integrating an in-depth qualitative analysis of UDUMA's contractual model and quantitative assessments of waterpoint data covering multiple sites over time. The research's stepwise analytical strategy first explores how UDUMA's service model evolved over time (Paper 1), and subsequently provides insights into the consequences of change to contractual arrangements on water use and revenue outcomes (Papers 2 and 3).

3.4.1 Qualitative content analysis

The analytical strategy guiding Paper 1 posits that "aspects of institutions and institutional change appear in the form of qualitative evidence" (Skarbek, 2020, p. 409). To apply the conceptual proposition of incomplete contracting to rural water and to understand the process of contract renegotiation, different sources of qualitative empirical material were analysed through an inductive, data-driven approach (Mayring, 2014; Silverman, 2017). UDUMA's initial and revised contracts were systematically reviewed to identify changes in contractual provisions. The analysis included the appendices of the formal contract documents detailing the service level agreement of UDUMA. Subsequently, interview material, field reports, and project documents were purposively analysed to extract relevant information pertaining to perceptions and underlying motivations of the relevant actors involved in UDUMA's model (Ercan and Marsh, 2016; Saldaña, 2013; Silverman, 2017). This allowed to unravel the processes leading to the identified changes in UDUMA's contracts. Through comparison of stakeholders' perspectives and synthesis across the diverse data, the interpretative analysis identifies points of convergence and recurring motives, enhancing the consistency of the interpretations drawn. This increases the study's internal validity within the study context (Onwuegbuzie and Leech, 2007). To avoid misrepresentation and misinterpretation and build credibility for the research's conclusions, informant feedback was sought by sharing the manuscript with key informants (Onwuegbuzie and Leech, 2007, p. 241).

3.4.2 Interrupted time series design

Paper 2 applies an interrupted time series (ITS) design to longitudinal waterpoint data and exploits the distinct time point of the infrastructure upgrade to ascertain whether the switch from handpump to solar kiosk has an effect on the level and the trend of water use, payment collections, and revenue outcomes. ITS analysis is particularly suitable for assessing observational data to infer the effect of an exogenous change on a dependent variable where randomisation is not an option, and control groups are not readily available (Li et al., 2021; Lopez Bernal et al., 2019; Soumerai et al., 2015). The method assumes linearity in pre- and post-intervention trends, and that any change in the outcome of interest is due to the intervention itself. Because the method is based on observing a single population over time, rather than on a comparison with a control group as utilised in difference-in-differences designs, an ITS design is free from problems related to unmeasured between-group differences. In addition, the method is malleable enough to account for underlying trends and measured time-varying confounders (Li et al., 2021; Soumerai et al., 2015). Until now, this method has been mainly used for the evaluation of public health interventions (Kontopantelis et al., 2015; Lopez Bernal et al., 2018, 2016; Penfold and Zhang, 2013; Turner et al., 2021). With the growing availability and quality of continuously collected data before and after specific interventions, ITS designs are increasingly applied to other sectors (Chintalapati, 2021; Hollander et al., 2020). Inspired by this analytical approach, Paper 2 assesses the effects of a specific infrastructure change at a clear cut-off in time and applies segmented regression models to monthly records of observed payments and volumetric water usage of two separate cohorts of waterpoints. Recognizing that climatic conditions likely influence water use and payment behaviours, the models account for rainfall and temperature at the necessary spatial and temporal resolution.

3.4.3 Fixed effects regression

Finally, Paper 3 applies fixed effects regression models to longitudinal water use records, observed payments, and climatological data to estimate how a change from volumetric to monthly flat fee payments affects water use, payment collections, and revenue outcomes. In most non-experimental social science research individual units differ in so many respects that it is impossible to control for all of them. Fixed effect models using panel data allow to mitigate this limitation by comparing within unit change instead of estimating effects from a comparison between different units (Best and Wolf, 2014; Henningsen and Henningsen, 2019; Wooldridge, 2010). Since each individual waterpoint in the panel data is observed over multiple time periods, the analysis in

Paper 3 exploits the within variation per unit to estimate the effect of the change in payment modalities, while controlling for seasonal confounders. The regression models include unit-fixed effects at the waterpoint level to alleviate omitted variable bias arising from time-invariant, unobservable, location-specific confounders, such as localised community practices or the number of alternative sources surrounding the respective waterpoint. To account for correlation between recurring observations for an individual unit, the models use robust standard errors, clustered at the waterpoint level (Abadie et al., 2022; Cameron and Miller, 2015).

3.5 Limitations

The reported research has several limitations with regard to the research's focus and scope, data collection, and analytical techniques.

First, relying on secondary data from a service provider comes with risks. For instance, self-reported data is prone to errors and manipulation. As outlined in the description of the data generating process (Section 3.3.1), the longitudinal waterpoint performance data is processed. However, the traceability of the data is ensured, as primary data in the form of time-stamped data collection transactions for meter readings and payments at individual waterpoints are available. During fieldwork in Mali in May 2022, specific checks were conducted to verify the accuracy of the reported data. For instance, the 10 waterpoints that were part of UDUMA's solar pilot were used as a sample to compare the primary reports for volumetric water usage and registered payments with the records received as part of UDUMA's regular data sharing. Here, photos of the meter readings recorded through Kizeo forms were compared with the reported volumetric data. In addition, UDUMA's waterpoint performance data was verified by conducting in-person spot-checks at 27 waterpoints across 9 villages in May 2022. The spot-checks consisted in confirming the reported functionality status and meter readings of the respective waterpoints. While the short-term fieldwork in Mali in May 2022 allowed for conducting checks for data consistency and assessing the reliability of UDUMA's data generating process, it was not possible to verify the accuracy of the reported data at scale. Nonetheless, having access to metered water usage and observed payment data from manual pumps and solar kiosks from rural Mali may outweigh this shortcoming.

Second, while the quantitative research reveals water use and revenue patterns over time and across specific service adaptations, its capacity to explain the identified trends is limited. This is mainly due to various unknowns. For example, the exact service population, the presence, price, or reliability of alternative water sources, or local changes in socioeconomic conditions are largely unknown. These limitations are considered in the research which acknowledges the existence of various factors that cannot be controlled for due to lack of data. Therefore, the research does not make causal claims based on the quantitative findings of Papers 2 and 3. It is emphasised that the site selection for the introduction of solar kiosks is not random, and Paper 2 is not based on a formal experiment. As detailed in Paper 2, for the initial solar pilot, UDUMA selected sites with potential for success, biasing the infrastructure upgrades to supportive communities and handpumps with consistent use and payment records. The analysis of the observational data suffers hence from endogeneity due to bias in the introduction of the infrastructure intervention, leading to a biased sample (Abdallah et al., 2015; Scott and Stern, 2018). To address this limitation, the analysis focuses on two separate waterpoint cohorts, comparing the initial intervention cohort with a subsequent cohort (Lopez Bernal et al., 2018, p. 2087). The ITS estimations across the two separate waterpoint cohorts yield similar effect sizes and directions, suggesting consistency of patterns across contexts. The ITS results have been confirmed by applying fixed-effects regression models to the full panel data. Nonetheless, further research is needed to substantiate the findings of Paper 2, for instance by identifying a comparable control group of waterpoints for applying a comparative interrupted time series (CITS) analysis (Lopez Bernal et al., 2019, 2018) or by conducting a randomised control trial.

Third, while qualitative evidence was collected during an in-person field stay in May 2022 allowing to corroborate the quantitative findings of Papers 2 and 3, it was not possible to conduct long-term fieldwork in Mali to investigate wider cultural, social, or political processes at scale. For instance, the thesis does not assess decision-making dynamics at the community level which would be relevant for understanding revealed payment behaviours of monthly flat fees (Paper 3). Linked to this, the revealed patterns of water use and payment behaviours at solar kiosks would require further qualitative investigation to identify the underlying mechanisms that drive these outcomes (Paper 2). Some of these shortcomings are discussed as emerging opportunities for future research (section 7.3). In addition, the selection of participants for interviews at the local level was guided by purposive sampling and was biased to waterpoints managed by UDUMA.

Finally, it must be emphasised that interviews were not recorded. As notes were taken using pen and paper to limit perceived power imbalances between participants and researcher and to accommodate the preferences of interviewees, interview quotes are not strictly verbatim.

Fourth, the project faces limitations in its scope and scale. Selecting UDUMA as one provider offering guaranteed services excludes other possible approaches for delivering reliable rural water services from the analysis. A recent assessment identified "a group of 77 service providers delivering water services for about 5 million people in 28 countries" (Nilsson et al., 2021, p. 5). While the research provides a detailed analysis of one of the first examples of a commercial contract for professional drinking water service delivery in rural Africa, the implications from this thesis must be seen in its case-study context. Yet, the conceptual and empirical insights provided by this research are still of value to other contexts.

It must also be noted that the Covid-19 pandemic created practical barriers for the success of this research project. For instance, fieldwork originally planned for early 2021 had to be postponed. In addition, the possibility of conducting long-term fieldwork in rural Mali to qualitatively investigate revealed patterns of user behaviour was limited due to security concerns. A coup by the Malian military on 18th August 2020 destabilised Mali's already fragile political situation. A second coup on 24th May 2021, a subsequent embargo by ECOWAS since January 2022, and diplomatic tensions with France throughout 2022, leading to the withdrawal of French troops from Mali in September 2022, and putting French official development aid on hold since November 2022 further increased travel risks. The United Nations Security Council decision taken on 30th June 2023 to end the United Nations Multidimensional Integrated Stabilization Mission in Mali (MINUSMA) by 31st December 2023 (MINUSMA, 2023) made further fieldwork even more impractical. The short-term field stay in May 2022 was only possible due to an existing local support network and UDUMA's intimate understanding of the fieldwork setting addressing some of the challenges of conducting fieldwork in remote areas in Mali.

3.6 Statement on research collaboration and joint publications

Individual contributions to the research and its corresponding papers are summarised in Table 3.4.

Table 3.4 Collaborators and individual contributions to the research and related publications

Dimension	Contributor Role (based on CRediT taxonomy)	Collaborators*						
		JW	RH	JK	SM	SI	AG	MD
Overall DPhil research	Conceptualisation	●	○	○				
	Investigation	●						
	Data Curation	●						
	Writing – Original Draft	●						
	Writing – Review & Editing	●	○	○				
	Visualisation	●						
	Supervision		●	○				
	Project Administration	●	○					
	Funding Acquisition	●	●					
Paper 1	Conceptualisation	●	●	○				
	Methodology	●						
	Investigation	●						
	Writing – Original Draft	●						
	Writing – Review & Editing	●	○	○				
	Visualisation	●						
Paper 2	Conceptualisation	●	●					
	Methodology	●	○			○		
	Investigation	●					○	
	Data Curation	●			○			
	Software	●			●			
	Formal Analysis	●			●			
	Writing – Original Draft	●	○					
	Writing – Review & Editing	●	○		○	○	○	
	Visualisation	●			○			
Paper 3	Conceptualisation	●	○	○				
	Methodology	●						
	Investigation	●						○
	Data Curation	●						
	Software	●						
	Formal Analysis	●						
	Writing – Original Draft	●	○					
	Writing – Review & Editing	●	○	○				○
	Visualisation	●						

*JW: Johannes Wagner, RH: Rob Hope, JK: Johanna Koehler, SM: Sara Merner, SI: Stefania Innocenti, AG: Alinta Geling, MD: Mikael Dupuis; ●: lead, ○: support.

Chapter 4: Managing contractual uncertainty for drinking water services in rural Mali (Paper 1)

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Note: To ensure a coherent format throughout the thesis, the numbering of tables and figures in this chapter have been adapted compared to the submitted version of the paper.

Abstract

Contracts allocate rights, obligations, and risks between various parties to achieve specific results. In response to slow progress to deliver safe drinking water to rural populations, governments across Africa are increasingly introducing contracts with professional service providers as a new institutional and financial arrangement. Contracts for drinking water service provision are designed to align operational outcomes with financial objectives. Contract theory indicates that renegotiation is a critical mechanism to adapt an incomplete contract design to uncertainties in operational and financial performance. The article examines contract renegotiation with an empirical analysis of a professional water service delivery model operating in rural Mali. Drawing on qualitative data, the analysis provides insights on the functioning, limitations, and prospects of formal contracts for rural drinking water services. Results suggest that contract renegotiation is conditional on the agreement of the original parties to adapt the contract and also requires the involvement of external actors and capital to address the shortcomings of an incomplete contract. In the Mali case, we find that contract design is incomplete due to the inability to enforce local water demand, hindering progress to revenue targets aligned with commercial finance. This condition is likely to hold in most rural contexts which requires contracting models for rural water services to combine public and philanthropic funding and private finance to deliver on desired outcomes.

Keywords: Africa; contract theory; drinking water; Mali; professional service delivery; SDG 6.

4.1 Introduction

Contracts are part of everyday life. They govern interactions in a wide array of sectors and structure related activities, including employment, bank services, utilities (e.g.: energy, water, or sanitation), insurance, or mobile phones. In its most basic form, a contract is an arrangement between two or more parties which allocates rights and obligations that can be legally enforced. Such an arrangement involves the exchange of goods or services, or a promise to exchange those at a future date, and defines expected outcomes. Finally, a contract provides a process for resolution of contract infringements and termination (Hart and Moore, 1988; North, 1990).

We explore the extent to which contracts may provide a mechanism to support safe drinking water services in rural Africa where historically formal contracts have not been applied. Rural water services have commonly been delivered through informal community-based management. Despite significant investments in community approaches, progress has been largely unsatisfactory in maintaining rural water supply infrastructure (Foster, 2013; Hutchings et al., 2015; RWSN, 2010; van den Broek and Brown, 2015; Whaley et al., 2019), leaving approximately 25%-30% of waterpoints in rural Africa non-functional (Foster et al., 2020).

In response to this, and given four in five people without safe drinking water live in rural areas (UNICEF and WHO, 2023), professional service providers are increasingly being mandated across rural Africa to ensure the operational sustainability of water supplies (McNicholl et al., 2021; Nilsson et al., 2021; WHO et al., 2022). This institutional shift towards more formal service delivery is organised through contracts which are designed to align operational outcomes with financial objectives (Hope et al., 2020; Hope and Rouse, 2013). Contracts between professional service providers and governments may offer a suitable means to attract investment and capacity to accelerate progress towards the Sustainable Development Goal for Water, SDG 6.

Criteria pertaining to the drinking water service ladder (UNICEF and WHO, 2023) can provide guidance on specific service outcomes that a rural water contract may define. Once contractually agreed, outcomes, such as water quantity, quality or service reliability can be tracked over time to assess compliance, inform enforcement, and increase efficiency. In exchange, it is expected that a contract clarifies the service provider's revenue base, mainly by granting the right to collect tariffs from users (Gia and Fugelsnes, 2010; Kleemeier and Lockwood, 2012; Kleemeier and Narkevic, 2010; McNicholl et al., 2019). This is in line with a widely established policy principle stipulating that operation and maintenance costs of drinking water services are to be covered through tariffs paid by users (Fonseca et al., 2013; Hope et al., 2019; Hutton and Varughese, 2016; Kolker, 2023; Kolker et al., 2016; Leigland et al., 2016; Pories et al., 2019; Winpenny et al., 2016).

While this policy objective informs contract design for sustainable rural water services, in practice, contracts fall short of achieving anticipated results. Evidence indicates that professional service providers generally deliver on their obligation to provide high quality drinking water services in accordance with contracted performance indicators. Yet, they only rarely generate sufficient revenue via user payments to cover operating costs (Foster et al., 2022; McNicholl et al., 2021, 2020; Smith et al., 2023). In other words, while operational results are achieved, revenue goals are missed – and this despite contracts that are meant to promote financial sustainability are in place. Contract theory provides a conceptual framework for understanding the functioning, advantages, and limitations of contracts and may shed light on the challenges regarding their implementation for delivering sustainable rural water services.

4.2 Conceptual foundations

4.2.1 Incomplete contract design and renegotiation

According to North, formal contracts form part of the human-made strategies for organising and sustaining societal relations and economic performance and are established to reduce "uncertainties involved in human interaction" (1990, p. 25). Any contract design may vary regarding the number of parties involved, the duration of the contract, or still the specific characteristics of the contracted outcomes. Yet, their common feature is that they provide the structure necessary to exchange goods and services over time. Here, Hart and Moore (2008) demonstrate that contracts act as reference points, shaping future performance by anchoring initial expectations of the contracting parties. Hence, when signing a contract, parties know how future payoffs will be distributed amongst them, how resources flow, or how risks are allocated.

This reduction of uncertainty is particularly relevant for more complex exchanges of services or goods that involve asset-specific investments (Goldberg and Erickson, 1987; Hart, 2003; Hart and Moore, 1988; Williamson, 2002). Here, long-term contracts may mitigate risks associated with the lock-in effect of asset-specificity where "buyers cannot easily turn to alternative sources of supply, while suppliers can redeploy the specialized assets to their next best use or user only at a loss of productive value" (Williamson, 2002, p. 176). Hence, when specific investments, such as infrastructure, are required for an exchange, parties may write a long-term contract, providing the necessary foundation for subsequent investments.

Regarding the outcomes permitted by a contract, parties must navigate trade-offs between flexibility and rigidity (Fehr et al., 2011; Hart and Moore, 2008). A rigid contract anchors parties' expectations through a fixed price and clearly defines the specific characteristics of the relevant good or service. A flexible contract, on the other hand, seeks to set a price range for a good or service whose specific characteristics will be defined during contract implementation. This allows parties to adjust the outcomes permitted by the contract to the contingent states of the world but may lead to friction as the buyer and seller may have different preferences regarding which outcome to choose: "when the contract permits more than one outcome, each party may feel entitled to a different outcome", leading to inefficiencies (Hart and Moore, 2008, p. 3). Besides, costs associated with writing and implementing a flexible contract are generally high (Gottardi et al., 2017; Hart, 2017; Hart and Moore, 2008), and the relative simplicity of a rigid contract seems to be appealing to contracting parties (Fehr et al., 2011; Gottardi et al., 2017). Therefore, in practice, parties tend to write more rigid contracts, particularly when asset-specific investments are involved (Hart, 2017; Hart and Moore, 2008).

Regardless of its rigidity or flexibility, contract theory suggests that any contract is necessarily incomplete (Hart, 2017, 2003; Hart and Moore, 2008, 1988). This inherent incompleteness is likely to become apparent during contract implementation when parties realise that specific issues have been overlooked in the initial contract design and expected outcomes will not be achieved (Awortwi, 2012; Hart and Moore, 1988; OECD, 2011; Sansom et al., 2003). To overcome contractual incompleteness, Hart and Moore (1988) demonstrate that parties may renegotiate the terms of the contract or improve contract enforcement. Empirical research shows that uncertain demand is a central factor for adjustments of long-term contracts through renegotiation (Athias and Saussier, 2018, 2007; Feng et al., 2023; Guasch, 2004; Guasch et al., 2008), reflecting wider challenges related to demand forecasting and information asymmetries (Flyvbjerg et al., 2005). Since contractual performance essentially depends on the motivation of the parties involved, adapting the "incentive-disincentive structure" embedded in a contract may allow to make progress towards expected outcomes (North, 1990, p. 52). For instance, renegotiation can improve the efficiency of a contract as it enables the parties to readjust the expected outcomes to experiences and information from implementation (Fehr et al., 2011; Hart and Moore, 2008). Besides, adapting contractual arrangements through experimentation may provide opportunities for wider learning to inform policy design and service delivery practice (Huitema et al., 2009).

In addition to challenges related to incompleteness, for a contract to perform, the wider institutional environment matters, that is, the capacity of the contract parties or outside actors to enforce contractual terms (Messick, 2005; North, 1990). The legal enforceability and regulation of contracts varies in a spectrum from conditions of mature contract markets to more informal social contexts. As such, it may be challenging to introduce formal contracting approaches to rural areas of developing countries where the reach of enforcement capabilities of state authorities is limited (Herbst, 2014; Messick, 2005; North, 1990).

Finally, the scope of renegotiation is dependent on the willingness of the parties to renegotiate (Frydlinger and Hart, 2023). Reputation and loyalty between the contracting parties can enable renegotiation to address incomplete contracts (Athias and Saussier, 2018; Beuve and Saussier, 2021), particularly when formal enforcement mechanisms are missing (Messick, 2005; North, 1990). Frydlinger and Hart (2023) demonstrate that frequent and transparent communication between the parties during contract implementation can help when changes to a contract are needed.

The following section explores how these general contracting conditions and principles apply to contractual arrangements for rural water service delivery.

4.2.2 Rural water service delivery in Africa

The delegation of service delivery functions through contracts is widely established as a policy principle in rural water supply (Gia and Fugelsnes, 2010; Kleemeier and Lockwood, 2012; Kleemeier and Narkevic, 2010; Simone et al., 2016). In more than 19 countries in sub-Saharan Africa, service authorities holding the infrastructure assets must delegate service delivery to a service provider which can either be a public entity, private enterprise, or a legally recognised water user association. In various other countries, the involvement of the private sector in rural water service delivery is encouraged but the modalities of this participation are not further specified (Figure 4-1).

The increasing interest in contractual approaches to service delegation is part of a wider institutional shift in rural water (Nilsson et al., 2021). In comparison to traditional community-based management, professional service providers deploy formal contracts tailored towards long-term service delivery, including repairs and wider support services for rural drinking water infrastructure (Lockwood et al., 2021). By defining expected service outcomes through contractual frameworks, results can be tracked by key performance metrics such as volume of water, local revenue, water quality, or repair time (Charles et al., 2023; McNicholl et al., 2019). This provides a basis for accountability, oversight, and user protection (Gerlach, 2019; Lockwood, 2021). In exchange, the contract defines a tariff that users are expected to pay for the service received (Gia and Fugelsnes, 2010; Janssens, 2011; Kleemeier and Narkevic, 2010; Koehler et al., 2018; McNicholl et al., 2019).

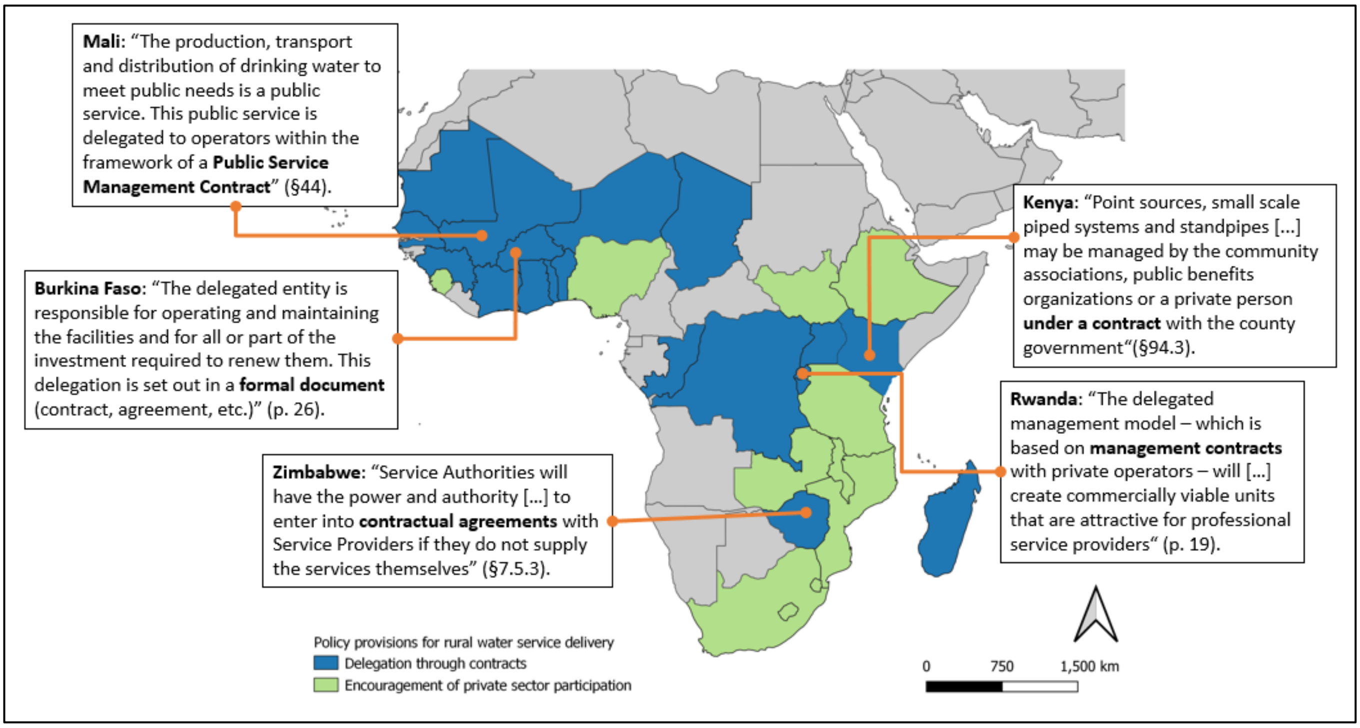

Figure 4-1. Delegation and private sector participation in rural water service delivery. Results of a desk review of national water policies, laws, and regulations. Quotations taken from the following sources: National Strategy for Drinking Water Services in Rural Areas (Ministry of Water and Sanitation of Burkina Faso, 2018), Water Act of Kenya (Republic of Kenya, 2016), Water Act of Mali (Republique du Mali, 2002), National Water Supply Policy (Ministry of Infrastructure of Rwanda, 2016), National Water Policy (Ministry of Water Resources Development and Management of Zimbabwe, 2012). This overview of policy provisions does not draw conclusions about their implementation in practice.

In addition to the specific service outcomes that a contract may define, the particular type of contract in place has implications on how risks are distributed amongst contracting authority and service provider. In the literature three main contract types have been identified for rural water services, ranging from management, over lease or *affermage*, to concession contracts (Table 4.1).

Table 4.1 Contract types for the delegation of rural water services

Type of contract	Management	Lease/Affermage	Concession
Obligations of service provider	Provide specific management services	Operate and maintain assets, deliver water services, undertake billing and tariff collection	Finance and construct new infrastructure, operate and maintain assets, deliver services, undertake billing and tariff collection
Typical payment mechanism	Fixed fee	Revenue from customers minus lease fees	Revenue from customers minus concession fees
Capital investments	Contracting authority	Shared (infrastructure from contracting authority, operating assets from service provider)	Service provider
Asset ownership	Contracting authority	Contracting authority	Contracting authority or service provider
Risk transferred to provider	Low	Significant	Major
Typical duration	3-5 years	6-15 years	15-30 years

NB: Adapted from existing typologies (Hydrophil, 2013, p. 23; OECD, 2011, p. 16; REACH and RWSN, 2023, p. 43; Sansom et al., 2003, p. 20; WSP, 2014, p. 19).

Generally, delegation involves a transfer of financial risk from the asset holder to the operator. Depending on the scope of delegated service functions and associated risks, the duration of the contract will vary (Gia and Fugelsnes, 2010; Hydrophil, 2013; Janssens, 2011; OECD, 2011; Sansom et al., 2003; WSP, 2014). For instance, if a contract requires the service provider to make infrastructure investments, creating major financial risks, the timeframe for the contract will typically be of at least 15 years to allow for a sufficient pay-back horizon.

Yet, regardless of the particular contract type in place, revenue goals of contracted rural drinking water service delivery models are not achieved in many cases (Foster et al., 2022; Katuva et al., 2016; Koehler et al., 2021; McNicholl et al., 2021, 2020; Smith et al., 2023), pointing to wider issues of contractual incompleteness. Since “contracts are often drawn up using incorrect assumptions” (Gia and Fugelsnes, 2010, p. 16), it is only during contract implementation that mismatches between expected and actual outcomes materialise, suggesting that the initial contract design did not adequately consider the specific economics of rural water and associated uncertainties.

4.2.3 Uncertainties related to rural water user behaviour

Rural water is characterised by particular geographical, spatial, socio-political, and economic factors shaping its specific economics and uncertainties. Importantly, the prevalence of alternative water sources on which rural users potentially rely leads to uncertain demand since rural households can choose between various water sources for different uses (Briscoe et al., 1981; Gross and Elshiewy, 2019; Hoque and Hope, 2018; Martínez-Santos, 2017; Thompson et al., 2001; White et al., 1972).

This specificity may not always be considered in policy and practice, leading to flawed assumptions about the role and obligations of water users. It is assumed that users will use and pay for the service as planned. However, rural water is characterised by a high degree of autonomy of users, leading to relative demand uncertainty. The non-exclusive nature of rural water constitutes a fundamental challenge when a contract links revenue to water production and sales, thereby effectively allocating the commercial risk to the service provider (Janssens, 2011).

In addition, evidence indicates that user demand and payments are contingent on the quality of services provided (Foster and Hope, 2017; Nauges and Whittington, 2010; Shongwe and Dlamini, 2021; Van Houtven et al., 2017). Hence, a service provider has an incentive to influence user demand to generate sufficient revenues. Engaging in value creation by delivering high-quality services that people want and value (Garrick et al., 2020, 2017; Hope et al., 2020), appears as an adequate strategy for service providers to increase their revenue (Carter et al., 2010). Here, service attributes pertaining to water quantity, quality, affordability, proximity, and reliability may provide guidance on key priorities of rural water users (Hope et al., 2020).

Following the rationale that contracts can be renegotiated during contract implementation (Hart and Moore, 1988), contractually agreed service delivery objectives may be revisited to promote more sustainable outcomes. Yet, it is unclear what implications renegotiation and related service adaptations have for user demand and revenue generation.

To better understand the role of formal contracts for the delivery of sustainable rural water services, we investigate a particular service delivery model in rural Mali. We explore how contract incompleteness affects the sustainability of professional rural water service delivery, and how and to what extent an incomplete contract design might be addressed. By doing so, we examine how different actors behave and cooperate in overcoming the limitations of an incomplete contract, how risks and responsibilities are allocated amongst the various parties and assess to what extent the adaptation of service attributes allows to address contractual incompleteness. Based on these insights, we discuss wider implications for designing contracts for drinking water services in rural Africa and reflect on how contracted outcomes may be used to support sustainable service delivery.

Similar to Frydlinger and Hart (2023), our analysis aims to illustrate through a case study approach the prospects and limitations of implementing contracts for rural water service delivery. The analysis draws on contracting documents, interviews, and field reports to illustrate how renegotiation and related changes in service attributes affect contractual outcomes in rural Mali.

The following section lays out the study context and provides a detailed description of the provider's contractual model.

4.3 Case presentation

4.3.1 Context

Mali's water sector is based on the Water Act (Republique du Mali, 2002) which defines the general institutional framework, stipulating local governments as service authorities for rural water supply (Article 49). Municipalities, Mali's lowest government level, bear the ultimate responsibility for drinking water services on their territory (Article 50) but must delegate service provision to a provider which can either be a private or public entity, or a legally recognised water user association (Article 45). The delegation must be organised via a formal contract (Article 51) including a service level agreement which clarifies terms and conditions of the service (DNH, 2007). In our case, 30 local governments in the Region of Sikasso, located in the south of Mali, decided to contract UDUMA, a professional service delivery company (van der Wilk, 2019).

4.3.2 Professional service delivery model

Through the initial contracts signed in November 2018 (UDUMA, 2018a), these municipalities grant UDUMA for a duration of 15 years (§ 5) the exclusive right (§ 6) to set up its service model in their respective territories, covering all existing handpumps for community drinking water supply, and to collect tariffs from users (§ 1). In exchange, the provider invests in the rehabilitation of the water supply infrastructure which will be handed over to the service authorities after the end of the contract (§ 7). This contractual relationship, where an operator invests in existing infrastructure and is responsible for its operations and maintenance and bill collection from customers, is a particular type of a lease contract, called *affermage* (see Table 4.1). As part of the contract, UDUMA must ensure a bi-annual financial and technical reporting to the service authorities for accountability purposes (§ 12) and pay a fee of 3% on its annual billed and paid turnover (§ 20). Local governments have hence a financial incentive to adhere to the contractual agreement (UDUMA, 2017).

Regarding the user-provider relationship, UDUMA commits to providing a reliable service, guaranteeing a maximum downtime of 72 hours per waterpoint, and must conduct regular water quality monitoring and relevant interventions in case bacterial contamination is detected (Annex 2 of the contract). In exchange, water users must pay a volumetric, pay-as-you fetch tariff of 500 FCFA ($0.80) per m^3 (§ 21 and Annex 2), in line with Mali's tariff policy for rural water supply (DNH, 2007). Through the guaranteed service, users are insured against operational risks of handpump failure and can mitigate financial risks of high repair costs, which constitute a major factor for sustained downtime (Foster, 2013; Foster and Hope, 2016; Jones, 2013). Environmental risks related to groundwater pollution are addressed to some extent through regular water quality testing and water safety plans implemented at the village level (§ 14 and Annex 2). UDUMA's contract may be considered rigid as it defines expected outcomes clearly and "take[s] price off the table" (Hart and Moore, 2008, p. 25).

From the out-set UDUMA has clear expectations about the outcomes of exclusive contracts, as its financial model is based on full cost recovery through user payments. Once contracts are in place, officialising a shared understanding of the terms of the agreement, financial sustainability will be achieved since people will use and pay for the service provided (UDUMA, 2018b, 2017). UDUMA's business model foresees a daily water demand of at least two m^3 per handpump and projects no default in volumetric payments, effectively tying revenue to water demand, billing, and bill collection.

The formal contracts are complemented by informal community agreements (§ 15 and Annex 4), linking UDUMA with local governments and user communities (Figure 4-2). These arrangements at the local level are signed by representatives of the three parties and are meant to ensure social acceptance of the professional service delivery approach, contributing to "institutional sustainability" (UDUMA, 2017, p. 12). This hybrid system of formal and informal arrangements constitutes the institutional foundation of UDUMA's model.

To cover a share of the initial capital costs required for rehabilitating handpumps at scale, UDUMA received funding from the Netherlands Enterprise Agency (RVO), providing a grant of €3 million through its Sustainable Water Fund (RVO, 2017). In addition, the long-term contracts signed with the municipalities enabled UDUMA to secure private loans at market rates of a total amount of €2 million, thereby creating liabilities. As the French commercial banks required guarantees (van der Wilk, 2019), the *affermage* contracts turned into an "essential asset" (personal communication with UDUMA team, 19th July 2021). They mattered to build confidence in the long-term nature of the investment case, especially since the "political risk associated with investing in developing countries […] caused hesitation" (van der Wilk, 2019, p. 7). The business model at scale, with a cost-reflective tariff, was meant to allow "for reimbursing the initial 40% private capital investment" while generating an adequate return on investment (van der Wilk, 2019, p. 5).

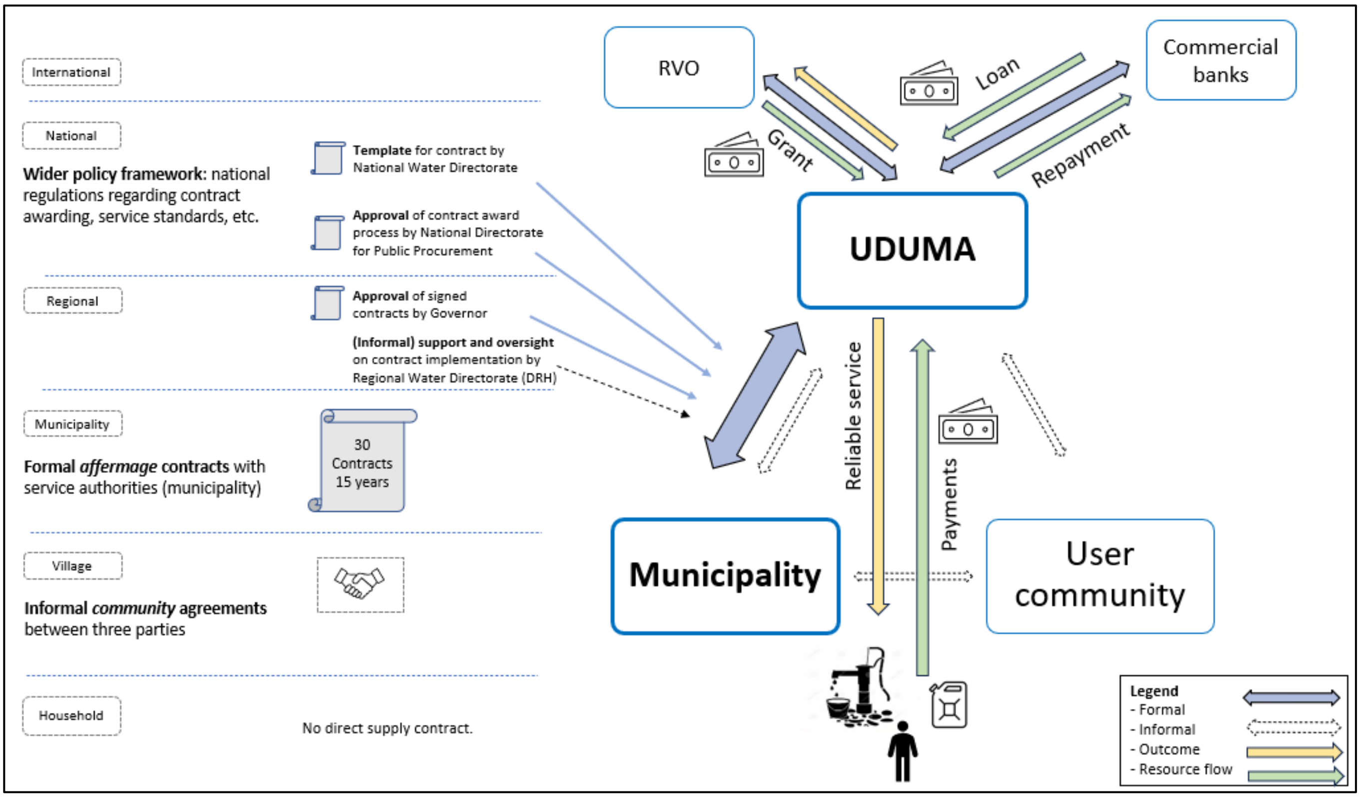

Figure 4-2. Illustration of UDUMA's contractual model

4.3.3 Evolution of the contractual model

Yet, the contracts encountered implementation issues on the operational level, leading to unexpected revenue shortfalls. As outlined above, UDUMA's initial business model assumed an average daily water usage of two m^3 per handpump and projected no default in volumetric payments, effectively tying revenue to water demand and payment collection. Operational and financial data from the first two years of operations, however, revealed that these assumptions were flawed. Only a quarter of the anticipated daily water volume was actually used, and users paid only 40% of water collected, emphasising that its contracts were incomplete due to the inability to guarantee water demand and enforce volumetric payments.

The payment enforcement challenge at handpumps is related to the fact that waterpoint caretakers in charge of volumetric payment collection did "not have the capacity to impose themselves when needed" (UDUMA, 2021c, p. 28). This illustrates wider issues of enforcing formal contracts in settings where more informal social practices and specific community dynamics may be at play. In response to the observed performance, UDUMA used Article 33 of its contract to renegotiate contractual conditions with local governments prompting two service adaptations related to water quantity and tariff design. Figure 4-3 provides an overview of the evolution of and relevant changes to UDUMA's contractual model.

UDUMA proposed to local governments to trial solar-powered water kiosks initially in ten villages, reflecting the diverse geographical, socio-economic, and environmental conditions of its service area. The infrastructure upgrade increased the production capacity of the existing waterpoint initially equipped with a manual pump supplying one spout to a solar kiosk supplying three on-demand taps. As part of the contractual revisions, UDUMA changed payment modalities at handpumps by replacing direct volumetric payments through a monthly flat fee of 15,000 FCFA ($24) per waterpoint, with no limit on water use (UDUMA, 2021a, 2021b).

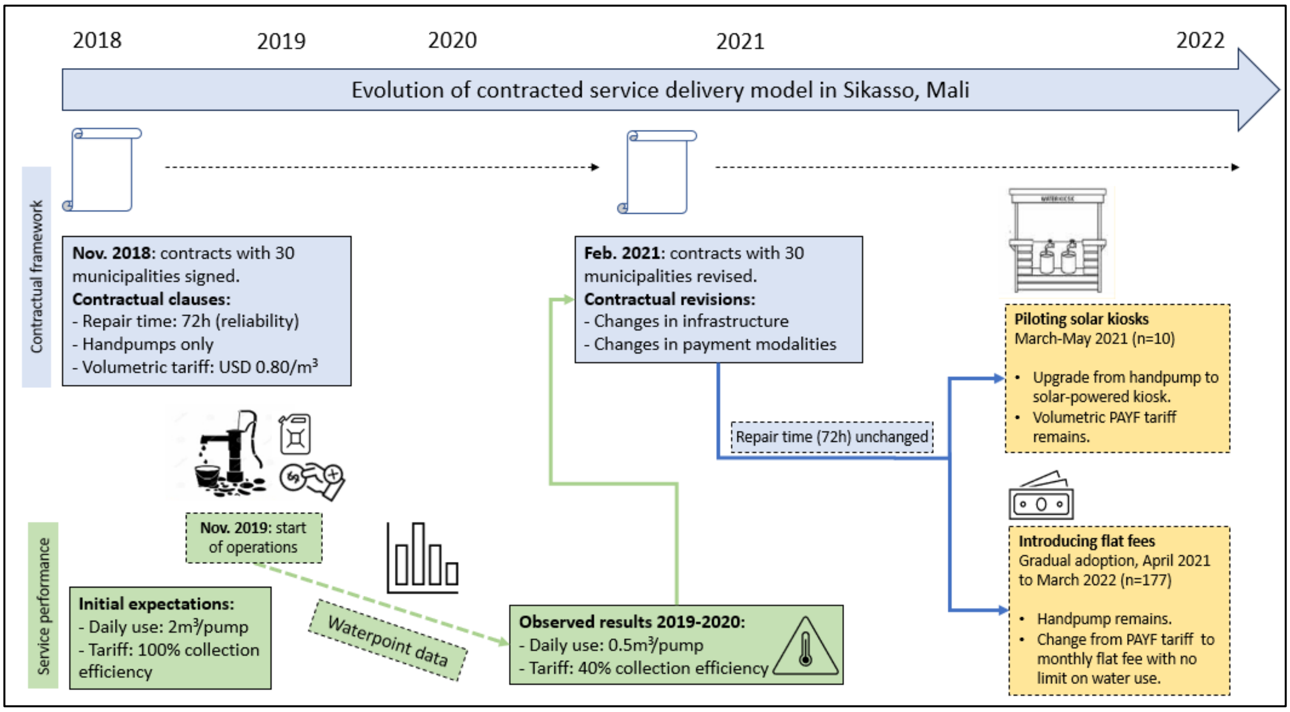

Figure 4-3. The evolution of UDUMA's contractual model

The subsequent sections provide an overview on the methodology underlying data collection and analysis.

4.4 Methodology

UDUMA’s formal contracts and informal agreements emerge from dialogue involving multiple stakeholders. Since “important aspects of institutions and institutional change appear in the form of qualitative evidence” (Skarbek, 2020, p. 409), conducting an intensive case study seems appropriate as it presents an opportunity for in-depth learning and exploratory investigation (Flyvbjerg, 2011, 2006; Gerring, 2004; Yin, 2009). To unpack the rationale, outcomes, and limitations of contractual renegotiation and related service adaptations, the empirical research applies qualitative approaches to data collection and analysis.

Prior to all data collection and analysis, ethical approval was obtained from the Research Ethics Committee at the corresponding author's university (SOGE 1A2020-195 and SOGE 1A2020-210).

4.4.1 Data sources and collection

The study draws on various sources of primary and secondary evidence. For the collection of the empirical material, specific sampling strategies were developed, guiding the data collection process. To contextualise the study case in Mali’s national water policy context, semi-structured expert interviews with representatives (n = 14) from organisations intervening in the water sector in Mali were conducted online throughout the year 2021. To ground the implementation of UDUMA’s contractual model and understand the implications of the service adaptations, in-person fieldwork was conducted in May 2022 in 9 villages of UDUMA’s service area to interview a total of 36 water users, 8 representatives of local governments, 9 representatives of village committees, and 3 UDUMA field staff. In addition, the lead author conducted 6 in-person workshops and 13 online meetings with staff from UDUMA France between 2020 to 2023 to understand the service model and trace its evolution. Finally, interviews with representatives of relevant funding agencies were conducted to clarify their role in UDUMA’s model.

4.4.1.1 Fieldwork in Mali: interviews with local stakeholders

In recognition of UDUMA's institutional model (Figure 4-2), the corresponding author conducted in-person fieldwork in May 2022 in 9 villages which are part of UDUMA's service area to interview representatives from municipalities as contracting authorities, drinking water users using and paying for UDUMA's service, and community representatives.

During interviews with the respective stakeholders, notes using pen and paper were taken to limit any perceived power imbalances between participants and researcher (Fetterman, 2010; Mannay and Morgan, 2015). Subsequently, these notes were transcribed for further analysis.

The field sites (see Supporting Information, Table S4.1 and Figure S4-1) were purposely chosen. As presented above, UDUMA selected 10 sites across 9 municipalities to trial solar kiosks. The selected waterpoints were upgraded between March to May 2021. Payment modalities at the remaining handpumps were shifted from volumetric payments to monthly flat fees. One year after these changes, allowing relevant stakeholders to gain experience with the new infrastructure and payment modality, fieldwork was conducted to understand their perceptions of the service changes prompted by the contract revision.

UDUMA facilitated the fieldwork by providing support in terms of logistics (dispatching a car and driver). In addition, UDUMA's field officer in charge of community engagement acted as a door-opener to the various stakeholders and ensured translation between French and Bambara.

A total of 36 semi-structured interviews with water users asking open-ended questions were conducted to understand their subjective perceptions, opinions, and experiences of the services delivered by UDUMA (Narayanasamy, 2009; Tong et al., 2007). Three to five users were interviewed at each site. The interviews (questionnaire available in Appendix II) covered key themes such as the degree of user satisfaction, practices, motivations, and interpretations regarding UDUMA's service and related service adaptations. The sample strategy for the user interviews was informed by purposive sampling to recruit participants who have the potential to provide rich and diverse data pertinent to the research question (Tong et al., 2007).

In addition, contextual data through waterpoint mappings were collected. The main alternative water sources in each village (e.g.: community wells, handpumps, small piped systems, surface water sources) were identified and source characteristics, such as functionality, perceived water quality, and management arrangements (e.g.: ownership and water price), were recorded using a mobile data collection tool (ONA/ODK). In case people were fetching water at alternative sources, short questions were asked to understand their motivations and perceptions of UDUMA's service.

Semi-structured interviews with eight representatives from local governments were conducted to gather insights on the perspective of the service authorities as formal party to the bilateral contract. The interview respondents were either the municipality's mayor, Secretary General, or the officer in charge of WASH. The interviews focused on understanding the municipality's rationale for initially joining the arrangement and its perception of the relationship with UDUMA.

Informal discussions with village and community representatives were designed to unpack collective perceptions of UDUMA's service. As the community agreements were meant to ensure community buy-in (see Section 4.3), the conversations were tailored to understand the communities' perceptions and motivations shaping the outcomes of the contract arrangements.

4.4.1.2 Data on the provider's perspective: interviews and project documents

Three interviews with local UDUMA staff in Mali were conducted to collect information on the provider's perspective regarding the implementation of the contract. Particularly, insights on the application of specific contractual clauses, such as payment enforcement, as well as the wider processes of renegotiation were gathered. In addition to the interviews with staff from UDUMA Mali, the lead author conducted a total of 19 in-person workshops and online meetings with staff from UDUMA France throughout the research process spanning 2020 to 2023 (anonymised list of meetings available in Appendix II). These consultations allowed to build a detailed understanding of UDUMA's service model and its evolution.

Lastly, the formal service delegation contracts (initial version from 2018 and revised in 2021) and related appendices were retrieved from UDUMA. In addition, relevant project documents were compiled, consisting of UDUMA's initial project proposal to RVO (UDUMA, 2017), various annual progress reports (UDUMA, 2022, 2021c, 2020, 2019, 2018b), a report from the Regional Water Directorate (DRH) from 2020 (DRH, 2020), and UDUMA's formal request to RVO for a strategy change of the initial project (UDUMA, 2021d).

4.4.1.3 Data collection at the national level: expert interviews

For the interviews at the national level, a combination of purposive (seeking representatives of government, donors, civil society, and NGOs) and snowball sampling was used to identify 14 key informants from relevant technical and political organisations intervening in the water sector in Mali (anonymised list of interviews available in Appendix II). The semi-structured expert interviews were conducted based on problem-centred expert interview methods (Merton and Kendall, 1946; Witzel, 1985) that restrict the information that is expected from interviewees but still allow respondents to identify aspects that are not addressed in the interview guideline (questionnaire available in Appendix II). The interviews lasted approximately for one hour and were conducted online in French by the corresponding author throughout the year 2021. Notes were taken during the interviews and subsequently transcribed for further analysis.

4.4.1.4 Data on the perspective of donors: interviews and project reports

Interviews with representatives of RVO and a private foundation were conducted to understand their role in the initial arrangement and for the evolution of UDUMA's model. The semi-structured expert interviews (questionnaire available in Appendix II) were conducted online by the corresponding author. Notes were taken during the interviews, and subsequently transcribed for further analysis. In addition, documentation (RVO, 2022) and project data (RVO, 2017) were retrieved online.

4.4.2 Data analysis

The study makes use of triangulation of multiple sources of empirical material (Johnson et al., 2007; Yin, 2009) to develop a coherent understanding of UDUMA's contractual model, its evolution, and related drivers. First, UDUMA's initial and revised contracts were systematically reviewed to identify changes in contractual provisions. Subsequently, interview notes were qualitatively analysed (Mayring, 2014) to generate insights on the functioning of contracts and the respective perceptions and experiences of the various stakeholders to unravel the process leading to the identified changes in UDUMA's contracts. Coding of the interviews was done following an inductive, data-driven approach building on the concrete empirical material, while being guided by the research questions. The open-coding approach allowed to extract relevant information pertaining to perceptions and underlying motivations of the respective actors (Ercan and Marsh, 2016; Silverman, 2017). The qualitative analysis focused on identifying key relationships and recurring motives to trace changes of the contractual model. Synthesis of findings across the interviews allowed to provide an expanded understanding of UDUMA's contract design and evolution. User interviews were analysed regarding factors related to water quantity, quality, affordability, reliability, and proximity and their relative priority. For the use of direct quotations from expert interviews, expressed approval from interviewees was received as attribution to individuals may be possible despite anonymisation.

4.5 Results

In exploring the implementation of formal contracts for drinking water service delivery in rural Mali, we found evidence that rigid conditions do not necessarily allocate risks effectively. A certain degree of flexibility in UDUMA's financial arrangements was required for the service model to continue. The results emphasise the role outside actors to the formal contracts played in shaping the renegotiation process of UDUMA's initial contracts. Finally, we illustrate how contractual incompleteness was partially addressed by adapting specific service attributes, so that services better aligned with the preferences of water users and increased the enforceability of the contract.

4.5.1 Does a more rigid contract effectively allocate risks and responsibilities?

Within the first months since UDUMA had started its service in Sikasso, evidence indicated that the initial contract was incomplete. While the first year of operations was deemed too early to draw conclusions about the sustainability of the model (UDUMA, 2020, p. 25f), UDUMA stated in its third progress report to RVO: "The past year (April 2020 to March 2021) has been eventful for Uduma. […] We have been forced to rethink our model" (2021b, p. 2). With an "average daily water use of 544 litres per pump" instead of the anticipated daily volume of 2 m^3 and users paying "only 40% of total water used" (UDUMA, 2021c, p. 31), the provider missed its viability target by a margin. The commercial risk of linking revenue to water production and sales materialised, suggesting that the initial contract had overlooked relevant contingencies (Hart and Moore, 1988).

Despite the revenue shortfalls, UDUMA remained responsible for guaranteeing a reliable service in line with the performance indicators of its service level agreement, thereby covering operational risks related to handpump failure. Due to the recurring commercial losses, UDUMA was "determined to take the necessary actions to adapt the model" (2021b, p. 6). Yet, the company was dependent on the agreement of the municipalities as contract authorities to permit changes to its rigid contracts.

Here, the Regional Water Directorate (DRH) came into play. With its role steered towards supporting contract implementation, DRH staff conducted four field missions in Sikasso in April 2020 to exchange with water users, village leaders, municipalities, and UDUMA to understand the reasons for non-compliance with the contractual arrangements. DRH recommended that UDUMA should consider installing solar-powered water kiosks or water ATMs to respond to the user population's increasing demand for higher service levels (DRH, 2020, p. 11). Other donors such as UNICEF and Helvetas already had started investing in small solar-powered drinking water systems in the region of Sikasso, providing a precedent for user communities and local governments (interviews with Donor-ML-1, Donor-ML-2, Donor-ML-3 in 2021, and with UDUMA-1 in 2022).

As the initial contracts limited the infrastructure portfolio to handpumps, an amendment of the contract with the local governments was necessary. All 30 municipalities expressed their agreement with the proposed change in strategy. Since upgrading all existing handpumps to solar kiosks was not feasible due to economic, technical, or environmental constraints, UDUMA proposed to change modalities for collecting user payments at handpumps as the volumetric payment approach was contested by the user population (DRH, 2020; UDUMA, 2021c). The municipalities signed amendments to the formal contracts with UDUMA allowing the installation of solar kiosks and the introduction of monthly flat fees at handpumps.

By doing so, the municipalities not only ensured a reliable service to their populations but as well received improved infrastructure without having to provide additional commitments as UDUMA continued to carry the commercial and operational risks. Yet, the municipalities' agreement to revise the contracts may not only be related to strategic considerations. Through UDUMA's bi-annual reporting, the municipalities were aware of the significant operational and commercial challenges. Annual in-person meetings between UDUMA and the local governments were held to discuss problems related to contract implementation and fostered a "climate of trust" between the contracting parties (UDUMA, 2021c, p. 15). As findings from contract theory suggest, frequent and transparent communication can promote a constructive relationship where contracting parties are more likely to apply principles of fairness or loyalty when changes to a contract are needed (Frydlinger and Hart, 2023, p. 9). During interviews, representatives of local governments indicated an appreciation of UDUMA's continued commitment, despite the difficulties related to contract execution.

While the formal parties to the bilateral contracts agreed to revise some of the rigid clauses, upgrading infrastructure required additional financial resources. However, the provider's capital was constrained, providing no room for further investments – and potential losses. Since the revenue generated in Mali was insufficient to fulfil the loan obligations, ODIAL SOLUTIONS, UDUMA's holding company, ensured the repayment of the €2 million loan, taking on the financial risks associated with the private capital investment (interview, UDUMA-3, 4th October 2023).

In October 2020, UDUMA presented the conclusions of the DRH report and a financial analysis to RVO to demand a re-allocation of funds towards the installation of solar kiosks. According to UDUMA (interview, UDUMA-2, 19th May 2022), RVO requested a proof-of-concept regarding the financial and operational sustainability of solar kiosks. RVO had initially committed to funding a public-private partnership tailored to installing 1.400 handpumps and subsequently maintaining them throughout 15 years, expecting to reach approximately 500,000 beneficiaries at relatively low costs (RVO, 2017; UDUMA, 2017).

In December 2020, a foundation supporting UDUMA's wider work, agreed to fund the installation of ten solar kiosks as a pilot project in nine municipalities (UDUMA, 2021c, p. 34). When asked for the reasons to support piloting solar kiosks in Mali, the foundation staff commented:

> "Regarding the transition to solar in Mali, we already had a grant in place with UDUMA. This grant covered a broad range of activities in Mali and Burkina. Both countries are priority countries for us [the foundation]. UDUMA said that they wanted to re-allocate the money to pilot solar pumps in Mali. I approved since our grants do provide that flexibility. UDUMA can reallocate the money, as long as they remain within the boundaries of the initial grant approval. We knew that there was the RVO funding as part of the UDUMA model. But it was UDUMA who knew how to use our funding to convince RVO to change

> the initial strategy and to integrate the solar pumps into the portfolio. In the end, UDUMA used our flexible money to make a point they needed to demonstrate." (interview, 28th November 2023)

This agreement illustrates the foundation's flexible funding approach which permits risk taking in comparison to bilateral donor funding or commercial financing sources:

> "As part of our funding approach, we try to be non-prescriptive and flexible. We want to align with the grantee's priorities. We give them the freedom to do what they think is best for them and their beneficiaries or clients. We want to be complementary to other funders, so we fund things that others do not want to or cannot fund. And we aim to do things where perceived risks are high. Mali as a context is risky, fine. UDUMA is an established company, linked to Vergnet Hydro. That is not very risky. But UDUMA's business model is. It is a market-based approach for rural drinking water services, this is something very unusual in the rural water sector. I don't think that they managed to really prove their business model yet." (interview, foundation staff, 28th November 2023)

The solar pilot proved to be catalytic for adapting UDUMA's model. As UDUMA pointed out: "We were able to show that something works in Mali. At least, the revenues improved with the solar kiosks. This was certainly one of the reasons why RVO agreed to re-allocate the funding" (interview, UDUMA-2, 28th November 2023). The results of the pilot allowed UDUMA to secure additional funding from new partners, such as foundations organised in the "WASH Funders Group", and to scale up investments in solar kiosks, providing a basis to support continued work (UDUMA, 2022, 2021d).

However, RVO "needed time to come to a decision" regarding the transition to solar as investing in more expensive infrastructure meant that "the number of beneficiaries decreased significantly. We needed assurance that the proposed model would be accepted by the population and be viable" (interview, RVO staff, 7th December 2023). According to UDUMA, as part of RVO's formal change request process, the Dutch Embassy in Mali was invited to give their perspective on the proposed strategy. In addition, RVO required that the change of the project aligned with the policy priorities of the Government of Mali. Here, the DRH report from 2020 allowed UDUMA to demonstrate its alignment with Mali's official position (interview, UDUMA-2, 28th November 2023).

At the end of 2021, RVO agreed to re-allocate the initial funds permitting investments in solar kiosks:

> "We looked at the changes of the solar pilot and reflected on the implications forward. Data and feedback from the field showed that the willingness to pay, the revenues, and cost-recovery improved. And we saw that other donors were convinced as well. So, we agreed to the change in strategy. I think that we have still been quite flexible in our approach, particularly in comparison to the initial project." (interview, RVO staff, 7th December 2023)

UDUMA staff indicated that besides the encouraging financial performance registered at solar kiosks, the involvement of other donors was a salient argument for RVO. The additional funding from other partners allowed to mitigate to some extent the reduction of the number of beneficiaries reached (interview, UDUMA-2, 28th November 2023).

As the interview insights illustrate, the respective priorities and constraints of UDUMA and RVO did not necessarily align for permitting a rapid adaptation to changing circumstances. Yet, at the end of the process, an agreement was reached. Here, the entrepreneurial attitude of the provider may have mattered: "UDUMA made suggestions to adapt the project strategy and the solar pilot was part of it. As the private partner, UDUMA had invested €2 million as their own contribution. UDUMA really wanted to achieve results" (interview, RVO staff, 7th December 2023). Besides, RVO's approach must be seen in the light of the requirements attached to spending tax-payers money for development projects. While tracking the achievement of its political commitments through numbers of people reached, RVO was as well looking for a "systemic change by trying to do new things or [by] doing things differently" (interview, RVO staff, 7th December 2023).

Five years after allocating the initial grant to UDUMA, RVO reflected on wider learnings related to projects supported through its Sustainable Water Fund, putting an emphasis on allowing for more flexibility during project implementation:

> "a more flexible procedure for future programmes will allow (more) room for adjustments […] of contracted projects, and for better exploration of interesting new concepts and ideas that otherwise might be lost (too) early" (2022, p. 6). [Therefore,] "programme design should allow for flexibility and adaptation of a project, while maintaining the focus on sustainability. […] Learning by doing, and the willingness to improve is at the heart of this, rather than monitoring for accountability only " (RVO, 2022, p. 18).

UDUMA's rigid contracts with municipalities allocated operational, commercial, and financial risks to the provider while omitting that flexibility in the financial arrangement may be required to allow for navigating uncertainties. The results suggest that contract renegotiation and effective risk allocation is not only conditional on the agreement of the formal parties to the contract but intimately linked to the behaviour of outside actors to the contract and the availability of catalytic resources, permitting contractual changes.

4.5.2 How can renegotiation address incomplete rural drinking water service contracts?

While local water users do not have a direct contract with UDUMA (Figure 4-2), they are crucial for the sustainability of the model as they provide revenue based on their water consumption. Since contractual performance essentially depends on the motivation of the parties involved (North, 1990), service providers have an incentive to deploy a delivery approach aligned with the priorities of rural water users to increase their revenue. Hence, adapting specific service attributes may be a strategy to make progress towards expected revenue goals.

Table 4-2 provides an overview of the service attributes defined in UDUMA's contract and summarises the observed results related to the service adaptations. Water quantity relates to the guaranteed minimum supply of volume of water per day and is linked to the infrastructure's production capacity and borehole yield. Affordability focuses on the tariff design, mainly the tariff structure and level that are defined in a contract in accordance with prevalent tariffing policies. Water quality encompasses actions dedicated to ensuring drinking water is free of faecal and priority chemical contamination and may include measures such as chlorination or regular testing. Reliability defines the maximum time allowed to repair breakdowns. Finally, proximity specifies the distance between the point of source and the household which is related to the source type.

The introduction of the solar kiosks augmented the supply capacity of the waterpoint (water quantity) and reduced the physical effort for pumping as well as the time costs associated with fetching water. In addition to the infrastructure upgrades, the tariff structure at remaining handpumps was changed, by switching from a volumetric tariff to a monthly flat fee for collecting user payments. The change of the tariff structure complies with Mali's tariff policy for rural water supply, officially recognising two payment modalities at handpumps: direct volume-based payments or regular flat fee contributions (DNH, 2007, p. 44).

Table 4.2 UDUMA's contract model and the implications of service adaptations on contractual performance

Service attribute	Contractual condition (Contracting clause)	Initial contract design	Initial contract performance	Renegotiation option	Contract performance after renegotiation	Remaining uncertainties
Water quantity	Management of manual pumps (§1&2). Maximum supply of 8m³/day/pump (§3)	Expected average use of 2m³ per day per pump.	Actual average use of 500 litres per day per pump.	**Done** – (higher service level provided through solar kiosks)	• Similar water use. • Payment collection improves. • Monthly revenues increase.	• Uncertain demand: impossible to impose which source and how much water to use. • Additional costs
Affordability	User payments as revenue base (§1). • Tariff structure: Volumetric (§21) • Tariff level: 500 FCFA/m³ (Annex 2)	100% collection efficiency for volumetric payments (PAYF).	40% collection efficiency	**Done** – (volumetric tariff structure changed to flat fee)	• Water use increases. • Payment collection improves. • Monthly revenues increase.	• Uncertainty about long term effect. • Possible to change tariff level but unclear demand and revenue implications.
Water quality	Water quality (§14 & Annex 2). • Annual test of bio-physical & bacterial parameters. • Shock chlorination in case E. Coli.	Groundwater assumed to be of good quality (UDUMA, 2017, p. 9).	Qualitative data indicate users are satisfied with water quality.	**Potential** – (increase frequency or range of tests, chlorination)	NA	• Additional costs.
Reliability	Max. downtime of 72 hours (Annex 2)	Users value fast and guaranteed repairs (van der Wilk, 2019).	Qualitative data suggest UDUMA service is appreciated.	**Potential** – (preventive maintenance, <24h downtime)	NA	• Unclear if higher reliability is priority for users. • Additional costs.
Proximity	Point sources: manual pumps (§1&2).	Users accept manual pumps.	Qualitative data suggest preference for higher service levels.	**Potential** – (develop standpipes or private connections)	NA	• Indicative evidence for user demand but uncertainty prevails. • Additional costs.

For the ten pilot sites, UDUMA reports that water use remained relatively similar after a handpump was upgraded to a solar kiosk. Yet, the solar kiosks generated higher revenues compared to handpumps as "there is no reluctance to paying for this service" (UDUMA, 2021c, p. 35). Regarding the change in payment modalities, field reports from UDUMA indicate that monthly revenues increased and that flat fees appeared to stimulate water use at handpumps (UDUMA, 2022). In the following, we contextualise these observed changes by drawing on evidence from interviews conducted with water users in Mali.

Qualitative evidence from the pilot solar kiosks illustrates that users do more readily agree to pay volumetric tariffs at solar kiosks that are professionally managed:

> "We accept to pay for the tap. But, paying for pumping – that did not work for us!" (Female user, Village 8)

> "The water is fresh, and the service at the solar kiosk is good. I agree to pay per bucket, that works. Before with the handpump, I came here, too. But the price bothered me. Pumping was really tiring!" (Female user, Village 2)

> "With the solar kiosk, it is really easy. You pay, you get the water, and you leave after only one minute or so. But with the handpump, you had to work hard – and this for the same price!" (Male user, Village 3)

> "Paying by volume for pumping, this did not work for us. But we accept to pay as we fetch at the solar kiosk. Opening the tap is good – if water is coming when needed. The UDUMA system is reliable, and the water is of good quality. So, I am happy to pay for it" (Female user, Village 9)

While these results suggest that adapting services to user preferences can unlock payments and increase revenue, seasonal fluctuations in water demand do affect volume-based revenues. For example, even if a solar kiosk is reliably managed, users may decide not to use the guaranteed service but prefer an alternative source for multiple reasons. Insights from user interviews illustrate, for instance, how environmental factors, economic constraints, or specific preferences do influence user behaviours and their source choice, highlighting the challenges of non-exclusive service settings:

> “In the hot season, I fetch about ten buckets per day at the solar kiosk. In the rainy season, I use less – maybe five buckets. There is the rainwater, and water is abundant in our wells.” (Female user, Village 2)

> “People are tired of walking – even to the solar kiosk. We want good quality water in proximity, and we would pay our monthly bills. But the solar kiosk does not offer this – I have three wells around me, they are all close by, always available, treated with chlorine bleach, and free of charge.” (Male user, Village 5)

> “Normally I use the UDUMA kiosk. This is closer to my home. But today, I don’t have money, so I go to the Health Centre to get water.” (Female user, Village 4)

> “Today, I collected six 20L-buckets from a traditional well. It is much closer to my house and free of charge. The quality is ok; it is treated with chlorine bleach.” (Female user, Village 5)

These insights emphasise that while revising contracts to provide higher service levels by design can lead to improved financial performance, such service adaptations remain a partial response to complex user behaviours. In particular, even if larger quantities of water can be supplied, it is not certain that this level of supply will effectively be demanded by users. As qualitative evidence from Mali suggests, dynamic and contextual water demand is a defining characteristic of rural water supply and a challenge for designing exclusive contracts given the prevalence of alternatives.

The change of the payment modalities at the remaining handpumps allowed to increase the enforceability of the contract. Under the flat fee approach, the user community self-organises to collect the required fee and pays UDUMA in advance. As such, the revised contract provides a clear payment enforcement mechanism regarding payments: if the monthly flat fee is not paid, the UDUMA service is not activated, and the pump is locked by a service area manager until a payment is made (UDUMA, 2021b). This mechanism mitigates the payment enforcement challenge encountered under the volumetric modality, and simultaneously incentivises users to make monthly payments against unlimited water use and guaranteed repairs.

However, the strict application of this enforcement mechanism can result in adverse outcomes. When the monthly flat fee is not paid, the pump is closed in the respective month. As a consequence, users are more likely to shift to unimproved water sources, as the following user account illustrates: "Before, I used the handpump. Now, it is closed – and I rely on the traditional well. I barely use other sources" (Female user, Village 4). In addition to the foregone socio-economic and health benefits associated with accessing an improved drinking water source (Prüss-Ustün et al., 2019), the provider receives no revenue.

UDUMA may seek to further adapt its services. For instance, the provider could increase its efforts regarding water quality, service reliability, or develop standpipes and household connections to get water closer to the users' households (Table 4.2). Any of these interventions would require additional investments (Hutton and Varughese, 2016). While it is an open question whether such service adaptations would generate additional revenues, it is, however, unlikely that any of these strategies would overcome the structural barrier of uncertain user demand in the short term.

4.6 Discussion

Our application of contract theory to Mali illustrates the potential of and barriers to the delivery of contracted rural water services. Three findings emerge from our study with implications for the design and implementation of drinking water service contracts in rural Africa. First, we emphasise that outside actors and capital play a crucial role in contract execution and renegotiation. Second, we highlight that the financial architecture of rural water service contracts requires flexibility, particularly when long-term investments are involved, and uncertainties are high. Third, our findings suggest that the ability to revise contracts to adapt services is helpful but remains a partial response to uncertain user demand.

While contract theory stipulates that "the parties always have the option to renegotiate [the contract] later on" (Hart and Moore, 1988, p. 756), this fundamental assumption did not really apply to our case in Mali. Neither did the expressed agreement of the formal parties to the bilateral contract really matter for changing the model (Frydlinger and Hart, 2023). UDUMA's case emphasises the crucial role outside actors and non-repayable capital from a foundation played to permit renegotiation and support continued work. Any negotiation between UDUMA and the municipalities would most likely not have allowed to fundamentally change the outcomes as additional resources were required. Without the philanthropic funding, UDUMA would have had few options to continue their operations. These insights emphasise that renegotiating complex contract arrangements is conditional on the agreement of the original contract parties but also depends on the involvement and attitude of external actors.

The original financial architecture of the initial contract allocated most financial risks on UDUMA. UDUMA made infrastructure investments by attracting private capital and more traditional donor funding to Mali. While asset-specific investments require longer time horizons to allow for expected outcomes to be realised (Goldberg and Erickson, 1987; Hart and Moore, 1988) and tend to be facilitated through more rigid contracts (Hart, 2017; Hart and Moore, 2008), our case study illustrates the importance of financial flexibility to adapt to uncertainties. We emphasise that the willingness and ability of UDUMA's holding company to absorb the financial losses was critical for the model to continue. Yet, ODIAL SOLUTIONS was not willing or able to cover further investment risks related to trialling solar kiosks. As the flexibility of the philanthropic grant illustrates, unconditional funding can allow to buffer such risks, particularly in circumstances where investors are facing high uncertainties. Therefore, we suggest that future rural water service contracts involving infrastructure investments may combine a flexible funding component with a certain risk-appetite, such as philanthropic funds, with more traditional donor funding and commercial finance, allowing to navigate a contract impasse.

Finally, we underline that contract design is informed by assumptions about future states of the world. Yet, conducting accurate demand forecasts remains a fundamental planning challenge – even in well-organised sectors in the Global North where reliable data are more readily available (Flyvbjerg et al., 2005). Therefore, allowing for contractual renegotiation can be desirable in the face of changed circumstances or additional experience. In our case, we see the contractual revisions and related changes in service attributes as a means to promote financial outcomes by increasing the value proposition to users and clarifying mechanisms for payment enforcement.

Despite adapting its services, UDUMA remained confronted with volatile and low revenues. While UDUMA's initial contracts assumed that no subsidy for operations was needed, the operational reality indicates that in almost all of its sites some form of subsidy is required to meet recurring costs. We argue that rural water contracts are likely to be defined by increasing economic, climate and social risks which requires a more pragmatic financial model for supporting service delivery. Governments, service providers, and donors must recognise and adequately plan for these realities. Here, contract theory may help to propose models that combine rigidity in terms of service quality with flexibility in funding arrangements to sustain services. For instance, contracts can provide for flexible compensation mechanisms to cushion revenue shortfalls (Gottardi et al., 2017) or include minimum income guarantees (Guasch et al., 2008, 2006) to achieve desired social, economic, and health impacts associated with safe drinking water.

4.7 Study limitations

Four limitations are recognised in this study. First, the study site lies in one region of Mali characterised by a unique cultural, social, and political context. While certain drinking water problems common to rural Africa may be illustrated by using Mali as an example, we do not claim to generalise our findings.

Second, we emphasise that the contractual arrangements underpinning professional service delivery models must be designed in light of the diverse socio-economic, cultural, and environmental settings in which they operate. Here, selecting UDUMA as one provider offering guaranteed rural water services excludes other possible service delivery approaches from the analysis.

Third, the purposive sampling in rural communities was biased to UDUMA's upgrades to solar kiosks. We collected data across 8 municipalities, leaving 22 municipalities that also agreed to renegotiate contracts with UDUMA out of the investigation. As the fieldwork was conducted in collaboration with UDUMA, we were able to get a deep understanding of the model and wider context. However, we also recognise that this may have biased collecting data on the perceptions of the relationship linking the interviewees and UDUMA as the target organisation. Therefore, care was taken during analysis to corroborate different sources of empirical data before drawing conclusions.

Fourth, our case-study draws on qualitative data to illustrate how UDUMA's contractual model evolved over time. While we provide indicative insights on how users respond to service adaptations and how, in turn, changes in water use and payment behaviours affect revenues, the analysis falls short of estimating the size of these revenue effects. Since the service adaptations introduce variation in key variables which can be tracked over time (Nauges and Whittington, 2010), future studies may exploit the longitudinal water use and payment data generated by UDUMA to advance a more rigorous assessment of the demand and revenue implications associated with changes in service attributes.

4.8 Conclusion

Our study from Mali provides evidence that long-term contracts can attract capacity and finance to the rural water sector. We illustrated that contracts do provide an adaptable framework in which services can evolve and that flexibility in the financial architecture of contracts is necessary to navigate investment risks. Here we highlight the role of philanthropic grants that can act as catalytic and complementary resources to more traditional funding and commercial finance.

Furthermore, the results suggest that while contracts can be revised to adapt services to variable water user demand, professional service delivery models are likely to require operational subsidies to mitigate volatile revenues. Results-based contracts can play an enabling role in the allocation of such subsidies by aligning service outcomes with incentive payments. Permitting for a mix of user payments and performance-based funding may mitigate the risk of service failure due to insufficient local revenue. This is illustrated by an emerging approach which uses a standard contract design in ten countries in sub-Saharan Africa to allocate flexible subsidies against the provision of rigid results, measured through verifiable key performance indicators related to safe drinking water services (Charles et al., 2023; Uptime, 2023).

We emphasise that formal contracts with professional service providers are not a definitive solution to complex water problems. We agree that an enabling policy environment, characterised by a clear legal and institutional environment, with strong regulation and accountability practices and effective subsidy mechanisms is fundamental to support the wider shift towards service delivery. We recognise that these are new practices to the rural water sector which is still focused on more infrastructure-driven approaches, largely ignoring the difficulty of maintaining systems over time. Yet, we argue that well-designed contracts may ultimately allow to crowd in new funding sources and to more effectively allocate responsibilities and risks to deliver drinking water service outcomes that so far have not been achieved in rural Africa

4.9 Supplementary File (Chapter 4)

Supporting Information for

Managing contractual uncertainty for drinking water services in rural Mali

This file includes:

- Supporting text
- Supplementary Table S4.1
- Supplementary Figure S4-1

Field sites in Sikasso

The study site comprises the Region of Sikasso, located in the south of Mali. To trial solar kiosks, UDUMA selected 10 sites, reflecting the diverse geographical, socio-economic, and environmental conditions of its service area (Figure S4-1). Between March and May 2021, UDUMA sequentially converted boreholes equipped with manual handpumps (two pump types are managed by UDUMA: Vergnet-Hydro and India Mark 2) to solar-powered water kiosks. Table S4.1 presents the population size, illustrating the variability across sites, and provides the dates at which the handpump management started and the upgrade to solar kiosk happened.

UDUMA selected the sites for piloting solar according to the following criteria: socio-political context and local security situation, environmental conditions (borehole yield and pump test) and population size (minimum 700 people per waterpoint). We emphasise that UDUMA targeted sites with potential for success as the involvement of leaders and local authorities supporting the project was considered essential.

In May 2022, the lead-author conducted in-person fieldwork in nine of the ten villages. Due to security reasons, it was not possible to visit one site.

Table S4.1 Overview of fieldwork sites

Municipality	**Village**	**Start of handpump**	**Upgrade to solar**	**Population of village**
Fakola	Dionkoni	01/09/2020	25/03/2021	2,036
Kebila	Bougoula	16/12/2019	30/03/2021	2,635
	Kebila	23/01/2020	31/03/2021	4,826
Koumantou	Tiefala	21/10/2019	30/04/2021	2,717
Meridiela	N'tenkoni	25/11/2020	10/05/2021	1,227
Sere Moussa Ani Samou	Moribala	28/02/2020	21/05/2021	1,217
Sibirila	Fangala	17/03/2021	19/05/2021	2,100
Sido	Tinkole	05/06/2020	05/05/2021	744
Tagandougou	Binko	09/10/2020	21/05/2021	2,536
Wola*	Dionkala*	08/12/2020	04/05/2021	1,179

*Not possible to visit during fieldwork due to security concerns.

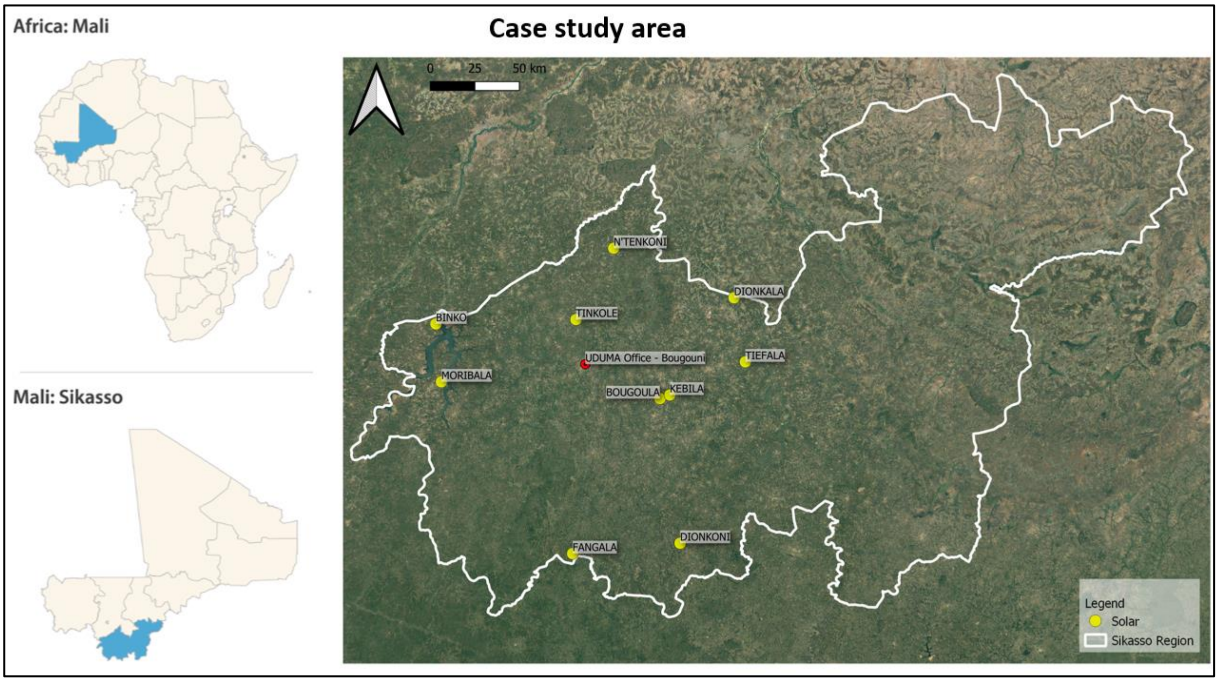

Figure S4-1. Case study area in Sikasso, Mali.

Chapter 5: Can solar water kiosks generate sustainable revenue streams for rural water services? (Paper 2)

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Note: In this chapter, minor modifications have been made compared to the published version of the paper. To ensure a coherent format throughout the thesis, the numbering of tables and figures in this chapter have been adapted compared to the published version of the paper.

Abstract

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

Key words

Drinking water; solar kiosks; financial sustainability; payment behaviours; rural Mali.

5.1 Introduction

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

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

Professional service delivery models have emerged across Africa to ensure the operational sustainability of rural water infrastructure investments (Nilsson et al., 2021). These models generally manage to repair broken rural water infrastructure within three days or less, an improvement compared to the weeks or months communities often take to complete repairs. Despite this higher operational performance, professional service delivery models rarely generate sufficient revenue via user payments to be financially viable (Foster et al., 2022; Smith et al., 2023).

Revenue shortfalls are more pronounced for handpumps (McNicholl et al., 2019) which remain the most widely used water supply technology in rural Africa (Foster, 2013; Foster et al., 2020).

Studies in Kenya (Koehler et al., 2021) and Uganda (Smith et al., 2023) have investigated if professional maintenance services for rural handpumps, providing rapid responses to breakdowns, increase revenue generation. Both studies find that user payments remain limited and diminish over time. In the light of these findings, Smith et al. call for empirical investigations of user responses to service improvements "using real payments over meaningfully long periods of time" (2023, p. 13).

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

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

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

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

5.2 Materials and Methods

5.2.1 Study context and site selection

The study site comprises the Region of Sikasso, located in south of Mali. The area is characterised by an annual dry season from approximately March to June followed by a wet season from July to October, with annual rainfall of 510 to 1,400 mm. The average monthly temperature varies seasonally, ranging from 24°C in January to 35°C in May (World Food Programme, 2021). Mali's overarching socio-political and security situation is volatile, with Sikasso being the region with the highest poverty incidence (INSTAT, 2019). The study utilises data from UDUMA, a private company, providing reliable rural water services in 30 rural municipalities, the lowest governmental level in Mali's administrative structure (van der Wilk, 2019).

UDUMA installs and maintains rural waterpoints fitted with water meters. Payment modalities, service levels, and volumetric tariffs are formally established in a management contract signed between UDUMA and local governments as service authorities. UDUMA is responsible for maintenance services, guaranteeing service reliability with short breakdown durations of less than 72 hours, and must conduct regular water quality monitoring (UDUMA, 2017). As part of the contract, water users must pay a volumetric tariff of 500 FCFA ($0.80) per m^3, in accordance with Mali's tariff policy for rural water supply (DNH, 2007). The "pay-as-you-fetch" (PAYF) approach requires users to make payments to a waterpoint caretaker for the volume of water collected. However, UDUMA encountered challenges in collecting volumetric payments from users, resulting in low revenue generation at handpumps.

To respond to unstable payment collections, UDUMA shifted its original strategy from managing handpumps to piloting solar kiosks. National and local government entities in Mali supported UDUMA's shift towards installing solar kiosks in an attempt to increase payment collection and water use, thereby enhancing revenues. The infrastructure upgrade replacing a manual pump with a solar kiosk (Figure 5-1) across a total of 15 sites was introduced by the service provider within existing contractual arrangements. Between March and May 2021, UDUMA sequentially converted boreholes equipped with manual handpumps (UDUMA manages two pump types: India Mark 2 and Vergnet-Hydro) to solar-powered water kiosks in ten sites (cohort 1). In December 2021, an additional cohort of five waterpoints under UDUMA's management received an identical infrastructure upgrade from handpump to solar kiosk (cohort 2).

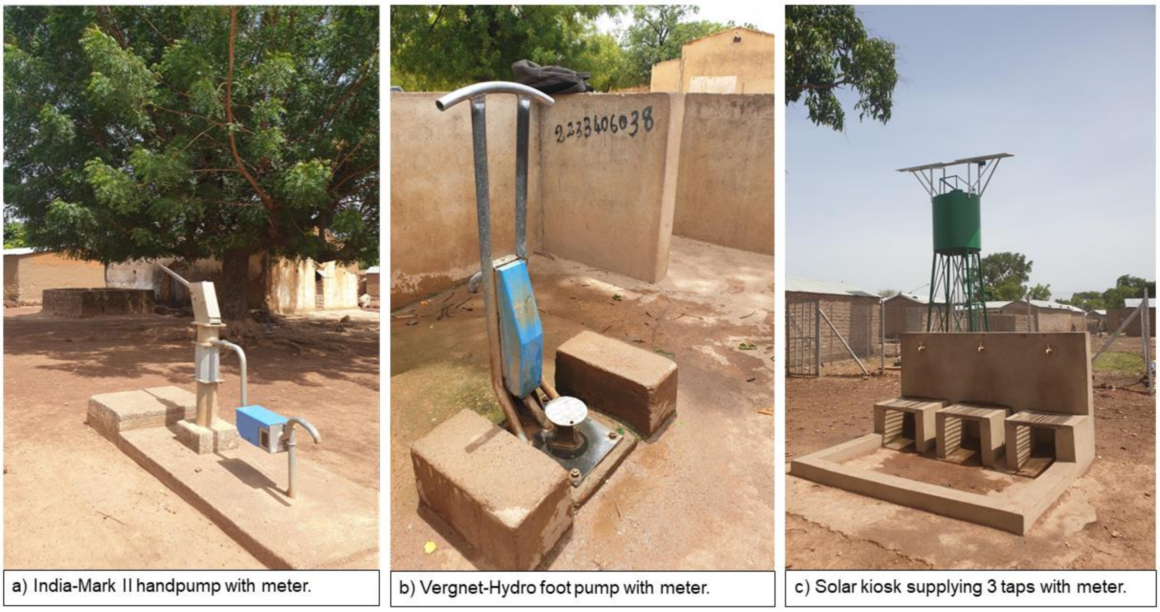

Figure 5-1. Water supply technologies managed by UDUMA in the Region of Sikasso.

The upgrade from a handpump to a solar kiosk reduced the physical effort for pumping, the time to fill a 20 litres bucket, and the queuing time as a result of the three taps and a higher flow rate. While the tariff level, the volumetric payment modality (PAYF), the service quality, distance between the users' household and the waterpoint, and the socio-cultural context remain unchanged, a higher service level is provided. Table 5.1 summarises the main differences and similarities between the infrastructure types and related service levels.

Table 5.1 Comparison of service attributes across technology types.

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

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

UDUMA selected the sites (Figure 5-2), reflecting the diverse geographical, socio-economic, and environmental conditions of its service area, to trial the solar kiosks (additional information can be found in Table S1, Supporting Information, SI). The site selection through the operator was informed by the following criteria: socio-political context and local security situation, environmental conditions (borehole yield and pump test) and population size (minimum 700 people per village), with the distinct service population per waterpoint unknown. We emphasise that UDUMA targeted sites with potential for success. The conditions for the installation of a solar kiosk are thus not random and the study is not based on a formal experiment. However, we use the two cohorts of waterpoints as an opportunity to explore the effects of an infrastructure upgrade on user behaviour.

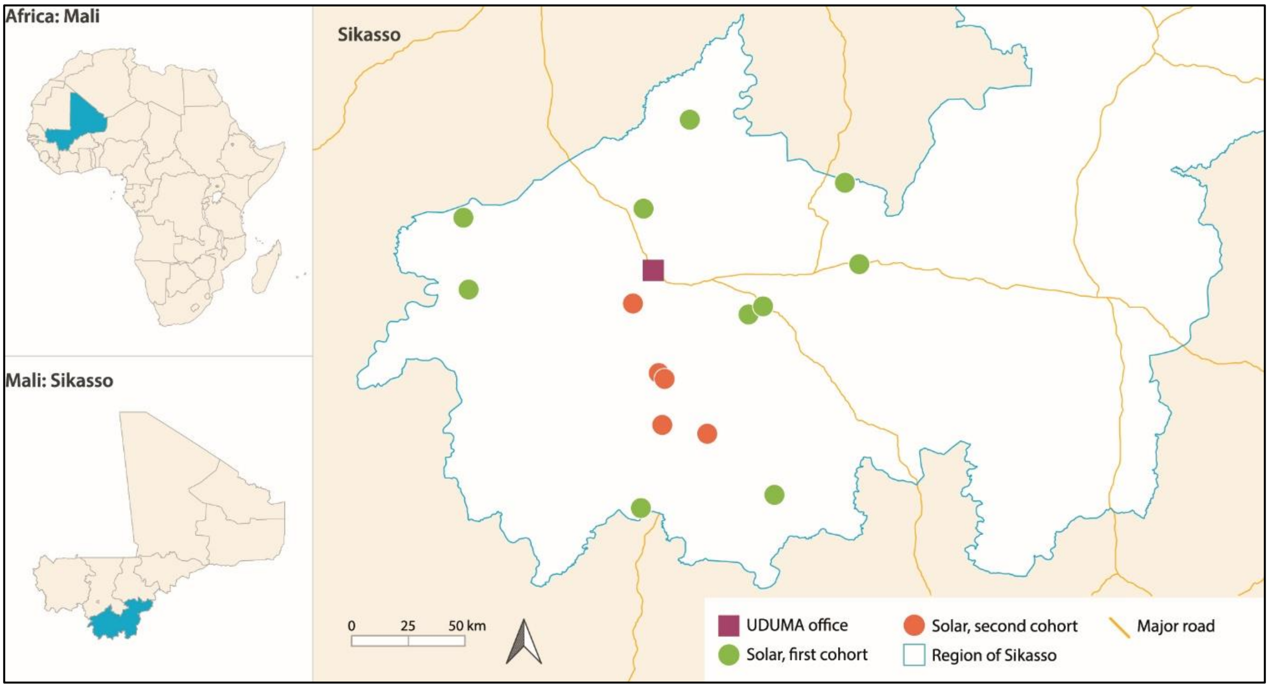

Figure 5-2. Case study area in Sikasso, Mali. Map presenting the 15 sites where solar kiosks were installed across two separate cohorts of waterpoints.

Finally, we highlight that over a period of four months, from October 2021 to January 2022, UDUMA replaced its initial mobile money payment system with a cash-based payment system. The initial digital system required users to charge a payment card. At the waterpoint, users paid for the volume of water collected by using their card and a card reader device handled by the caretaker. The payment card is debited according to the volume of water collected (PAYF), with a volumetric tariff of 500 FCFA ($0.80) per m³. Since January 2022, all payments are cash-based, following the same tariff ($0.80/m³) and payment modality (PAYF) as the initial digital payment system. For cash payments, users pay the required volumetric payment amount directly in cash to the caretaker.

The shift from mobile money to cash payments was motivated by cost considerations given high operating costs for digital payment systems (software license, data collection devices, fees for digital payment provider, etc.). While this shift in the payment system stipulated internal changes at the provider level, the user experience did not fundamentally change. Before, during, and after the transition from digital to cash payments, users continued to make direct payments to the caretaker at the waterpoint. We emphasise that the gradual change from digital to cash payments did not affect the tariff level ($0.80/m³) or the PAYF payment modality. At any point in time, users are required to pay for the volume of water collected – regardless of if using the initial digital payment system or cash. Nevertheless, we recognise that the change in payment systems constitutes an additional limitation of the methodology of the analysis.

5.2.2 Data collection and variable definition

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

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

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

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

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

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

Recognising that changing climatic conditions, especially seasonal rainfall and temperature, may influence user demand (Armstrong et al., 2021; MacAllister et al., 2020; Thomas et al., 2019; Thomson et al., 2019), the empirical estimates account for the total amount of rainfall in a month and monthly average temperature for each site. Rainfall data was retrieved from Tropical Applications of Meteorology using SATellite data and ground-based observations, TAMSAT (Maidment et al., 2017, 2014; Tarnavsky et al., 2014), whereas temperature estimates were generated using Copernicus Climate Change Service information (Copernicus Climate Change Service, 2019). Summary statistics for these variables are provided in the Supporting Information (Table S5.1, SI).

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

5.2.3 Empirical strategy and statistical models

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

Our estimates rely on interrupted time series (ITS) analysis which allows us to assess whether the switch from handpump to solar kiosk influences the level and the trend of the outcomes.

Additionally, the ITS analysis accounts for autocorrelation of the outcome variables, therefore providing a more accurate estimate of the longitudinal effect of the infrastructure change (Kontopantelis et al., 2015; Linden, 2015; Lopez Bernal et al., 2016; Penfold and Zhang, 2013). An ITS design does not "require the intervention to be introduced overnight" (Lopez Bernal et al., 2016), however, there must be a clearly defined intervention period. In the case of the first cohort of ten waterpoints, the intervention period is between March and May 2021, and for the second cohort of five waterpoints the intervention period is 1 December 2021, a clear cut-off point (further detail on intervention period and time series choice in Section 5.6).

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

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

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

More complete models include monthly rainfall and temperature to account for seasonal confounders, likely to affect the outcomes of interest. When controlling for climatic conditions, model tests (ACF, PACF, and Durbin Watson) indicate improvements in autocorrelation. ITS plots (Freyaldenhoven et al., 2021; Penfold and Zhang, 2013) visualise shifts in levels and trends across the outcomes (Figure S5-2, SI).

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

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

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

Fixed effect models allow the presence of arbitrary correlations between unobserved individual effects and covariates, and control for these unobservable factors to alleviate omitted variable bias (Best and Wolf, 2014; Cunningham, 2021; Wooldridge, 2010). We control for time-variant confounders (rainfall and temperature) and include a unit-fixed effects at the waterpoint level (the unique waterpoint ID is used a fixed intercept) to avoid omitted variable bias. We use robust standard errors, clustered at the waterpoint level, to account for autocorrelation occurring between periods within each unit (Abadie et al., 2022; Cameron and Miller, 2015). The results for the fixed-effects regression estimation are reported in Table S5.3, SI.

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

A final check consists in accounting for seasonality in the intervention period of the first cohort of ten waterpoints by grouping the data by the time period in which the individual waterpoints received the infrastructure upgrade (Schochet, 2022). Grouping based on time periods allows for a more fine-grained approach and enables to check whether there are different changes in the coefficients based on intervention timing (results are reported in Table S5.4, SI). All statistical analyses were conducted in R (Version 4.0.3).

5.3 Results

We report summary statistics for the first cohort of ten waterpoints and present the results of the ITS model for both waterpoint cohorts to illustrate consistency and divergency across contexts. Summary statistics for the second waterpoint cohort, as well as the results of the robustness checks (fixed-effects regression model and ITS model accounting for seasonality during the intervention period) can be found in the Supporting Information (section 5.6) and are referenced in the manuscript as necessary.

5.3.1 Water use is not affected by the infrastructure upgrade but subject to seasonal variation

Longitudinal monitoring across three consecutive dry and wet seasons reveals seasonal variation in daily water usage affecting both infrastructure types, with water usage varying importantly across sites (Figure 5-3). Increases in daily use levels align with Mali's hot season (March to June), whereas water demand falls during the rainy season (July to October). While we observe an unconditional average increase in daily volumetric use when a handpump (mean: 1.36m^3, median: 0.88m^3) is switched to a solar kiosk (mean: 1.84 m^3, median: 0.94 m^3), our analyses indicate that this change is not significant (Table 2, and Tables S5.3 and S5.4 in SI).

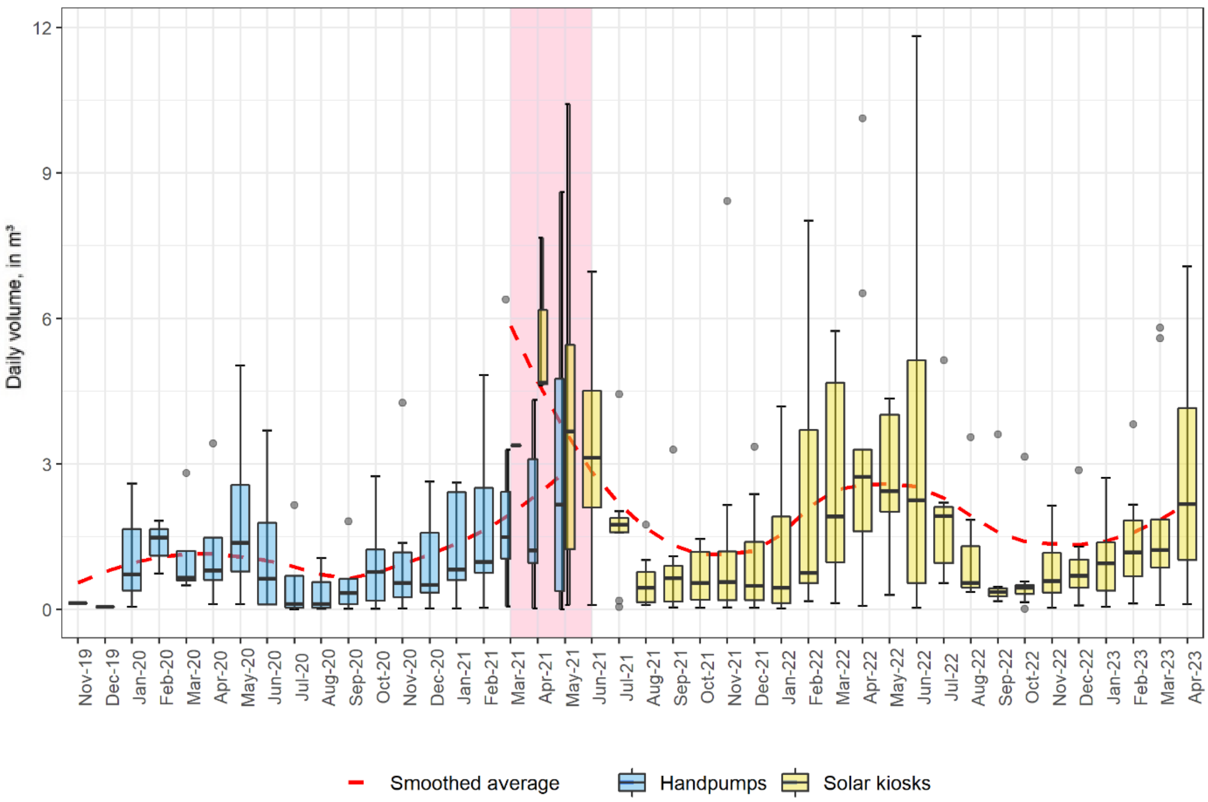

Figure 5-3. Daily volumetric water use over time. Box and whisker plots (interquartile range and outliers) across the 10 waterpoints of the first cohort on daily volumetric use, separating between infrastructure types. Dashed line displays mean average. Shaded area highlights the period of the infrastructure transition (March to May 2021).

Table 5.2 reports the results of the ITS regression models for both cohorts of waterpoints. The ITS approach allows to model the shift in magnitude occurring as a result of an intervention, measured by the difference in outcomes at time points immediately before and immediately after the solar upgrade (level change). Besides, our ITS models provide an estimate of the change in slope from pre- to post-intervention (trend change). Since the relevant diagnostics for model fit (R^2 and adjusted R^2) improve when controlling for seasonal confounders, we only describe the conditional models.

Table 5.2 ITS regression results for daily volumetric use (in m^3) for both waterpoint cohorts

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

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

When controlling for temperature and rainfall, the results show no significant level or trend change following the switch from a handpump to a solar kiosk (Table 5.2). Model 2 indicates that for the first cohort of ten waterpoints, solely monthly temperatures are significantly associated with higher water use. An increase of 1°C in monthly average temperature translates into additional daily water abstraction of 366 litres per waterpoint. An ITS plot visualises this result (Figure S5-2, SI). Estimates for the second cohort of five waterpoints show a consistent pattern, with temperature being significantly associated with an increase in daily water use of 352 litres per waterpoint (Model 4).

The reported ITS estimates are consistent with the fixed-effects regression models (Table S5.3, SI). Finally, we find no effect of the infrastructure upgrade on daily water use when accounting for seasonality in the intervention period (Table S5.4, SI). Our regression models and robustness checks indicate that daily water use per waterpoint does not significantly increase when a handpump is upgraded to a solar kiosk. However, water use depends on climatic conditions, suggesting that higher monthly temperatures translate into increased water demand.

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

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

Monthly revenues, similar to the seasonal fluctuation in water demand, are also affected by seasonal trends (Figure 5-4). Solar kiosks experience revenue shortfalls during the rainy season, reaching average decreases of 40% compared to the annual mean revenue. Furthermore, there is high variation across the ten solar kiosks, as shown in Figure 5-4, emphasising that volumetric water usage varies importantly across the sites, affecting monthly revenue.

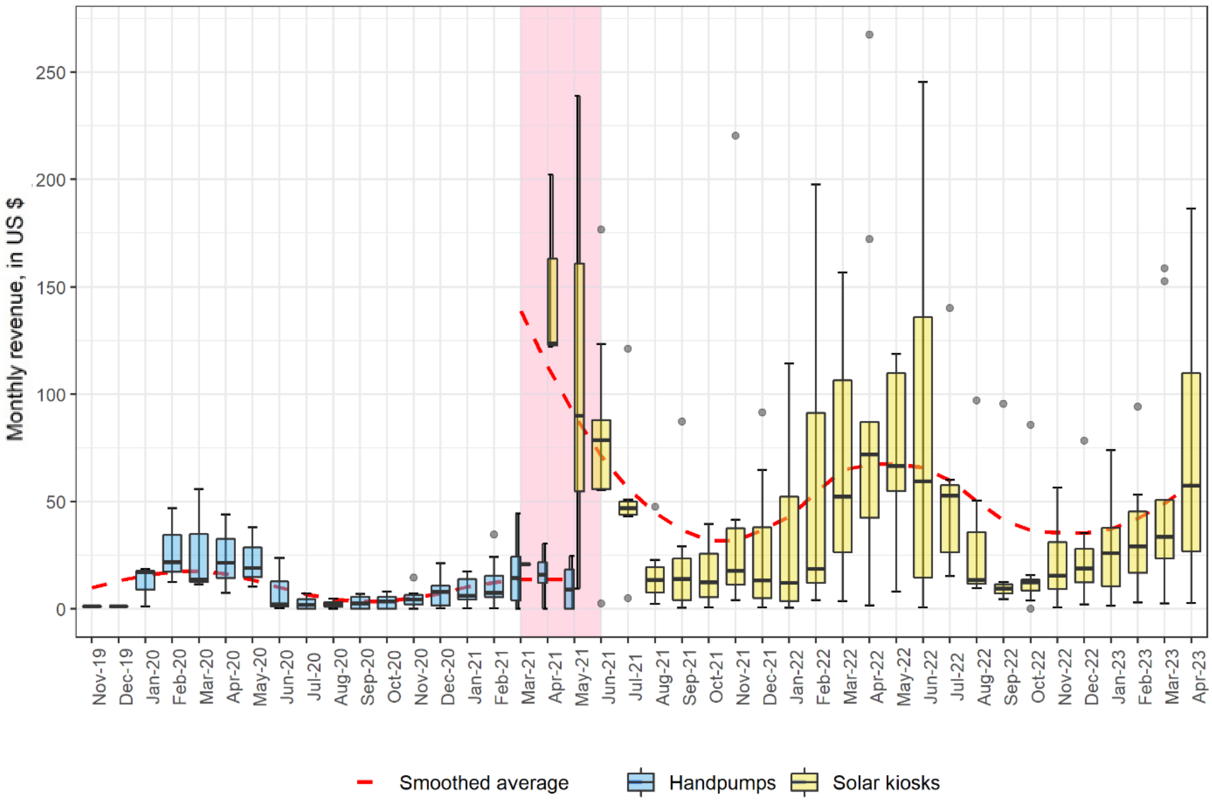

Figure 5-4. Monthly revenue over time. Box and whisker plots (interquartile range and outliers) across the 10 waterpoints of the first cohort on monthly revenue per waterpoint, separating between infrastructure types. Dashed line displays mean average. Shaded area highlights the period of the infrastructure transition (March to May 2021).

The results of the ITS regression model for both waterpoint cohorts indicate that significant and large changes in monthly revenue are associated with the introduction of the solar kiosks and higher temperatures (Table 5.3). For the first cohort, the infrastructure upgrade is associated with a revenue increase of $46 per month per waterpoint, when controlling for seasonal factors (Model 2). An ITS plot (Figure S5-2, SI) visualises the shift in revenue levels over time. Furthermore, the estimates indicate that an increase of 1°C in monthly average temperature translates into $9.30 more revenue per waterpoint per month, reflecting that revenue increases align with higher water demand during the annual dry season. ITS estimates for the second cohort of five waterpoints (Table 5.3) show similar results: the introduction of the solar kiosks is associated with a revenue increase of $31.46 per month per waterpoint (Model 4). Furthermore, increases in monthly average temperature are associated with higher monthly revenues. These findings are consistent with the revenue patterns of the first cohort.

Table 5.3 ITS regression results for monthly revenue (in $) for both waterpoint cohorts

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

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

The fixed-effects regression model yields similar results, with increases in monthly revenue associated with the infrastructure upgrade and higher temperatures (Table S5.3, SI). Finally, when accounting for seasonality in the intervention period, our findings remain consistent (Table S4.4, SI).

5.3.3 Collection efficiency increases substantially following the technology shift and remains stable over time and across contexts

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

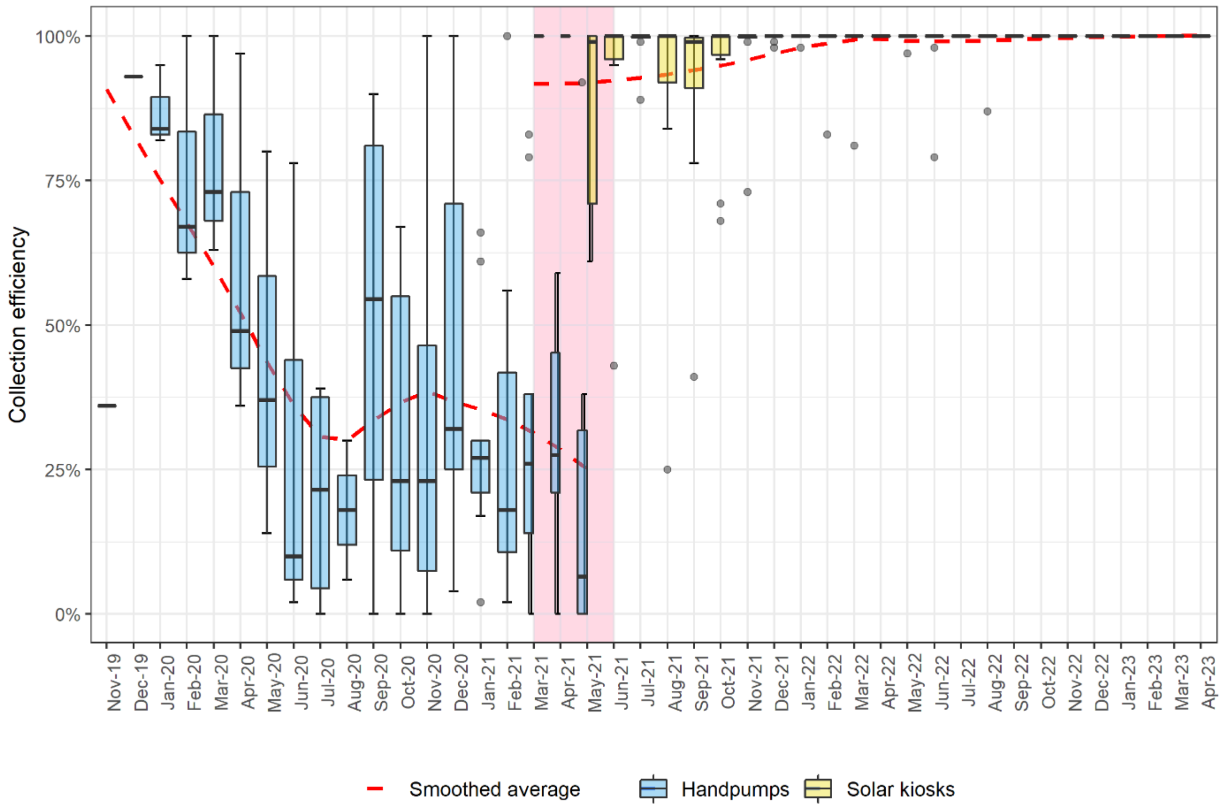

Figure 5-5. Payment collection efficiency over time. Box and whisker plots (interquartile range and outliers) across the 10 waterpoints of the first cohort on payment collection, separating between infrastructure types. Dashed line displays mean average. Shaded are highlights the period of the infrastructure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

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

This pattern might be driven by various external factors. For instance, COVID 19 took its toll on Mali, with the national government declaring a state of national health emergency on 26th March 2020. A coup by the Malian military on 18th August 2020, further destabilised Mali's fragile economy, contributing to the ongoing economic recession related to the pandemic (World Bank, 2021b). A second coup on 24th May 2021 and an embargo by ECOWAS since January 2022 further increased the economic pressure on Mali. In addition, France withdrew its troops from Mali in September 2022, and put its official development aid on hold from November 2022. These factors may have affected livelihoods and hence the users' ability to pay. Yet, these broader socio-economic and political shocks do not seem to affect user payments at solar kiosks as their trend remains stable over time (Figure 5-5 and Figure S5-2, SI).

The ITS regression results across both waterpoints cohorts support the descriptive insights (Table 5.4). Following the upgrade to solar kiosks, the level of payment collections increases significantly by 62.7% for the first cohort of waterpoints. When controlling for seasonal confounders, there is no significant change in the collection efficiency trend following the solar upgrade, showing consistency over time (Model 2). An ITS plot (Figure S5-2, SI) visualises this result.

The second cohort registers a similar pattern, with a larger effect on payment collections of 98.2% (Model 4). Furthermore, the positive and significant trend change of 5.1% indicates that payments experience an upward increase following the solar upgrade, suggesting that payment behaviours at solar kiosks slightly improve over time. Unlike volumetric use and monthly revenues, the results across both cohorts reveal that collection efficiency remains unaffected by seasonal drivers since temperature and rainfall controls are not significant (Table 5.4).

Table 5.4 ITS regression results for collection efficiency (in %) for both waterpoint cohorts

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

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

Finally, the findings on collection efficiency are coherent when modelling the data through a fixed-effects regression (Table S5.3, SI) and when applying the seasonal robustness check (Table S5.4, SI).

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

5.4 Discussion

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

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

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

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

Recent research estimates that keeping to the 1.5 °C target agreed at the 2015 Paris climate conference would still mean that some 200 million people are exposed to unprecedented temperature increases (Rockström et al., 2023). Climate-resilient water supplies are important to adapt to these threats. Using solar energy to pump widely available groundwater resources may be an effective adaptation response, provided that groundwater resources are correctly managed and monitored (MacAllister et al., 2020; MacDonald et al., 2021; Meunier et al., 2023; Rodella et al., 2023). As our assessment reveals, water demand varies importantly across sites, and future infrastructure investments may target locations under pressure as a priority. With capital investments in water infrastructure expected to increase in Africa within the next decade (International High-Level Panel on Water Investments for Africa, 2023), evidence to guide their allocation and to ensure their effectiveness is instrumental to achieve SDG 6.1 by 2030.

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

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

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

Providing piped water to the home may not overcome fluctuations in revenue or water consumption (Armstrong et al., 2022, 2021; Armstrong, 2022). Based on data from Ghana, Rwanda, and Uganda, Armstrong et al. show that extended rainfall periods can reduce revenue by up to 30% compared to dry periods – regardless of whether supplies are provided off- or on-premises (2022). We find similar patterns of seasonally fluctuating demand and revenues at handpumps and solar kiosks. For this reason, understanding how tariff design can support revenue generation to promote operator sustainability is important. For instance, regular flat fees instead of volumetric tariffs may be a more socially acceptable payment method (Foster and Hope, 2017) and could incentivise rural populations to rely on improved waterpoints throughout the year. Future research may engage with professional service providers which offer high quality and standardised operational and financial data to assess how different payment modalities affect water use and revenue outcomes (McNicholl et al., 2019).

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

5.5 Conclusion

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

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

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

5.6 Supplementary File (Chapter 5)

Supporting Information for

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

This file includes:

Supporting text

Supplementary Figures S5-1 and S5-2

Supplementary Tables S5.1 to S5.4

Data availability and summary statistics

a) **Information on study sites**

The study site comprises the Region of Sikasso, located in the south of Mali. Table S5.1 presents summary statistics across the 15 sites (for the two cohorts) for total amount of rainfall in a month, monthly average temperature estimates and population size, illustrating the variability across sites.

Population data was retrieved from the latest official census run in Mali in 2009, adjusted for an annual growth rate of 3.5 %, providing insights into the range of population size across the villages (mean: 2,844; median: 2,036). The distinct service population per waterpoint, however, is unknown. Collecting daily, weekly, or even monthly data on the distinct number of users would require extensive fieldwork which was not feasible during the period of investigation.

Table S5.1. Summary statistics for climatic controls and demographic conditions

#	Village	Cohort	Monthly rainfall (mm)			Monthly temperature (°C)			Population
			Mean	Min	Max	Mean	Min	Max	Total
1	Binko	1	67.86	1.4	313.6	27.46	24.78	31.63	2,536
2	Bougoula	1	76.63	0	285	27.69	24.83	31.96	2,635
3	Dionkala	1	70.17	0	276.6	27.84	25.06	32.27	1,179
4	Dionkoni	1	64.08	0	320.1	27.66	24.82	31.12	2,036
5	Fangala	1	104.43	3	362.9	27.21	24.61	30.83	2,100
6	Kebila	1	76.29	0	285.8	27.72	24.85	31.99	4,826
7	Moribala	1	100.06	0	342.3	27.75	24.9	31.93	1,217
8	N'Tenkoni	1	65.23	0	330.4	27.95	25.14	32.5	1,227
9	Tiefala	1	71.86	0	286.5	27.74	24.98	32.27	2,717
10	Tinkole	1	89.72	0	297.6	27.34	24.96	32.37	744
11	Diologola	2	87.83	0	342.3	27.40	24.32	31.56	972
12	Zena Farabale	2	86.37	0	328.4	27.41	24.29	31.46	808
13	Sirakoroble	2	88.65	0	317.8	27.30	24.29	31.35	915
14	Markala	2	87.83	0	342.3	27.40	24.32	31.56	16,121
15	Kologo	2	94.24	0	304.8	27.70	24.53	32.23	2,633

Rainfall data was retrieved from Tropical Applications of Meteorology using SATellite data and ground-based observations, TAMSAT (Maidment et al., 2017, 2014; Tarnavsky et al., 2014) whereas temperature data was generated using Copernicus Climate Change Service information (Copernicus Climate Change Service, 2019). Figure S5-1 tracks seasonality across rainfall and temperature across the study sites to visualise Mali's annual hot (March to June) and rainy seasons (July to October) throughout the study period.

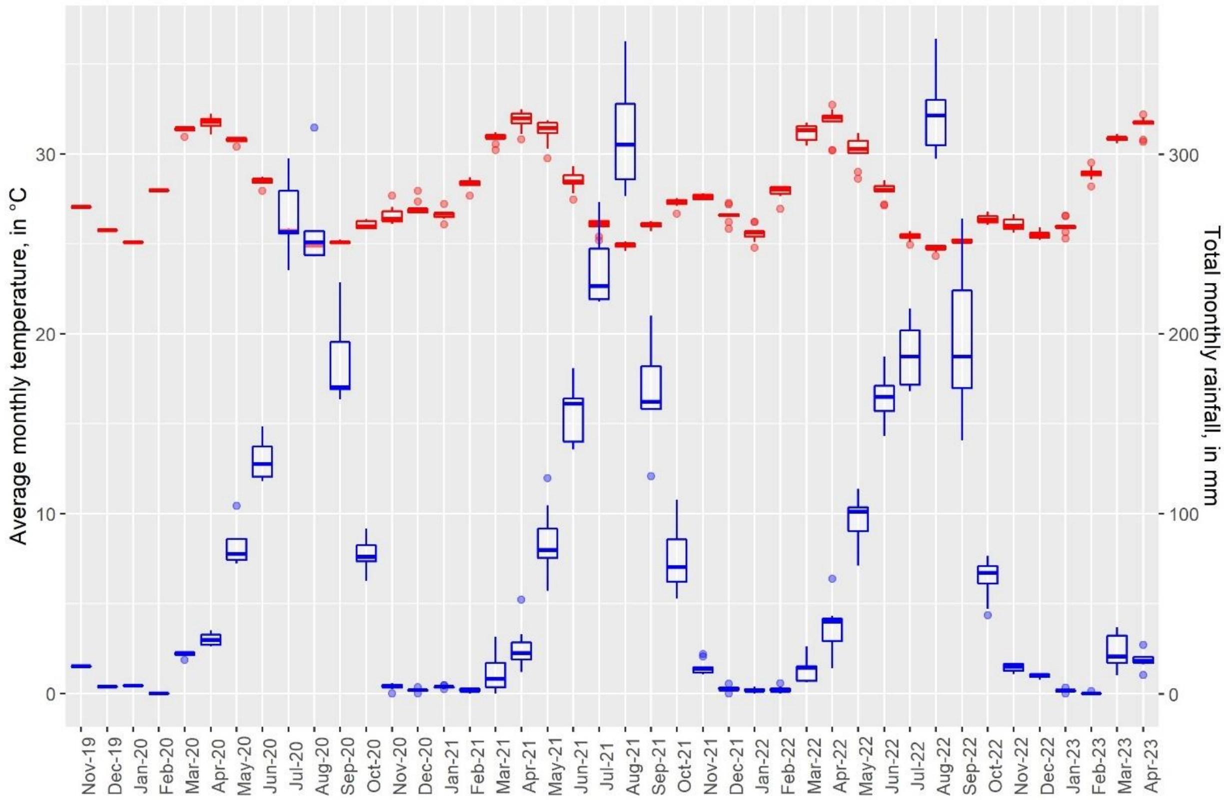

Figure S5-1. Rainfall and temperature in the study area. Seasonal boxplots display variability in average monthly temperature (red) and total monthly rainfall (blue) across the sites and over time.

b) Summary statistics for outcome variables

Table S5.2 presents relevant summary statistics across the three outcomes of interest, separating between infrastructure types and waterpoint cohorts. The dependent variables are daily volumetric use (m^3), monthly collection efficiency (%), and monthly revenue ($) per waterpoint.

Table S5.2 Summary statistics for outcomes of interest across both waterpoint cohorts

- **A) Daily volumetric use, m³**

	First cohort (10 waterpoints)		Second cohort (5 waterpoints)	
Metrics	**Handpump**	**Solar kiosk**	**Handpump**	**Solar kiosk**
Mean (SD)	1.36 (1.51)	1.84 (2.18)	2.38 (1.81)	1.62 (1.33)
Median	0.88	0.94	2.45	1.27
Min	0	0	0	0.03
Max	8.61	11.82	6.29	5.83
Monthly observations (n)	98	215	41	80

- **B) Collection efficiency, %**

	First cohort (10 waterpoints)		Second cohort (5 waterpoints)	
Metrics	**Handpump**	**Solar kiosk**	**Handpump**	**Solar kiosk**
Mean (SD)	40% (31%)	97% (10%)	17% (20%)	99% (8%)
Median	30%	100%	6%	100%
Min	0	25%	0	48%
Max	100%	100%	76%	100%
Monthly observations (n)	86	205	38	78

- **C) Monthly revenue, US$**

	First cohort (10 waterpoints)		Second cohort (5 waterpoints)	
Metrics	**Handpump**	**Solar kiosk**	**Handpump**	**Solar kiosk**
Mean (SD)	11.69 (12.15)	48.70 (54.69)	12.47 (20.29)	41.56 (35.45)
Median	7.85	26.49	0.23	32.52
Min	0	0	0	0
Max	55.80	267.34	89.73	159.10
Monthly observations (n)	86	205	41	80

ITS model specifications and plots

This section outlines additional specifications of the statistical models, including the choice of the longitudinal data used for the time-series analysis, and presents plots for the ITS approach and findings from the fixed-effects regression model to supplement the main results of the analysis.

a) ITS model specifications on time series choice and intervention period

The ITS analysis includes a stationary pre-intervention time period of 6 time points (months) and a post-intervention period of 23 time points of monthly observations, covering a period from October 2020 to April 2023. The final ITS analysis that we run includes 6 pre-intervention time points and 23 post-intervention time points, from October 2020 to April 2023. The starting point of the time series is based on data stationarity determined through stationarity testing confirming linearity of the pre-intervention time trend (Kontopantelis et al., 2015), and completeness of data. The Kwiatkowski-Phillips-Schmidt-Shin (KPSS) stationarity test shows that the data is not stationary prior to time period 10 (August 2020) and is excluded from the sample. To ensure completeness of the time series data, the dataset only includes time periods where observations for more than five waterpoints are recorded (unbalanced panel). Therefore, the time series begins in October 2020, 6 months prior to the infrastructure change.

The intervention period covers March to May 2021, with varying dates for the infrastructure upgrade at each site (the ten solar kiosks were installed between 25/03/2021 and 21/05/2021). For each waterpoint, the exact date of the solar upgrade is known. In the case that the upgrade happened after the 15th of the month, the month is classified as a handpump (binary = 0). Upgrades that occur after the 15th of the month are coded as solar only in the subsequent month (binary = 1). In March 2021, the majority of the data was collected using handpumps (0). Similarly, in June 21 the majority of the data for each village was collected at solar kiosks (1).

b) ITS plots across the outcomes of interest

ITS plots (Figure S5-2) across the three outcomes of interest visualise level shifts following the infrastructure upgrade and display pre- and post-intervention trends. For collection efficiency, a visible jump in levels is associated with the solar upgrade, followed by a stable and consistent post-intervention trend. Volumetric water use is characterised by a seasonal pattern when controlling for climate metrics and does not yield a clear jump (level) or shift in trend following intervention. Monthly revenue displays a seasonal pattern (trend), confirming the temperature signal of the segmented regression, and reveals a shift in levels following the solar upgrade.

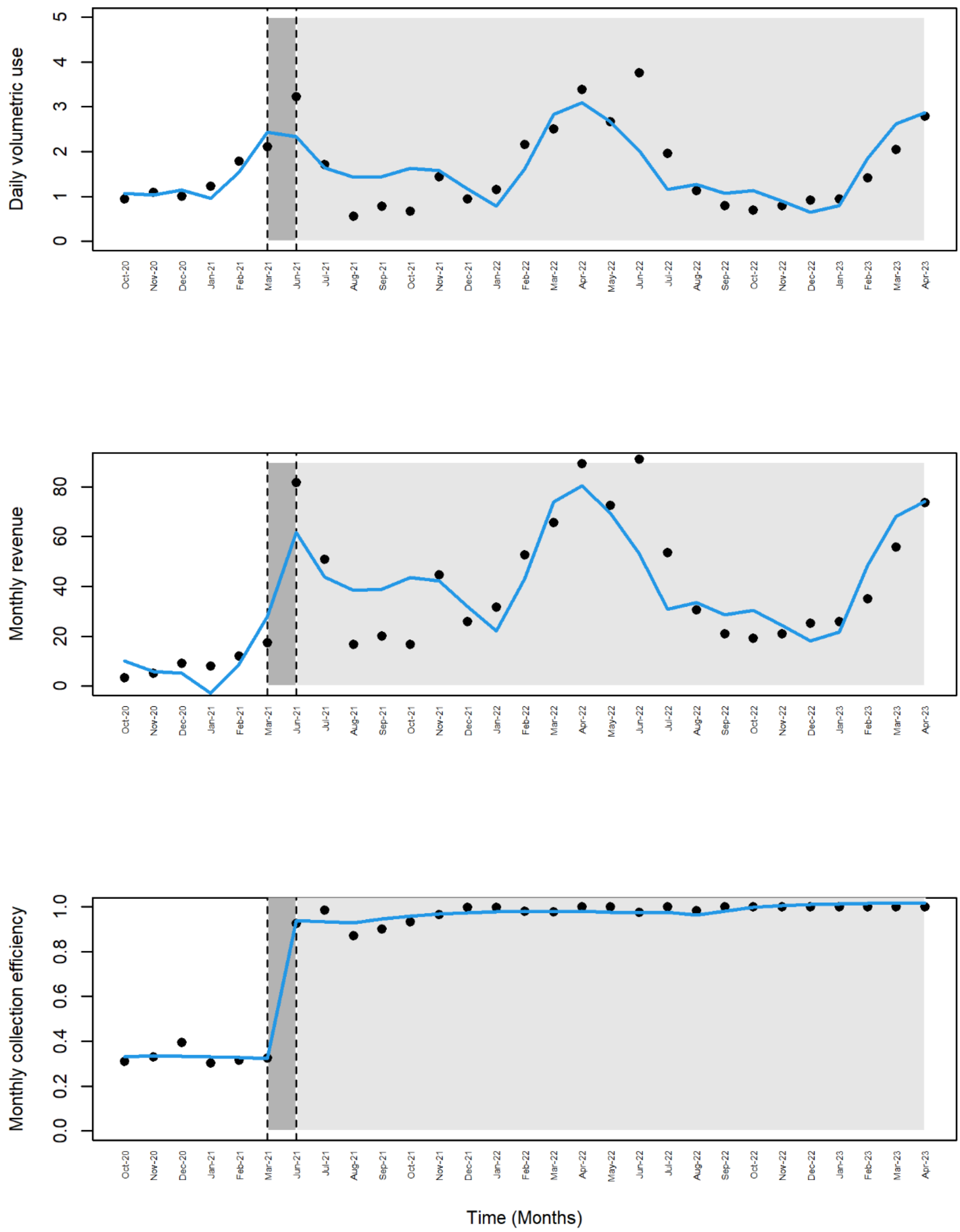

Figure S5-2. ITS plots across the three metrics of interest. Shaded area presents intervention period, given staggered treatment adoption, between March and May 2021. Continuous line (blue) presents line of best fit controlling for seasonal confounders (temperature and rainfall). The dependent variables are mean daily volumetric use (m^3), mean monthly collection efficiency (%), and mean monthly revenue ($) per waterpoint.

Results of robustness checks

a) Fixed-effects regression results

Table S5.3 presents the results of the fixed-effects regression estimation, applied to the full panel dataset (N=10), to estimate the effect of the infrastructure upgrade on the three outcomes of interest. The fixed effects results corroborate the ITS results. When controlling for temperature and rainfall, solar kiosks are significantly associated with increases in collection efficiency (70.16%) and monthly revenue ($53.34) but do not significantly influence volumetric use. The significance level and direction of the temperature signal for volumetric use and revenue is consistent with the ITS results.

Table S5.3 Results for fixed effects model with first cohort of waterpoints (N=10)

	Volumetric use (in m³)		**Collection efficiency (in %)**		**Monthly revenue (in $)**	
	(1) Basic	(2) With controls	(3) Basic	(4) With controls	(5) Basic	(6) With controls
Level change after solar	0.306 (0.620)	0.645 (0.514)	**66.50*** (9.14)**	**70.16*** (8.01)**	**45.39** (12.76)**	**53.34** (11.69)**
Trend change after solar	-0.156 (0.081)	-0.121 (0.07)	**2.9*** (0.49)**	**3.0*** (0.5)**	-0.84 (1.00)	0.23 (0.78)
Temperature		**0.366*** (0.08)**		0.1 (0.89)		**9.26** (1.96)**
Rain		0.001 (0.001)		0.0 (0.0)		0.05 (0.03)
Number of observations	313	313	291	291	291	291
R^2	0.326	0.486	0.731	0.737	0.425	0.587
R^2 adjusted	0.299	0.462	0.719	0.725	0.400	0.566

Notes: Robust standard errors, clustered at the waterpoint level, are reported in parentheses. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Bold for significance level of 5% and higher. Controls include monthly total rainfall and average monthly temperature for each of the 10 sites. The dependent variables are daily volumetric use (m³), monthly collection efficiency (%), and monthly revenue ($) per waterpoint. Level change refers to the shift in magnitude occurring as a result of the intervention, measured by the difference in outcomes at time points immediately before and immediately after the solar upgrade, and trend change refers to the change in slope from pre- to post-intervention.

b) Accounting for seasonality in intervention period

To account for seasonality in the intervention period given variation in treatment timing (Schochet, 2022), the data is grouped by the time period (month) in which the waterpoints received the infrastructure upgrade. The goal of the grouping method is to adjust the segmented regression model to the heterogeneity of the intervention period. Based on the definition of the intervention period, we group the individual waterpoints receiving the upgrade from a handpump to a solar kiosk as follows: 15th March to April 15th (April), April 16th to May 15th (May), and May 16th to June 15th (June). Out of the ten sites, three waterpoints receive the solar upgrade in April, four in May, and three in June 2021.

Each monthly grouping represents all units treated within the same time period, with one regression model per intervention group reported (Schochet, 2022). In the intervention period approach, all differences between the regression coefficients of each group are attributed to the intervention, however, breaking down the interventions based on time periods allows for a more fine-grained approach, and enables to check whether there are changes in coefficients based on time periods. Results in Table S5.4 corroborate the positive and significant effect for the main regressor, the solar upgrade, on collection efficiency (all three groups) and revenue (for April and May), and confirm the temperature signal positively affecting volumetric use (April and May) and monthly revenue (all three groups).

Table S5.4 Effect of infrastructure shift from handpump to solar kiosk on outcomes of interest, grouped by monthly intervention period controlled for seasonal conditions (N=10)

	Volumetric use (in m³)			**Collection efficiency (in %)**			**Monthly revenue (in $)**		
	April	May	June	April	May	June	April	May	June
Level change after solar	3.22* (1.56)	0.30 (0.68)	-0.96 (-0.24)	**62.3***** **(7.9)**	**63.6***** **(16.7)**	**57.9***** **(5.80)**	**4.62***** **(1.05)**	**1.27**** **(0.54)**	1.1 (2.0)
Trend change after solar	0.16 (0.25)	-0.12 (0.17)	-0.24 (0.28)	-0.9 (3.2)	6.2* (3.3)	-6.1*** (1.7)	0.33 (0.22)	0.15 (0.13)	0.08 (0.22)
Temp.	**0.68***** **(0.18)**	**0.28***** **(0.05)**	0.31 (0.18)	-0.5 (0.8)	0.2 (1.2)	0.6 (0.6)	**0.64***** **(0.16)**	**0.26***** **(0.05)**	0.33* (0.17)
Rain	0.00 (0.00)	0.00 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0.00 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
Number of obs.	20	19	18	20	19	18	20	19	18
R^2	0.73	0.76	0.66	0.96	0.89	0.99	0.83	0.7	0.69
R^2 adj.	0.64	0.67	0.52	0.94	0.85	0.98	0.73	0.58	0.56

Notes: Robust standard errors, clustered at the waterpoint level, are reported in parentheses. Significance levels: $*$ $p < 0.1$, $**$ $p < 0.05$, $***$ $p < 0.01$. Bold for significance level of 5% and higher. Controls include monthly total rainfall and average monthly temperature for each of the 10 sites. The dependent variables are daily volumetric use (m^3), monthly collection efficiency (%), and monthly revenue ($) per waterpoint. Level change refers to the shift in magnitude occurring as a result of the intervention, measured by the difference in outcomes at time points immediately before and immediately after the solar upgrade, and trend change refers to the change in slope from pre- to post-intervention.

Chapter 6: Is volumetric pricing for drinking water an effective revenue strategy in rural Mali? (Paper 3)

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Note: In this chapter, minor modifications have been made compared to the published version of the paper. To ensure a coherent format throughout the thesis, the numbering of tables and figures in this chapter have been adapted compared to the published version of the paper.

Abstract

Africa lags behind the world on operational and financial progress to maintain safe drinking water services. In rural Mali, we explore the implications of monthly flat fee contributions and volumetric (pay-as-you-fetch) payments for water use and revenue generation. By assessing 4,413 months of data across 177 handpumps, we find that once payment modalities switch from volumetric payments to monthly flat fees, a waterpoint registers a more than three-times higher monthly revenue. While flat fees cover a higher share of the operational costs of providing reliable water services, a subsidy gap persists. Flat fees appear to stimulate daily water use which more than doubles compared to volumetric payments. We estimate that a 1°C increase in average monthly temperature is associated with 180 more litres of water used every day per handpump, emphasising the importance of climate-resilient water supplies. Based on these insights, we discuss the role of professional service delivery models to support reliable drinking water services for rural communities.

6.1 Introduction

The global challenge of providing safely managed services to approximately two billion people (WHO et al., 2022) is amplified in rural Africa where approximately 25%-30% of rural waterpoints are non-functional at any point in time. This leaves about $1.5 to 2.5 billion of capital investment unused (Foster et al., 2020). Hand- and foot pumps which are the most widely used technology in Africa for providing basic water supply experience breakdown durations lasting on average 30 days (Foster and Hope, 2017; Hope, 2015; McNicholl et al., 2019). Despite significant investments in community-based management over several decades, progress has been largely unsatisfactory in maintaining rural water supply infrastructure (Hope, 2015; Hutchings et al., 2015; Koehler et al., 2015; Whaley et al., 2019). Cross-country evidence from rural Africa shows that significantly higher operational performance can be achieved by professional service delivery models (Foster et al., 2022; McNicholl et al., 2019). Yet, these professional service providers struggle to cover related operating costs requiring a subsidy, as is common in most urban piped systems (Andres et al., 2019; McNicholl et al., 2020, 2019).

Policy and practice generally expect that some of the costs of providing rural water services are to be covered through user payments (Banerjee and Morella, 2011; Fonseca et al., 2013; Hutton and Varughese, 2016; Jones, 2013; Kolker et al., 2016; Leigland et al., 2016; Pories et al., 2019; Winpenny et al., 2016, 2003). Global assessments indicate that user payments are the largest source of WASH financing (WHO, 2021, 2019, 2017). Yet, debate prevails on how to effectively generate sufficient local revenue from user payments and which pricing strategies are the most effective in aligning affordability goals with cost recovery targets (Andres et al., 2021; Fuente, 2019; Nauges and Whittington, 2017; OECD, 2011; Whittington, 2003; World Bank, 1993). As costs for maintaining existing water infrastructure are globally expected to outgrow capital investments by 2030 (Hutton and Varughese, 2016), empirical insights on the effectiveness of revenue collection approaches for funding maintenance services can inform policy and practice to meet SDG 6.1.

Volumetric pricing is most common in urban piped water supply to increase revenue collection and improve financial sustainability while encouraging efficient water use (Cook et al., 2020). Volumetric pricing is becoming more common in water supply across rural Africa with the increasing development of small piped systems, water kiosks and ATMs, and cashless payment facilities (Ingram and Memon, 2020; Kulinkina et al., 2016; Nagel et al., 2015; Sharpe et al., 2022; van der Wilk, 2019; Wutich et al., 2021). Water policies in Africa promote different approaches to generate revenue to fund the recurrent costs of providing water services (Hope et al., 2019). Mali, for instance, officially recognises two payment modalities for rural water supply: regular flat fee contributions or volume-based payments at the waterpoint (DNH, 2007; Jones, 2013). Yet, the applicability and effectiveness of volumetric pricing in funding maintenance services for handpumps remains empirically unclear.

Across Africa, there has been increased interest in testing professional service delivery models to guarantee higher service levels and to promote greater financial sustainability (McNicholl et al., 2021; Nilsson et al., 2021). For example in Mali, a professional service delivery company, UDUMA, has raised private capital for a public private partnership with the government to provide reliable rural water services from 1,400 handpumps (van der Wilk, 2019), subject to affordable user payments. This large-scale initiative is implemented in the region of Sikasso, located in Southern Mali. The area is characterised by an annual dry season from March to June followed by a wet season from July to October, with annual rainfall of 510 to 1,400 mm. The average temperature varies seasonally, ranging from 24°C in January to 35°C in May (World Food Programme, 2021).

At the start of the professional service in November 2019, UDUMA charged a volumetric tariff of 500 FCFA per m^3 ($0.80). Following a "pay-as-you-fetch" approach, users made direct payments to a local caretaker at the handpump for every 20-litre container collected (van der Wilk, 2019). Confronted with low revenue due to limited user payment collections, UDUMA gradually introduced a monthly flat fee of 15,000 FCFA ($24) per handpump, with no limit on water use. The flat fee payment approach stipulates that if the flat fee is not paid, the UDUMA service is not activated, and the pump is locked until a payment is made. User communities self-organise to collect the flat fee amount and pay it to UDUMA's service area managers during their monthly site visits. Since March 2022, all waterpoints are running under a monthly flat fee model. The change in payment modalities was introduced within existing contractual arrangements with local governments and communities.

By examining longitudinal volumetric use and payment data we explore what happens if payment modalities for reliable maintenance services at handpumps are changed from volumetric payments to monthly flat fee contributions. Findings from Kenya, Ethiopia, Ghana, Rwanda, and Uganda emphasise the prevalence of seasonal water demand in rural areas and related implications on revenue generation (Armstrong et al., 2022; MacAllister et al., 2020; Thomas et al., 2019; Thomson et al., 2019). Therefore, we ask how does a change in payment modalities affect 1) daily water use, 2) monthly revenue, and 3) collection efficiency at handpumps, conditional on seasonal fluctuations, and 4) what, if any subsidy, is required to sustain services across the two payment modalities?

The analytical strategy of the paper is based on observed water usage and payment data from manual pumps equipped with water meters which is uncommon in rural Africa. We model a total of 4,413 months of observed payments and metered water usage before and after the change in payment modalities across 177 manual pumps, covering a period from November 2019 to April 2023. The change from volumetric to flat fee payments, gradually introduced between April 2021 to March 2022, constitutes a shift in UDUMA's revenue strategy while the infrastructure type (handpump) as well as the level of service delivery (guaranteed repairs within 72 hours of breakdown and annual water quality monitoring) stay constant. Similar to other cost estimates for professional service delivery guaranteeing that any breakdowns are repaired within 72 hours (Smith et al., 2023), UDUMA's recurrent local operation and maintenance costs (WASHCost, 2012) are of approximately $24 per waterpoint per month.

The analysis focuses on four performance metrics which we track over time: daily volume of water used per waterpoint, monthly revenue generated, monthly working ratio, and monthly collection efficiency. A local working ratio (McNicholl et al., 2019; World Bank, 2017a) is a performance metric reflecting local revenue from user payments divided by local operation and maintenance costs. Working ratios may also include indirect costs, depreciation, inflation, and other operational costs. Here, we apply the simple local metric to support understanding of pathways to improve financial sustainability. Collection efficiency provides an indication for the acceptance of the payment principle in the context of rural Mali and reflects users' willingness and commitment to pay for reliable water services (Hope et al., 2020) (further detail on the performance metrics is available in Section 6.5). We apply a fixed effects regression model to estimate the effect of changes in payment modalities on the outcomes of interest while accounting for seasonal confounders.

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

6.2 Results

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

6.2.1 Flat fees stimulate water use which is subject to seasonal variations

Using 1,885 monthly meter records under the volumetric modality and 2,528 meter readings under the flat fee modality between November 2019 to April 2023, we find that the average daily water use per waterpoint more than doubles under a monthly flat fee (mean: 1.74 m^3, SD: 2.26 m^3) compared to volumetric payments (mean: 0.84 m^3, SD: 1.48 m^3). A month-on-month assessment (Figure 6-1 a)) comparing average daily water use across payment modalities indicates that the increase in daily volumetric use aligns with the shift from volumetric to flat fee payments. Under the volumetric payment modality average daily usage per pump exceeds 1 m^3 only during April and May, the hottest months in Mali, whereas water demand under a monthly flat fee in the same period reaches up to 3 m^3 per pump and decreases to 1 m^3 only during the rainy season. Across both payment modalities, increases in volumetric water use align with Mali's hot season (March to June), whereas water usage falls during the rainy season (July to October), emphasising a seasonal pattern in water demand.

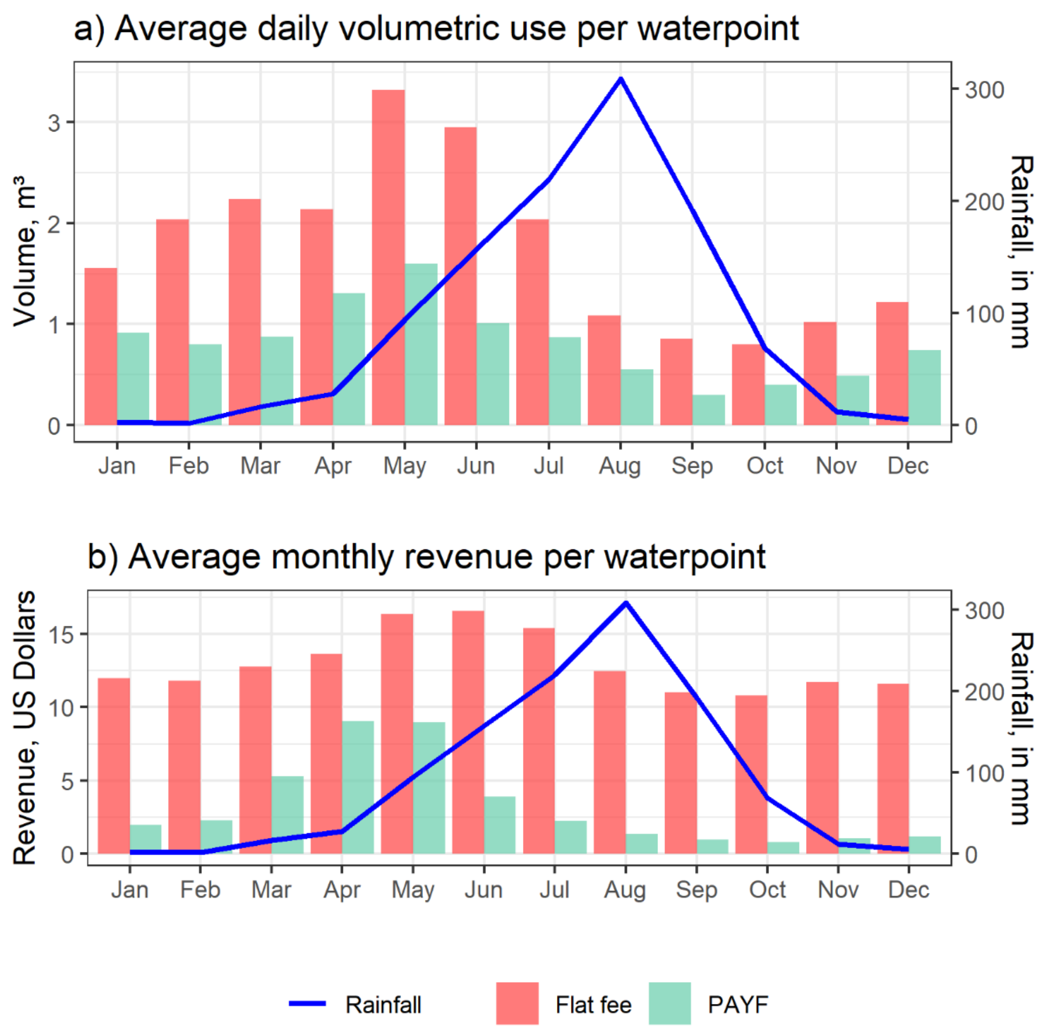

Figure 6-1. Average daily water use and monthly revenue per waterpoint. a) Average daily volumetric water use (in m^3) per waterpoint. b) Average monthly revenue generated per waterpoint (in US Dollars). Bar plots separating between payment modalities. Total of 4,413 monthly observations between 2019 to 2023 across 177 waterpoints. Rainfall is total monthly average.

Seasonal boxplots, disaggregated per payment modality (Figure 6-2), track daily volumetric use over three consecutive dry and wet seasons. This monitoring reveals the nuance and variation between months and within a month indicating different patterns for individual waterpoints. Again, daily volumetric water use levels align with Mali's hot and rainy seasons across both payment modalities, with higher average water use levels for the flat fee modality.

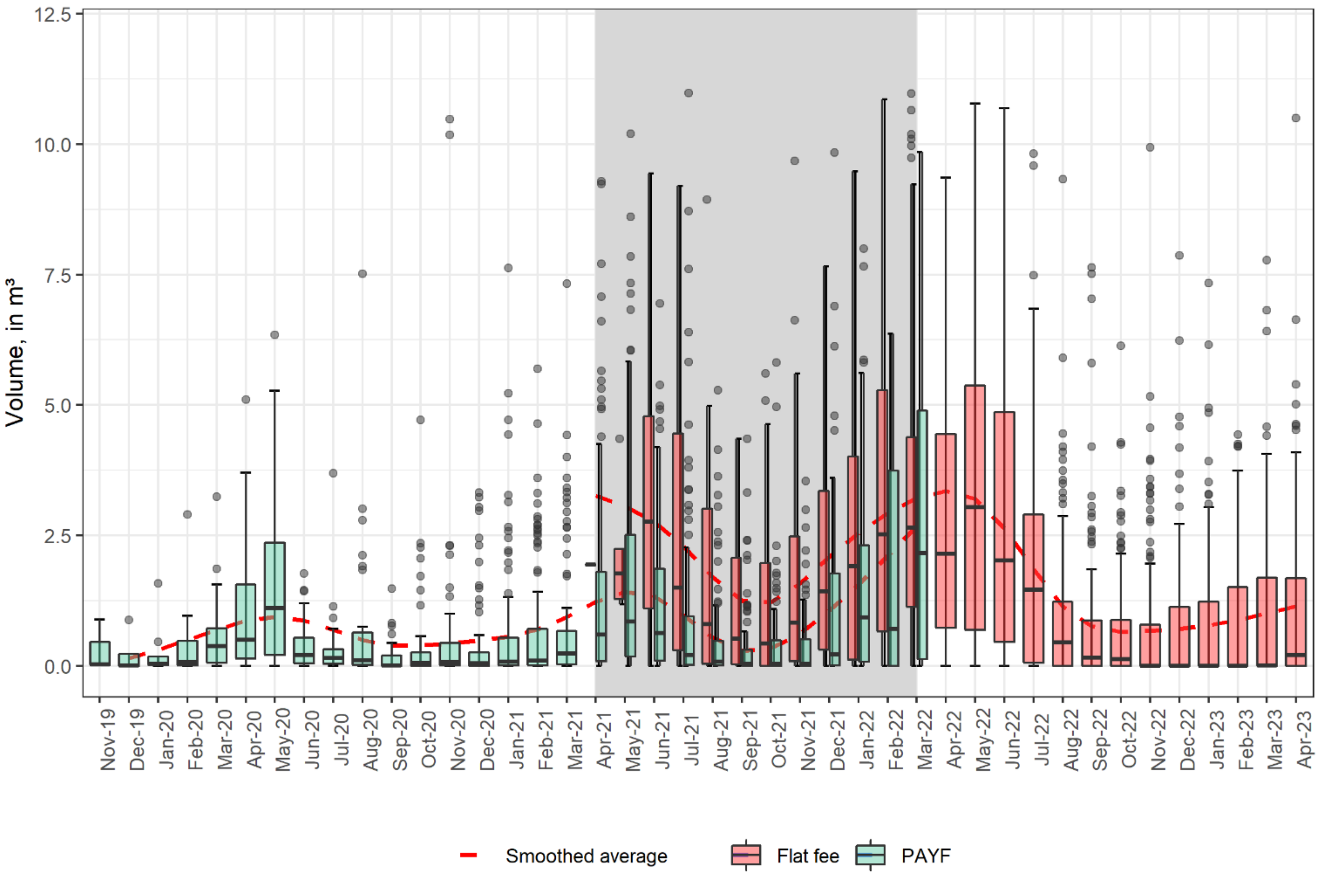

Figure 6-2. Daily volumetric water use per waterpoint, separating between payment modalities (n = 177 waterpoints). Box and whisker plots (centre line, median; box limits, upper and lower quartiles; whiskers, 1.5x interquartile range; points, outliers). Dashed line for average per payment modality. Shaded area highlights the period of the payment modality transition (April 2021 to March 2022).

A fixed-effects regression model supports the descriptive insights: when controlling for climatic conditions, the flat fee modality is associated with an increase of 900 litres in daily water use per waterpoint (Table 6.1, Model 2). Higher temperatures are positively related to higher water use: an increase of 1°C in monthly average temperature translates into additional daily water abstraction of 180 litres per waterpoint.

Table 6.1 Results of fixed-effects regression models

	Daily volumetric use (in m³)		Monthly revenue (in $)		Working ratio (in %)		Collection efficiency (in %)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Flat fee	**0.837***** (0.098) [0.64-1.03]	**0.908***** (0.102) [0.71-1.11]	**9.03***** (0.67) [7.7-10.3]	**9.37***** (0.68) [8.0-10.7]	**37.62***** (2.8) [32.1-43.1]	**39.04***** (2.8) [33.5-44.6]	**22.3***** (3) [16-28.7]	**24***** (3) [18-30]
Temp.		**0.180***** (0.016) [0.15-0.21]		**0.82***** (0.10) [0.61-1.02]		**3.4***** (0.45) [2.5 - 4.2]		2.6** (0.4) [2-3.3]
Rainfall		0.000 (0.000) [0.000 - 0.001]		0.009** (0.002) [0.005 - 0.01]		0.04** (0.01) [0.02 - 0.05]		0.00** (0.016) [0.0 - 0.0]
Nb of obs.	4,413	4,413	4,413	4,413	4,413	4,413	4,413	4,413
R^2	0.298	0.336	0.357	0.377	0.357	0.377	0.250	0.265
R^2 adj.	0.269	0.308	0.330	0.351	0.331	0.351	0.219	0.234

Notes: Robust standard errors, clustered at the waterpoint level, are reported in parentheses (). Confidence intervals are reported in brackets []. Significance levels: ∗ $p < 0.1$, ∗∗ $p < 0.05$, ∗∗∗ $p < 0.01$. Bold for significance level of 1%. Meteorological controls include total rainfall in a month and average monthly temperature for each of the 23 municipalities where the 177 waterpoints are located.

6.2.2 Flat fees are associated with higher payment collection

When comparing the two payment modalities regarding their performance in collection efficiency, it appears that flat fees (mean: 54%, SD: 50%) are approximately two times more likely to be paid than volumetric payments (mean: 29%, SD: 37%). Disaggregating average collection efficiency at the municipality level reveals a more nuanced pattern across the 23 municipalities where the 177 waterpoints are located (Figure 6-3). While the flat fee modality registers on average a two-times higher collection efficiency than the volumetric approach, we observe well-performing municipalities in volumetric payments, such as Sido or Kebila (Figure 6-3a)), rank relatively lower for flat fee payments (Figure 6-3b)). This insight highlights the spatial variation in effectiveness of payment modalities, emphasising that flat fees are not necessarily a “one-size-fits-all” approach.

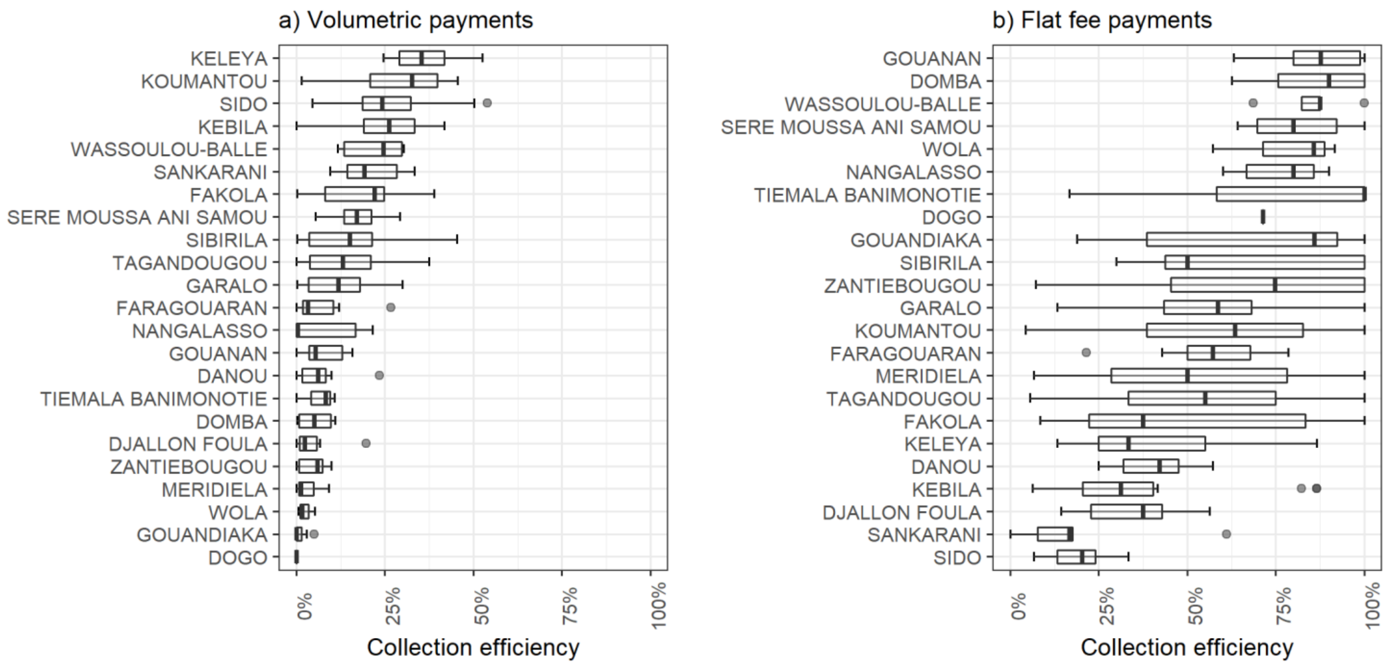

Figure 6-3. Collection efficiency per payment modality across 23 municipalities. a) displays collection efficiency for volumetric payments, b) for flat fees. Box plot present: median (centre line), upper and lower quartiles, interquartile range whiskers, outliers.

Tracking payment collections over time (Figure 6-4) reveals variation across months and localities. From the outset, the compliance with the volumetric approach is low and on average never exceeds 50%, illustrating the challenge of enforcing volumetric payments when users must invest in time and physical effort for accessing water (Foster, 2017; Foster et al., 2020; Jones, 2013). Collection efficiency for flat fee payments remains more stable throughout the first year, averaging around 75%. Flat fee payments, however, register a downward trend since the onset of the rainy season in July 2022. Examining the data up to April 2023 shows that the declining trend reduces. Yet, uncertainty about the future evolution prevails, requiring further monitoring. In terms of unlocking user payment, regression results suggest that the flat fee approach performs better than the volumetric modality in the period of this study (Table 6.1, Model 8).

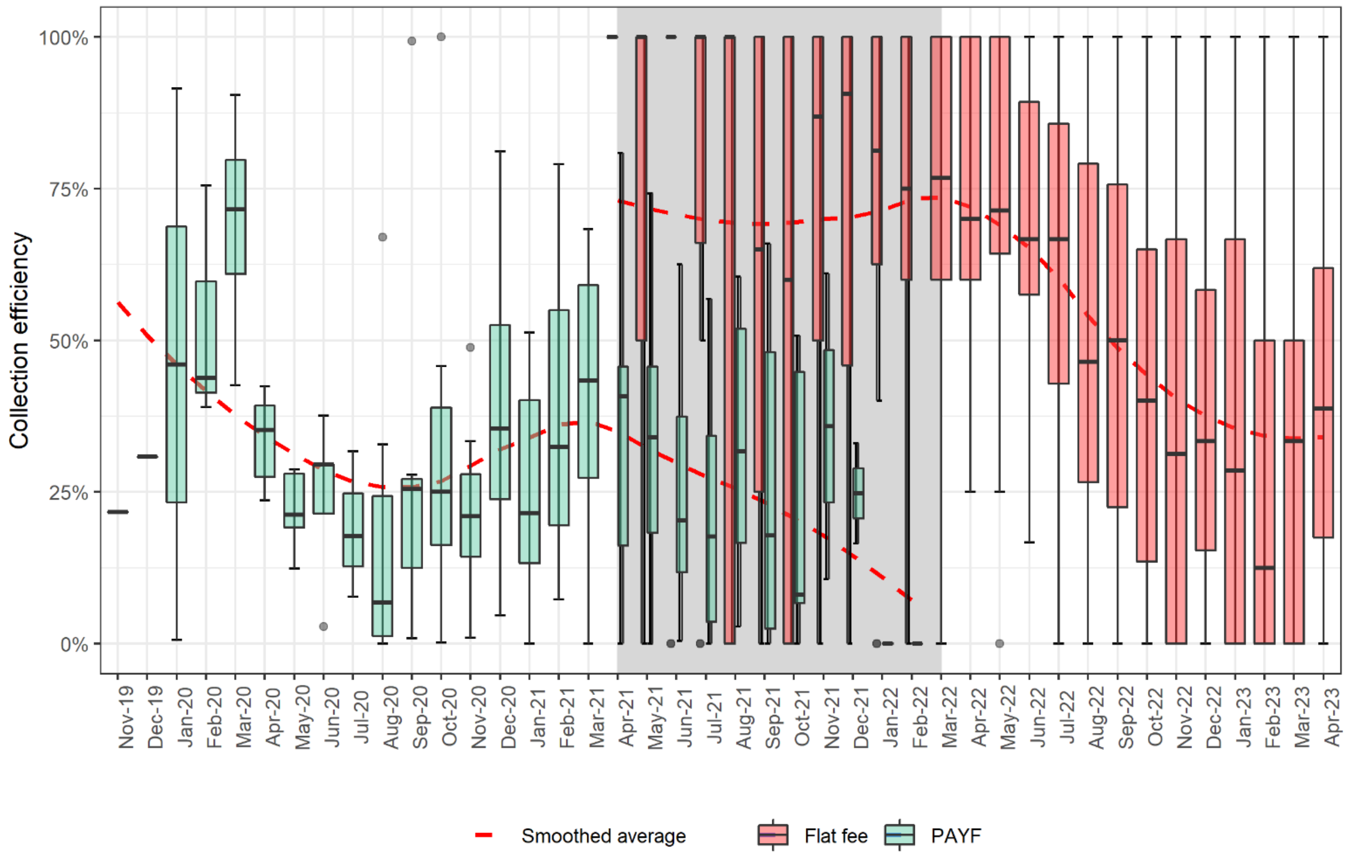

Figure 6-4. Monthly collection efficiency aggregated by municipality, separating between payment modalities. Box and whisker plots (centre line, median; box limits, upper and lower quartiles; whiskers, 1.5x interquartile range; points, outliers). Dashed line for mean per payment modality. Shaded area highlights the period of the payment modality transition (April 2021 to March 2022).

6.2.3 Flat fees generate higher monthly revenues, lowering subsidy requirements

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

Month-on-month comparisons (Figure 6-1 b)) reveal the seasonal variation in monthly revenue. When payments are based on volumetric usage, revenues reflect the seasonal variation in water demand. Under the volumetric approach, some waterpoints generate revenue peaks aligning with peaks in water demand during the annual hot seasons (the highest monthly revenue generated at an individual waterpoint under the volumetric modality was $163, registered in May 2021). However, on average, the volumetric modality registers a consistently lower revenue compared to the flat fee approach throughout the year.

Fixed-effects regression results indicate that average monthly revenue per handpump is driven by the flat fee modality (Table 6.1, Model 4). When controlling for seasonality, the flat fee modality is associated with an increase of $9.37 in monthly revenue per waterpoint. Furthermore, we estimate that a 1°C rise in monthly temperature is associated with $0.82 more revenue per waterpoint.

While flat fees do not translate into single high-performing waterpoints, they provide a considerable contribution to the total revenue generated per month. The gradual shift from volumetric to flat fee payments translates into an increase in total monthly revenue for a comparable number of active waterpoints (Figure 6-5). Starting operations in late 2019, UDUMA progressively deployed its service model to handpumps located in its service area throughout 2020, to achieve a scale of around 100 handpumps in early 2021. The total number of actively paying waterpoints per month (Figure 6-5 a)) stays relatively stable between February 2021 until July 2022. Following a general downward trend in waterpoints registering payment activities, reflecting the decreasing performance in collection efficiency for flat fees (Figure 6-4), the total monthly revenue is declining, too (Figure 6-5 b)). Importantly, the total monthly revenue generated through flat fee payments since the rainy season 2022 equals the revenue registered under the volumetric modality during its best-performing period (April and May 2021), and this despite a 50% reduction in the number of actively paying waterpoints (Figure 6-5 a)).

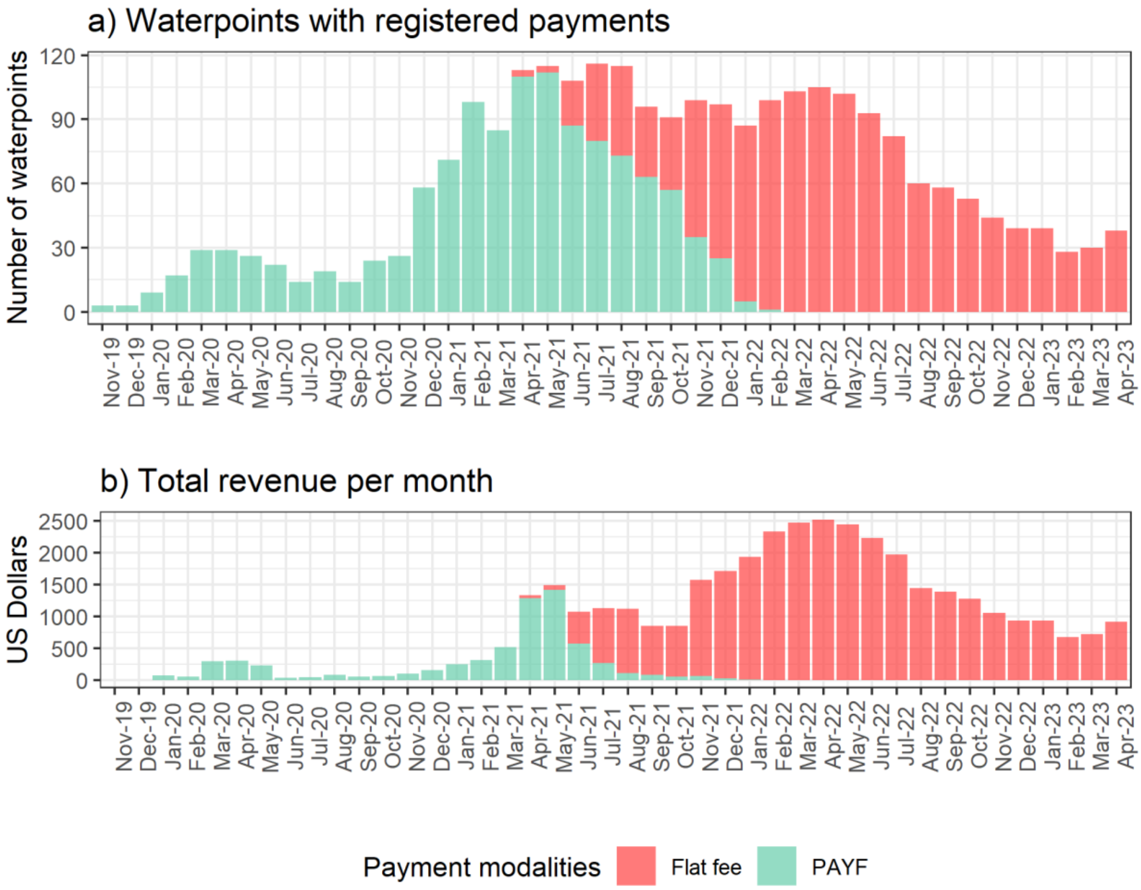

Figure 6-5. Scale of payments and total revenue. a) Number of waterpoints per month registering a payment activity. b) Total revenue generated per month. Bar plots separating between payment modalities. Total of 4,413 monthly observations between 2019 to 2023 across 177 waterpoints.

Similar to revenue, the average working ratio improves under the flat fee modality (mean: 53.5%, SD: 49.8%) compared to volumetric payments (mean: 14%, SD: 41%). Following the change in payment modalities, the share of local operational costs covered through local revenue improves by 39% when controlling for temperature and rainfall (Table 6.1, Model 6). This result is driven by the increase in monthly revenue generated through flat fee payments. Finally, working ratios are evolving over time, reflecting that volumetric payments translate into seasonal cost recovery peaks, whereas the working ratio for flat fee payments experiences a similar downward trend as collection efficiency (see Figure 6-4).

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

6.3 Discussion

Three findings from our study may contribute to delivering more sustainable rural water services amidst increasingly uncertain climates. First, drinking water use at handpumps is influenced by seasonal and contextual drivers across both payment modalities. Second, flat fees are more effective in funding professional handpump maintenance services than a volumetric approach, with implications for subsidy design. Third, professional service delivery models can guarantee rural drinking water supplies are reliable and provide performance data with relevant insights for policy and practice.

First, there is evidence that higher temperatures increase average water demand. Various empirical studies reveal such patterns for urban utilities around the world (Breyer and Chang, 2014; Rasifaghihi et al., 2020; Ziervogel et al., 2010). We find similar patterns of behaviour in rural Mali and estimate that a one degree increase in monthly temperatures increases daily demand by 180 litres per handpump. Unlike urban utilities (Krueger et al., 2019; Larsen et al., 2016), rural waterpoints are not supported by a network of storage infrastructure but are constrained by the capacity of the waterpoint to lift or pump groundwater. With handpumps often limited by around 1,000 litres per hour, the risk of failing to meet local demand in extended dry periods is increased.

The seasonality of waterpoint demand is clearly shown in our study. Across both payment modalities, dry season demand is far greater than during the wet season when alternative water sources become available, which are often favoured by rural people (Mu et al., 1990). These insights are consistent with previous findings from Kenya, Ethiopia, Ghana, Rwanda, and Uganda on seasonal interactions of water demand with temperature peaks and rainfall (Armstrong et al., 2022; MacAllister et al., 2020; Thomas et al., 2019; Thomson et al., 2019). Demand for waterpoints in the dry season is further complicated by non-drinking water demand by livestock, small businesses, and other productive uses (Elliott et al., 2019; Wagner et al., 2019; White et al., 1972). In such periods of high demand where multiple water uses intersect, handpumps come under extreme pressure, emphasising the importance of adapting rural water services to climate risks.

The value of the measured water consumption data from Mali is that it reveals these patterns and peaks to inform policy and practice. For example, demand varies spatially, and future infrastructure investment may target locations under pressure as a priority. Equally, professional service providers ensure services are reliable in the dry season, for which they are held accountable, and thus can contribute to building resilience to the impacts of climate change (WHO et al., 2022). Finally, understanding consumption patterns and payment behaviours may help to define appropriate subsidies.

Second, a subsidy is required for most rural water service providers except those targeting a few waterpoints in high density, relatively wealthy areas with limited water alternatives (Hope et al., 2020; McNicholl et al., 2019). The more taxing policy question is to determine an appropriate subsidy level which is affordable for a service level demanded by the population. Generally, tariff design in most rural contexts is a political decision based on limited or no data (Fuente, 2019; Nauges and Whittington, 2017; Whittington, 2003). Here, we are unable to provide a detailed affordability analysis, but we can chart the challenges of collection efficiency and potential responses.

The shift from volumetric to flat fee payments offers some insights for policy and practice. The considerable increase in water consumed and revenue collected in the short term of the study suggests a user preference for flat fees. However, monthly flat fees are not a “one-size-fits-all” approach to effectively collect user payments in all contexts given the revealed variability in collection efficiency across municipalities. Previous research (Foster, 2017; Jones, 2013; Koehler et al., 2021, 2015) shows that payment approaches and their respective revenue collection performance vary across local contexts due to multiple factors, such as the availability of alternative sources, user population size, social dynamics, and related coordination challenges, or established practices at the community level where multiple revenue collection approaches are likely to co-exist. Identifying which specific local characteristics affect collection efficiency across payment modalities could offer valuable insights for policy and practice and may ultimately inform rural water services that more adequately cater for local contexts.

In addition, performance in collection efficiency across both payment modalities registers a downward trend, leading to declining revenues over time. While we can only speculate on the drivers for this behaviour in our analysis, findings from other studies suggest that sustaining payments at handpumps is challenging as service levels require users to invest in time and physical effort to pump water (Foster et al., 2020; Jones, 2013; Katuva et al., 2016; Smith et al., 2023).

Nevertheless, the combined change in water used and payments made indicates a volumetric tariff is socially unacceptable for reliable rural water supplies delivered through handpumps, emphasising that tariff designs which are considered effective and efficient for urban areas may not necessarily respond to the specific challenges characterising rural water. Importantly, our insights on quantities of water used reflect similar findings from rural Kenya where volumetric payments result in lower income groups reducing water usage (Foster and Hope, 2017). Further research at the household level should assess the implications of payment modalities on water demand, with water user diaries being a potential method of investigation (Wutich, 2009).

The short-term effect of the switch from volumetric to flat fee payments is a 40% reduction in the subsidy required for local operating costs at handpumps. Assuming this trend holds, at scale, this effect is substantial with the positive social multipliers of higher volumes of water being consumed with likely health and welfare benefits (Prüss-Ustün et al., 2019). While groundwater resources need to be correctly managed and monitored, the volumetric increase in usage will have limited impact on the groundwater resources (MacAllister et al., 2022; MacDonald et al., 2021).

Our third reflection is on the role of professional service delivery providers. UDUMA is one of an emerging cohort of professional operators which is offering a utility-style service model based on performance metrics (McNicholl et al., 2021, 2020, 2019; Nilsson et al., 2021). Professional service providers are not necessarily private companies and may be social enterprises or NGOs (Cord et al., 2022; Lockwood, 2021, 2019). As in this case, they have incentives to develop more effective delivery by adapting their business models. Here, we see the change in payment modality as a means to increase local revenues for reliable service provision. There are checks and balances in this professional approach with UDUMA being effectively regulated through contractual agreements with government oversight (REAL-Water, 2022b; van der Wilk, 2019).

The performance data provided by professional service providers can support governments in having a clearer understanding of service provision. As noted, such insights reveal the seasonal patterns of water use which may influence what infrastructure investments may be appropriate. As capital investments for drinking water supplies are expected to increase in sub-Saharan Africa (International High-Level Panel on Water Investments for Africa, 2023), evidence is needed to guide their allocation and to ensure investments are effective over time. It is now more clearly documented that in comparison to professional service providers repairing failed waterpoints in a few days, communities can take months to complete repairs (Foster et al., 2022, 2020; Hope, 2015), and that effectively maintaining existing infrastructure is cheaper than rehabilitating run-down assets (Convergence, 2021; Smith et al., 2023).

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

6.4 Conclusion

We have shown the implications of two prominent payment modalities for reliable rural water services on use and payment behaviours at handpumps in rural Mali. Our results indicate that flat fee payments contribute substantially to funding reliable service provision and stimulate water use. Yet, subsidies are still required to ensure rural people access safe water throughout the year. Increasing efforts in adaptation finance (UNEP, 2022) may constitute an opportunity for addressing the subsidy gap for vulnerable rural water users. As our findings from Mali suggest, successful adaptation remains conditional on professional service delivery. Therefore, we propose linking infrastructure provisions with clear service delivery approaches to deliver more sustainable outcomes. While this would mean changing current practices, it would guarantee that infrastructure investments are effective for those facing the greatest climate risks in rural Africa. Finally, we emphasise that our empirical evidence is not based on a formal experiment and that our data are constrained by the period of the study and only cover handpumps. Therefore, it is unknown how our findings will hold over time and whether they may apply to other types of infrastructure, such as piped-water systems and kiosks, which are expanding in sub-Saharan Africa. While future trends of use and payment behaviours remain unclear, the value of performance data is that it enables policy, practice, and research to track these, and thereby provide an evidence base for more effective policy design and rural water service delivery.

6.5 Methods

6.5.1 Study context

The study site comprises the Region of Sikasso, located in south of Mali. The study utilises data from UDUMA Mali, a private company, providing reliable rural water services in 30 rural municipalities, the lowest governmental level in Mali's administrative structure (van der Wilk, 2019). Payment modalities, service levels, and volumetric tariffs are formally established in management contracts signed between UDUMA and local governments as service authorities. The provider delivers reliable maintenance services, guaranteeing high infrastructure uptime with short breakdown durations (less than 72 hours).

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

The volumetric "pay-as-you-fetch" approach initially required users to make direct payments to a caretaker at the handpump for every 20-litre container collected. The caretaker is a member of the local community, recruited and trained by UDUMA to collect volumetric payments and report any functionality issues to their supervisors. While formally agreed in contracts signed between UDUMA and local governments, the volumetric payment principle encountered enforcement challenges early on. Caretakers were not able to consistently enforce volumetric payments from users which could collect water without paying the required volumetric amount.

To address unstable payment collections at handpumps, UDUMA introduced a monthly flat fee per handpump, with no limit on water use. The change in payment modalities was introduced within existing contractual arrangements with local governments and communities. The flat fee payment approach stipulates that if the flat fee is not paid, the UDUMA service is not activated, and the pump is locked until a payment is made. Service area managers collect the monthly fee upfront from a representative of the user community which self-organises to collect the flat fee amount. This shifted the responsibility for payment enforcement from local waterpoint caretakers to service area managers.

6.5.2 Data collection, availability, and variable definition

The analysis is based on monthly use and payment records registered at individual waterpoints from November 2019 to April 2023. A total of 4,447 monthly records across 177 unique waterpoints, situated in 23 municipalities, is available. The 177 individual waterpoints are never operational simultaneously due to UDUMA's gradual extension of its service model to the waterpoints located in its service area and non-payments of monthly flat fees. Given that operations of the identified waterpoints started at different time periods, the panel dataset is unbalanced.

For every individual waterpoint, at least two monthly volumetric use and payment records per payment modality are available. Data cleaning on volumetric use records was conducted to remove potentially faulty meter readings. After confirmation with UDUMA staff, daily use levels were capped at $11m^3$ per waterpoint, removing a total of 34 monthly observations (more detail provided in Supplementary Information under Supplementary Methods, section 6.6).

The final dataset consists of 4,413 monthly observations, separated in 1,885 monthly records under the volumetric modality, 2,528 observations for monthly flat fees. Given this set-up, the analytical strategy of the paper explores how users respond to reliable maintenance services under different revenue collection approaches. We assess four outcomes of interest before and after the change in payment modalities (Table 6.2). Summary statistics for the outcomes of interest across the payment modalities are provided in the Supporting Information (Supplementary Table S6.1).

Table 6.2 Definition of outcomes of interest

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

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

The monthly working ratio provides information on cost recovery per waterpoint per month and is calculated as the share of recurring operation and maintenance costs covered through local revenue. UDUMA estimates that recurring local operation maintenance costs are of $24 per month and per waterpoint. UDUMA's local operation and maintenance costs include local human resources (remuneration of local technicians and supervisors), transport costs, costs for spare parts, water quality monitoring and repairs, and an annual fee paid to local governments. In WASHCost terminology (Smits et al., 2011; WASHCost, 2012), these costs include both operations and maintenance expenditure (OpEx) and expenditure on direct support (ExpDS). Other costs, such as Capital Expenditure, Capital Maintenance Expenditure, Cost of Capital, overheads for local administration and office costs or international project administration and management are excluded.

The metric of collection efficiency represents the ratio of expected to actual revenue collected in a month per waterpoint and is established separately for each payment modality. For volumetric payments, collection efficiency is calculated as the ratio of volume of water paid divided by the volume of water billed in a month per waterpoint. For flat fee contributions, the metrics reflects whether a flat fee was paid or not in a given month per waterpoint.

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

Recognizing that changing climatic conditions may influence user behaviour (Armstrong et al., 2021; MacAllister et al., 2020; Thomas et al., 2019; Thomson et al., 2019), the longitudinal approach includes total amount of rainfall in a month and monthly average temperature estimates for each municipality for the period under investigation. Rainfall data was retrieved from Tropical Applications of Meteorology using SATellite data and ground-based observations, TAMSAT (Maidment et al., 2017, 2014; Tarnavsky et al., 2014), whereas temperature data was generated using Copernicus Climate Change Service information(Copernicus Climate Change Service, 2019).

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

6.5.3 Specification of the fixed-effects regression model

As indicated, the introduction of the change in payment modalities is not random but has been gradually rolled out by UDUMA to its entire handpump portfolio, generating observational data. In most non-experimental social science research individual units differ in so many respects that it is impossible to control for all of them. Fixed effect models using panel data allow to mitigate this limitation by comparing within unit change instead of estimating effects from a comparison between different units (Best and Wolf, 2014; Henningsen and Henningsen, 2019; Wooldridge, 2010). Therefore, we apply fixed-effects regression models to the longitudinal dataset to estimate the significance of the change in payment modalities on the response variables. Since each individual handpump is observed over multiple time periods, our models exploit the within variation per unit (each waterpoint is observed over multiple months under the two payment modalities). Fixed effect models allow the presence of arbitrary correlations between unobserved individual effects and covariates, and control for these unobservable factors to alleviate omitted variable bias (Best and Wolf, 2014; Cunningham, 2021; Wooldridge, 2010).

Similar to Kulinkina et al.(2016), we include observed time-variant confounders (rainfall and temperature data) to capture seasonal variation and entity fixed effects for each waterpoint. This strategy allows to avoid omitted variable bias arising from unobserved factors at the waterpoint level that are time-invariant, such as localised community practices or the number of alternative water sources surrounding the respective waterpoint. Therefore, the unique waterpoint ID number is included as a constant intercept in the regression model allowing to control for waterpoint-level heterogeneity. This removes the effect of time-invariant characteristics at the waterpoint level, and accounts for seasonal confounders (climate metrics) to estimate the effect of the main predictor, the change in payment modalities, on the outcome variables. We report robust standard errors, clustered at the waterpoint level, to account for autocorrelation occurring between periods within each unit (Abadie et al., 2022; Cameron and Miller, 2015). All statistical analyses were conducted in R (Version 4.0.3).

6.6 Supplementary File (Chapter 6)

Supporting Information for

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

This file includes:

Supplementary Methods

Supplementary Table S6.1

Supplementary Methods

a) Data availability and summary statistics for dependent variables

A total of 4,447 monthly records across 177 unique waterpoints, situated in 23 municipalities, is available from November 2019 to April 2023. Data cleaning on volumetric use records was conducted to remove potentially faulty meter readings. The average hourly flow rate of the handpumps is estimated at 1 m^3. Supposing that waterpoints are only used during the day (14 hours), daily volumetric water usage higher than 11m^3 per waterpoint was deemed unlikely given an estimated time of 90 seconds to fill a 20 litres jerry can. Applying the cap threshold of 11 m^3, a total of 34 observations was removed. The final dataset consists of 4,413 monthly observations, separated in 1,885 monthly records under the volumetric modality, 2,528 observations for monthly flat fees.

Supplementary Table S6.1 (A to D) presents summary statistics across the four outcomes of interest, separating between payment modalities. The dependent variables are daily volumetric use (m^3), monthly revenue ($), monthly working ratio (%), and monthly collection efficiency (%) per waterpoint.

b) Supplementary Tables

Supplementary Table S6.1 Summary statistics for outcomes of interest across payment modalities

- **A) Daily volumetric use, m³**

Metrics	PAYF	Flat fee
Mean (SD)	0.84 (1.48)	1.74 (2.26)
Median	0.18	0.81
Min	0	0
Max	10.98	10.96
Monthly observations (n)	1885	2528

- **B) Monthly revenue, US$**

Metrics	PAYF	Flat fee
Mean (SD)	3.42 (9.78)	12.85 (11.97)
Median	0.06	24
Min	0	0
Max	163.43	24
Monthly observations (n)	1885	2528

- **C) Working ratio, %**

Metrics	PAYF	Flat fee
Mean (SD)	14% (41%)	53.5% (49.8%)
Median	0%	100%
Min	0	0%
Max	100%	100%
Monthly observations (n)	1885	2528

- **D) Collection efficiency, %**

Metrics	PAYF	Flat fee
Mean (SD)	29% (37%)	54% (50%)
Median	11%	100%
Min	0	0%
Max	100%	100%
Monthly observations (n)	1885	2528

Chapter 7: Conclusion

This research has been motivated by the persistent challenge to deliver drinking water services in rural Africa that effectively promote operational and financial sustainability. To address gaps in current understanding of rural water sustainability, this thesis has examined how contract design and consumer demand affect revenue generation to sustain the professional delivery of rural drinking water services.

Using a mixed-methods approach, the thesis has provided an in-depth study of a professional service delivery model operating in rural Mali. The particularity of the UDUMA case lies in its commercial approach, involving significant private investments facilitated through long-term contracts established between the service provider and local governments. UDUMA's model thus represented a relevant study case to investigate whether and to what extent long-term contracts with a professional service provider are an effective mechanism to deliver desired rural water outcomes, expected to be sustained through user payments.

Although this case study does not attempt to provide generalisable conclusions, several cross-cutting findings and overarching considerations are identified that may apply to other decentralised governance contexts where professional service providers are contracted to deliver rural water services and users are expected to pay for the services they receive (Section 7.1). The findings nuance common assumptions that guide current rural water policy and practice in sub-Saharan Africa and may ultimately inform more realistic policy approaches (Section 7.2). Based on the research's approach and insights, directions for future research are suggested in Section 7.3.

7.1 Findings and contributions in relation to contract design and consumer demand

The main contribution of this work lies in the empirical application of contract and consumer demand theories to a contract-based model for rural water services delivery to understand both the process and consequences of changes to service arrangements on revenue outcomes. By integrating quantitative and qualitative analyses, the research provides new insights into how contracts evolve and perform over time, and how consumer demand is related to specific service attributes with associated revenue implications. The conceptual and empirical findings pinpoint to what should be thought about when designing rural water service contracts.

Finding 1 – Contract adaptation to navigate uncertainties

As demonstrated, UDUMA's long-term contracts were instrumental in setting-up its service model at scale and attracting initial investments. It was only during contract implementation that the incompleteness of UDUMA's contract design became observable to the parties involved. Under the initial model applying volumetric payments at handpumps, UDUMA faced a contractual breakdown as users did not comply with their obligation to pay. In addition, volumetric water use was on average four times lower than expected, further limiting revenues.

Formal contracts are often based on stable assumptions throughout the year and for multiple years ahead. This "stability assumption" of long-term contracts, similar to other medium- and long-term planning exercises (Flyvbjerg et al., 2005; Therkildsen, 1988), likely misses the complexity and uncertainties characterising rural water, such as variability in demand across seasons and sites. As the thesis reveals, contract renegotiation can be an institutional mechanism to respond to gaps between expected and actual performance by acting upon new operational knowledge from implementation. Hence, rural water service contracts require adaptability mechanisms to effectively deal with inherent uncertainty and unpredictability of user demand.

In UDUMA's case, observed data on consumer behaviour was valuable in informing renegotiation of and adaptations in contract design, stipulating changes in specific service attributes. Considering drinking water as a composite good, the thesis exploited these changes to generate new empirical knowledge about the relationship between service attributes, user demand, and revenue generation, providing useful insights for policy design and service delivery practice.

The empirical analyses show that demand is affected by the level of service consumers receive and the costs they face. In line with what consumer demand theory would suggest, rural water user behaviours change when services are made more attractive. Notably, users appear to be more inclined to pay a volumetric tariff at solar kiosks, significantly improving revenues (Paper 2). Qualitative evidence suggests that the higher convenience associated with improved service levels drives user acceptance to pay a PAYF-tariff at solar kiosks (Paper 1), whereas PAYF tariffs at handpumps are effectively rejected by users in Mali, as indicated by combined insights emerging from Papers 2 and 3. In addition, the flat fee modality allows UDUMA to ensure a stronger contract enforcement, as the responsibility for payment collection shifted from local caretakers to the more removed service area managers (Paper 1).

Yet, the ability to revise contracts and to adapt services is only a partial response to uncertain demand. Due to the non-exclusivity of rural water, contracts cannot offer exclusive service areas as people have alternatives with which UDUMA competes for scant revenue. Even with higher service levels provided at solar kiosks, average water consumption does not increase, tempering revenue streams (Paper 2). Service improvements are hence not a definitive answer to complex variability in demand, nuancing policy assumptions regarding the sustainability of solar kiosks. While monthly flat fees appear to stimulate water use and can increase the enforceability of the contractually agreed payment principle by shifting the responsibility for payment collection from local caretakers to service area managers, the downward trend of revenues at handpumps persists (Paper 3). This leaves a question of policy relevance which will be discussed further in section 7.2: what to do with handpumps given that revenues are low and uncertain?

The case study demonstrates that a contract is essentially an instrument that can be navigated to get to specific outcomes. However, the effectiveness of such an instrument in regard to achieving specific results depends on the behaviours of the parties involved. Here, the research highlights a structural limitation of UDUMA's model which is likely to hold in most contractual models for rural water services.

Finding 2 – Structural incompleteness of contractual models for rural water service delivery

UDUMA's model is based on the implicit assumption that local governments sign the contract on behalf of users. This principle inherent to the delegation of service delivery functions is widely established in rural water (Section 2.2). However, formal contracts between service providers and local governments are unlikely to enforce rural water users to behave as planned.

While individual users are expected to provide the revenue necessary to sustain the service model, they are not formally involved as a direct party to the contract. Therefore, the model is structurally incomplete. The community agreements established between UDUMA, local governments, and representatives of communities do not address this limitation (Paper 1). Consumers can express their agreement or disagreement with the contract and associated service delivery arrangement through their water use and payment behaviours: they can decide to use the service or not, and to pay for the service or not.

Municipalities, as the formal contract party, cannot enforce or guarantee that individual users meet their contractual obligations, particularly in terms of payment for services. This is amplified in weak institutional environments, where the state does not offer effective mechanisms of contract enforcement and oversight. This issue leads to interrogate whether there is a way to formally include individual consumers to contracting arrangements underlying professional rural water service delivery models, and to what extent a formal relationship between the operator and the customer, for instance through a direct supply contract, would change matters.

Even though piped drinking water coverage has only been expanding slowly in rural Africa over the last decade (UNICEF and WHO, 2023, 2022), individual household connections may allow to establish direct supply contracts between a service provider and end-users. This may be a mechanism to clarify contractual obligations and rights, and may facilitate payment enforcement and contract monitoring through metering. However, individual supply contracts governing on-premises water supplies are unlikely to address the issue of non-exclusivity and uncertain demand. Rural households draw on multiple water sources regardless of which infrastructure type is concerned (Cronk et al., 2024; Elliott et al., 2019), resulting in unpredictable revenue variability (Armstrong, 2022).

Formal contracts between service authorities and professional service providers establish a basis for accountability for performance and service outcomes but cannot guarantee that the service will actually be demanded by consumers. On the other hand, the status quo of not having a contract would likely mean that the current sub-standard performance of rural water services endures as informal community-based management does not deliver on expected outcomes.

The lack of effective user demand is thus the fundamental barrier for rural water sustainability. While the institutional arrangements underlying professional service delivery models can be designed to guarantee service outcomes, user demand, that could turn such models into an effective '*solution'* for rural water, cannot be designed. Strategies to create and sustain consumer demand for rural water services are hence needed. While this thesis provided some insights on how specific service adaptations affect demand and revenue generation, uncertainties persist, and open questions remain which future research could investigate (see Section 7.3).

This finding has important implications for rural water service delivery models whose viability depends on full-cost recovery from users. In the case of market-based consumer goods, a good not demanded by consumers would effectively disappear from the market (Lancaster, 1966a). Drinking water, however, is different.

Finding 3 – Limits of commercial contracts for rural water

UDUMA pursues an approach based on full cost recovery through user payments and aims at generating a profit margin. UDUMA's case demonstrates that long-term contracts can attract commercial finance to rural water by de-risking investments into markets that have historically been seen as risky ventures. These contracts provided room for innovation so that service levels meet consumer demand, enhancing revenues. But the long-term contracts are no guarantee for providing financial returns on investment.

Increasing service levels required engaging in partnerships with other stakeholders not involved in the initial contracting model. A philanthropic foundation invested in a calculated risk with no financial return that kiosks would increase revenue and water volumes. The former was true, the latter not (Papers 1 and 2). Financial returns on investments and full cost recovery for rural water services remain unlikely, mainly due to uncertain demand and non-exclusivity. Seasonal revenue variability at solar kiosks and a downward trend in revenue performance at handpumps regardless of which payment modality is applied emphasise the limits of a pure commercial contract. Therefore, subsidies to fund initial infrastructure investments remain necessary for rural water, as full cost recovery is unlikely. In addition, when user payments do not cover recurring service costs, subsidies are needed to sustain operations (Paper 3).

A recent study on the prospects of rural drinking water services in francophone West Africa finds that "operators will be able and interested in providing rural water services if the financial viability of the services to be delegated is ensured, and risks are adequately shared between the operator and the delegating authority" (REACH and RWSN, 2023, p. 24). UDUMA's case showed that the allocation of financial risks was unbalanced. Without the flexible funding from the foundation and the ability and willingness of UDUMA's holding company to cover financial losses, contract termination was the likely outcome as the model was not financially viable. The findings of this case study highlight the limits of a commercial approach for rural water services.

While rural water may not be a perfect market case since financial returns of investment are unlikely, the social returns and collective benefits of investing in professional rural water maintenance are high (Foster et al., 2022; Thomson et al., 2024). These insights have implications for policy and practice, pinpointing to the importance of flexible financial arrangements and partnerships to attract capacity to the rural water sector and to support progress towards viability.

7.2 Implications and recommendations for policy and practice

The detailed analysis of the UDUMA case allows for nuancing policy assumptions prevalent in the rural water sector. The empirical insights from Mali may hold value for designing more realistic policies and may help avoid planning fallacies in other service delivery contexts. Based on the reported evidence, the thesis offers three overarching recommendations to steer policy and practice towards more sustainable rural water services:

- **Recommendation 1:** Invest in incremental progress from basic to intermediate service levels.
- **Recommendation 2:** Recognise and leverage the value of continuously collected operational and financial service data to inform policy, investment planning, and service delivery practice.
- **Recommendation 3**: Develop more pragmatic cost-recovery policies that recognise the need and adequately plan for subsidies to sustain rural drinking water services.

Yet, there is an important caveat to these recommendations. A complex challenge like rural water sustainability is unlikely to be addressed through a one-size-fits-all approach (Foster et al., 2020; Meinzen-Dick, 2007). Professional service delivery models have to be designed in light of the complex socio-economic, cultural, and environmental contexts in which they operate. Since countries possess a unique blend of legal systems, policy frameworks and goals, and levels of rural development, it is not possible to put forward a single approach that would solve all problems at once. Therefore, the subsequent recommendations illustrate lessons learned from this case study and make them relevant to other contexts by identifying key elements that require consideration when setting-up and implementing professional water service delivery models in rural areas.

Implication 1 – Invest in sustainable infrastructure

The research finds that service improvements through infrastructure upgrades can make a service more attractive to consumers, thereby bolstering payment behaviours and enhancing revenue performance of professional rural water services (Papers 1 and 2). In stark contrast to the initial payment performance at handpumps, solar kiosks under UDUMA's management register steady payment collections in the period of the study and generate up to four-times higher average revenues per month. Furthermore, the observed payment collections and revenue performance at UDUMA-managed handpumps regardless of which payment modality is applied (Paper 3) confirm findings from earlier studies in Kenya (Koehler et al., 2021) and Uganda (Smith et al., 2023), demonstrating that actual payments diminished over time, undermining the long-term sustainability of these handpump maintenance services. These findings collectively indicate that user payments and revenue outcomes are not only related to the quality of the services delivered by professional service providers (e.g. high reliability, fast repairs, short breakdown durations, water quality monitoring) but intrinsically depend on the level of service by design.

The research's insights challenge the appropriateness of rural water policies, programmes, and projects focusing merely on the number of people reached by providing access to basic services. UDUMA, supported by Dutch donor funding, initially invested in a least-cost approach by deploying handpumps at scale, while subsequently guaranteeing reliable O&M services. This strategy did not achieve intended results, questioning the effectiveness of investing in handpumps when alternative rural water supply options are likely to deliver a better outcome in sustaining services. Even though infrastructure providing higher service levels are more capital intensive than handpumps (Armstrong et al., 2017; WASHCost, 2012), rural water investments should more explicitly target infrastructure that creates added value for water users, translating into improved payments and higher revenues, which is fundamental to secure investments over the longer term.

However, upgrades from handpumps to solar kiosks are unlikely to address the various uncertainties characterising rural water. Solar kiosks are found to be affected by seasonal and contextual water use dynamics, leading to variable revenues (Paper 2). Evidence from this research (Paper 1) and other studies (Mu et al., 1990; Van Houtven et al., 2017) suggests that users would prefer additional service level improvements, e.g.: individual household taps. One resulting empirical question is whether private taps would actually increase demand and revenues. Armstrong et al. find that piped water systems are subject to "seasonal revenue reductions regardless of whether services are provided on or off premises" (2022, p. 1), tempering expectations that supplying water to the homestead would overcome seasonal demand and revenue variability.

Recommendation 1: *Invest in incremental progress from basic to intermediate service levels.* In light of the research findings and wider evidence, the thesis recommends to policymakers, investment planners, donors, and service providers to invest in improving service levels by design (e.g.: kiosks and public standposts) to meet consumer demand and enhance revenues. Prioritising incremental progress from basic to intermediate service levels seems suitable to meet increasing user aspirations and achieve social impact as more people can be served through off-premises supplies compared to private household connections. Nonetheless, this recommendation recognises that improved infrastructure is not a panacea to rural water challenges and that handpumps are likely to remain essential for supplying drinking water to sparsely populated areas (Danert, 2022; Foster et al., 2020; MacArthur, 2015; REACH and RWSN, 2023).

The research emphasises that infrastructure must be adequately managed to deliver an agreed standard of service. This in turn may require a shift in political prioritisation from installing hardware in pursuit of coverage targets, to a longer term commitment to sustainable water service delivery. Linking investments to clear service delivery arrangements may be a mechanism to guarantee that infrastructure effectively delivers on its intended results. Here, contracts with professional service providers are a tool which can be applied to a portfolio of different waterpoint types, as illustrated by the introduction of solar kiosks in UDUMA's case.

Implication 2 – Recognise wider benefits and limits of professional service delivery models

Professional service providers can bring technical expertise and new investments to the rural water sector, contributing to addressing urgent policy challenges. In addition to ensuring that water keeps flowing, service delivery arrangements involving professional providers can offer wider benefits for policy design and decision making in the rural water sector.

Effective investment planning and designing service delivery models requires reliable and accurate data. Conducting precise demand forecasts remains a fundamental planning challenge – even in well-organised sectors in the Global North where reliable data are more readily available (Flyvbjerg et al., 2005). In rural Africa, reliable data on water demand generally remains scarce (Nauges and Whittington, 2010), negatively impacting the sustainability of many rural water supply investment programmes (Therkildsen, 1988). The lack in empirical data on observed water usage and payment collection is likely to lead to unrealistic revenue projections supposed to sustain services. For instance, UDUMA's model assumed a higher water usage for cost recovery which has not occurred.

Operational and financial service data continuously generated through professional service providers may hold the potential to contribute to closing such information gaps, track actual service performance, and inform investment decisions more objectively. For example, a basic handpump can generally provide a supply of water of $1m^3$ per hour. If data demonstrate that demand in the driest periods is substantially higher, infrastructure with higher production capacity, such as kiosks, may be required. Without empirical evidence, the design of policies and service delivery arrangements, and the allocation of investments is likely to be based on best guesses or ideology – neither of which are sufficient for financial or operational sustainability.

An additional benefit of empirical data collected at regular frequencies is to provide context-specific information on an enhanced temporal resolution. Resource-intensive nation-wide waterpoint inventories, as conducted in Mali in 2016 (DNH, 2016), are important and necessary for asset management, but do only provide a spotlight on performance for the day of the survey. In addition, such inventories for rural water supply have rarely in-built mechanisms for regular updates, therefore not providing relevant information on actual service delivery performance over time (Katomero et al., 2017). Leveraging data from professional drinking water service providers may allow for more regular updates of national data bases to facilitate planning purposes.

Furthermore, such data may reveal potential equity concerns. As shown in Paper 3, handpumps, regardless of which payment modality is applied, are unlikely to yield a clear prospect towards financial viability. At the same time, a large portion of the rural population in many African countries will continue to rely on handpumps for their drinking water supplies (REACH and RWSN, 2023; UNICEF and WHO, 2023, 2022). Given current cost recovery policies, professional service providers, in particular when following a for-profit approach, may have an incentive to focus on managing infrastructure providing higher service levels instead of handpumps. For example, UDUMA has recently established contracts in Benin and Côte d'Ivoire focusing on kiosks and piped systems (Jumelages&Partenariats, 2022; RIOB, 2023). Hence, there is a danger that remote and dispersed rural populations, which are more likely to depend on handpump supplies, will be left with stagnating service levels and poorly supported community-based management.

To avoid "cherry-picking", policy may need to develop safeguards and incentivise operations of handpumps through professional service providers. For instance, developing service areas with a mixed infrastructure portfolio could reconcile potential conflicts between public service delivery goals and the logic of the market. Here, service provider data, alongside other planning metrics, can be of value in defining such service areas and in designing related service delivery arrangements that encompass various infrastructure types of varying viability potential, including handpumps.

Recommendation 2: *Recognise and leverage the value of continuously collected operational and financial service data to inform policy, investment planning, and service delivery practice.* Professional service delivery models can generate financial and operational data at enhanced temporal and spatial resolution with the potential to reveal and address sustainability issues. This thesis emphasises that data are not a panacea to rural water sustainability but can be a relevant input to designing more objective policies and service delivery models. Policy should leverage data flows generated by professional service providers to both inform the design of potential service delivery arrangements and oversee their subsequent implementation.

Implication 3 – Design more realistic cost recovery policies that recognise the need for subsidies

Finally, based on this research and wider evidence it must be recognised that revenue generated through user payments is unlikely to be sufficient to sustain the professional delivery of drinking water services in rural Africa. Achieving sustainable rural drinking water services likely requires subsidies, and this must be recognised more explicitly in policies and investment approaches.

UDUMA has improved the standard of services in rural Mali by ensuring that handpumps and kiosks work reliably at scale but has failed to achieve cost-recovery goals. Cross-country evidence shows that service providers guarantee that water keeps flowing for millions of rural people but require subsidies to be viable (Lockwood et al., 2021; McNicholl et al., 2019; Nilsson et al., 2021; Smith et al., 2023; Uptime, 2023). This is consistent with urban water, where utilities worldwide depend on subsidies which are in the range of $300 billion per year, excluding both China and India (Andres et al., 2019). So, the question is less to know *if* but rather *how* subsidies can be allocated so they are efficient, effective, and transparent and *how much* subsidies are required so that services can continue as planned.

The issue of subsidy allocation largely relates to the design of an effective institutional mechanism backed by credible data flows. Contracts may facilitate the allocation of subsidies by defining an agreed standard of service with clear performance targets that are tangible, verifiable, and under the service provider's control. Subsidy allocation should prioritise complementing user payments, thereby creating an incentive for providers to enhance revenue collection and to deliver services in line with user demand. In principle, result-based payments are issued once contracted outcomes are demonstrated by data (Andres et al., 2019; Charles et al., 2023; McNicholl et al., 2021). For such mechanisms to work, clear reporting requirements and monitoring arrangements must be in place to ensure accountability. A pragmatic approach may first focus on building robust monitoring systems to track results and support subsidy allocation, with regulatory oversight to be developed in later stages (Gerlach, 2019; World Bank, 2017b).

The subsidy amount required is, however, an empirical question. Data from operators like UDUMA can help identify the funding needed to bridge the gap between what users are able and willing to pay and the real cost of service provision. Based on financial data from professional service providers operating in rural areas of Burkina Faso, the Central African Republic, Kenya, Mali, Malawi, Tanzania, and Uganda, McNicholl et al. (2021) show that user payments roughly cover one third of recurring service costs, and that, on average, a subsidy of less than $1 per person per year is necessary to sustain operations.

Recommendation 3: *Develop more pragmatic cost-recovery policies that recognise the need and adequately plan for subsidies to sustain rural drinking water services.* Governments should revisit the assumption that user payments must cover O&M expenditures for providing rural water services, particularly in the case of handpump maintenance. Considering full lifecycle costs, research from Uganda demonstrates that allocating subsidies to support professional operations of handpumps would be cheaper than assuming that these costs will be covered by users, which, in part, contributes to perpetuating the unsustainable status quo of investment, infrastructure failure, and rehabilitation (Smith et al., 2023).

Policies should hence more clearly identify which share of the costs of service delivery can realistically be covered through tariffs, and which will require funding from taxes or transfers.

While policy in Mali assumes that user revenue will cover recurring costs at handpumps (DNH, 2007, p. 44), Paper 3 reveals that this is not the case for professional service delivery, confirming previous findings from Mali for community-managed handpumps (Jones, 2013). Furthermore, policies should pay attention to the way in which payment modalities are designed. For handpumps, volumetric tariffs do neither seem suitable for promoting revenues nor socially desirable. Flat fees appear to be preferred by users and are more effective in revenue generation but can also constitute a barrier to safe water access when strictly applied (Paper 3). These trade-offs deserve further policy attention and may be mitigated by targeted subsidies.

Developing subsidy mechanisms should prioritise strengthening existing policy instruments. In Mali's water sector, a results-based funding mechanism for rural drinking water services could be set-up at the *Fonds de Dévelopment de l'Eau* (DNH, 2007, 2006; Republique du Mali, 2002), which is supposed to support sustaining investments, particularly by covering long term expenditure for capital maintenance. An opportunity to effectively operationalise payments against results may consist in supporting the existing STEFI (*Suivi Technique et Financier*)-system that monitors various operational and financial parameters of rural water services (DNH, 2007; Gerlach, 2019; REACH and RWSN, 2023). Such data may allow funders to confirm results reported by professional service providers, thereby providing a credible footing for issuing results-based payments, which in turn would contribute to addressing current sustainability challenges.

In the foreseeable future, funding that complements user payments is required to sustain rural water services. The state will likely have to bear a greater responsibility though it is recognised that time paths and priorities will differ from one country to another. A recent review of public spending in the water sector (Joseph et al., 2024) indicates that there may be an opportunity for increased government funding for service delivery by re-allocating non-executed budgets. While such a change requires institutional capacity, it could contribute to a shift from infrastructure provision towards service delivery. Ultimately, demonstrating tangible results at low costs may make it easier for governments to adopt and support professional service delivery models.

7.3 Directions for future research

Across rural Africa, professional service delivery models that provide drinking water services according to an agreed standard are gaining traction. This research has investigated the performance of a professional service delivery company operating handpumps and solar kiosks in rural Mali, generating additional research questions which will be outlined below. Also, this section briefly reflects on the methodology and the science-practitioner partnership underlying the research presented in this thesis.

The methodological strength of the research consists in the collaborative engagement with UDUMA to co-produce knowledge with relevance for policy and practice (Miller and Wyborn, 2020; Norström, 2020). Throughout the investigation, active exchanges with the target institution, which informed research priorities, have been a key pillar of the case study approach. Regular workshops have been organised to share insights, receive feedback, and collectively reflect on the research findings and their implications. To acknowledge this partnership, Papers 2 and 3 have been co-authored with representatives from UDUMA. As such, this research highlights the opportunities that can emerge from bridging the gap between practice and science. Such collaborations should be a more common mechanism for research seeking to generate practical knowledge.

Nevertheless, various improvements could be made in future research, particularly when science encounters the dynamics of project implementation. For example, the introduction of solar kiosks which forms the empirical basis for Paper 2 was not designed as a research project, as UDUMA led the site selection. The ITS design is a robust method and was a pragmatic choice given the available data but has limitations, as presented in Section 3.5. Future research designs in observational settings may be improved by identifying a group of comparable sites in terms of population size, availability of alternative sources, and use and payment records to enable more robust estimations of effects (Lopez Bernal et al., 2018).

The qualitative analysis of UDUMA's model (Paper 1), which involved in-person observational fieldwork in Mali, provided complementary insights on the underlying motivations of users, building confidence in the regression results reported in Papers 2 and 3. This emphasises the value of the case study's mixed-methods approach, where each of the methods has been purposely chosen to build on each other's strengths and close respective blind spots.

Based on the thesis' findings, further research is encouraged to determine whether and to what extent the changes related to specific adaptations in service attributes observed in Papers 2 and 3 hold in other contexts. Given the growing number of professional service providers that are contracted across rural Africa for delivering reliable water services (Nilsson et al., 2021), future studies may replicate how infrastructure improvements or changes in payment modalities affect consumer demand and revenue outcomes. The increasing push towards solar-powered water supplies in rural Africa (Armstrong et al., 2017; Check et al., 2017; REAL-Water, 2022a; UNICEF, 2016; World Bank, 2018), combined with professional service delivery, may open up new research opportunities to gain further evidence confirming or contesting the results reported in this thesis. Besides, it appears valuable for policy and practice to empirically explore the implications of changes to other service attributes on use and payment behaviours and revenue generation. As outlined in Paper 1, SDG 6.1 identifies further service attributes pertaining to water quality, reliability, and proximity, and future research may engage with professional service providers which offer high quality operational and financial data to assess how improvements across these attributes affect water use and revenue outcomes.

Also, additional evidence is needed on the role of contracts in other service delivery contexts. This research explored the effectiveness and limits of long-term contracts in a decentralised governance system where local governments act as service authorities. Investigating the performance of delegation of rural water services in different institutional settings may yield additional policy insights. A recent study found that some countries, such as Benin or Senegal, organise the contractual delegation of service delivery at a higher, regional level (REACH and RWSN, 2023), opening up an array of questions. For instance, is contracting at a regional level more effective than with local governments? Does contracting at wider scale solve the challenge of uncertain demand and limited enforceability of contractual clauses? To what extent and how does contractual incompleteness manifest in such arrangements? Does renegotiation occur and if yes, how? Answering these questions may inform the design of more sustainable rural water contracting arrangements.

Finally, this thesis highlights the critical importance of identifying strategies to create and sustain demand for professional rural water services. This research has begun to clarify some of the relationships between consumer demand and service delivery arrangements, and their implications for revenue generation, which is a necessary condition for sustainable services. For instance, the combined insights from Papers 2 and 3 indicate that adapting service attributes can motivate changes in user behaviours, including payment, with positive revenue implications. Yet, additional insights on the priorities of UDUMA's customers are needed.

For example, while solar kiosks register steady payments compared to handpumps, water use is unaffected by the infrastructure change and remains subject to seasonal fluctuations. Seasonal fluctuations of demand have also been revealed at handpumps, regardless of which payment modality is applied. This suggests that UDUMA is losing customers to alternative water sources, mainly during the wet season, while demand significantly increases during the dry season. Understanding how to incentivise users to shift water consumption from unimproved to improved sources throughout the year is an important area for future research which may yield practical insights to safeguard revenues from strong seasonal fluctuations, impacting the financial sustainability of services.

Elliott et al. (2019) suggest that multiple water source use is a strategy that households adopt to reduce their vulnerability to climate shocks. Climate change is associated with a higher likelihood of sustained droughts and more erratic rainfall (IPCC, 2022), which may lead to increased reliance on groundwater-based supplies. Such supplies must be reliable to be an effective resilience mechanism. Professional service providers that can guarantee supply reliability and water quality across seasons may enhance household resilience to the impacts of climate change. Prolonged user experience with such services may lead to the recognition of their added value which may ultimately enhance demand and revenue for such services. Hence, further longitudinal studies over meaningfully long periods of time are required to assess the long-term demand for and sustainability of professional drinking water services in rural Africa.

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In conclusion, this thesis has revealed that contracts are not a '*solution*' to the rural water challenge. While they represent an important institutional mechanism to make progress towards SDG 6.1, they cannot guarantee that the offered services will actually be demanded by consumers. This constitutes the fundamental barrier to achieving rural water sustainability. However, contracts are still critical: formal contracts with professional service providers establish a clear basis for accountability for service outcomes, contribute to drinking water keeping flowing, and can help attract capacity and investments to the rural water sector.

The research has demonstrated that providing services in line with user priorities is a strategy to increase demand and to make progress towards revenue targets. This is an important insight for policy and practice and may inform more sustainable interventions. Nonetheless, funding shortfalls are likely to persist. To achieve rural water sustainability, more pragmatic policy approaches are needed. The capacity of contract-based professional service delivery models to adapt to operational and financial uncertainties is as crucial as wider enabling conditions. Ensuring targeted financial support through tailored subsidies allocated against the verifiable delivery of contractually agreed performance targets is critical for sustaining rural water services. While drinking water services in rural Africa are unlikely to yield clear financial returns, their associated social and economic impacts constitute an essential outcome of value towards which policy and practice need to be steered.

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Appendices

Appendix I – Data Sharing Agreement with UDUMA

UNIVERSITY OF
OXFORD

THE CHANCELLOR MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD

and

UDUMA

DATA SHARING AGREEMENT

OU/LSO/0259/v2

THIS AGREEMENT is made on the date of the signature of the last party to sign **BETWEEN**:

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

(2) **UDUMA**, a private company incorporated in RCS Orléans with company number 815 141 635, whose registered office is at 6 rue Lavoisier, Ingré- 45140, France (the "**Provider**"),

each a "**Party**" and collectively the "**Parties**".

The Provider shall, for the purposes of this agreement, be considered as the "Uduma Group", such that the terms apply to Uduma and all its subsidiaries operating in various countries.

BACKGROUND

(A) The University is undertaking the Project as defined below.

(B) The Provider has certain information and data relevant to the Project and is willing to provide such information and data to the University for use in the Project subject to the following terms and conditions.

NOW IT IS AGREED as follows:

1. DEFINITIONS AND INTERPRETATION

1.1 The following words and phrases, when used in this Agreement, shall have the meanings given to them in this Clause 1.1:

"**Arising Intellectual Property**" means any Intellectual Property created, invented or developed in the course of performing the Project;

"**Background Intellectual Property**" means any Intellectual Property owned or controlled by either party that exists as at the date of this Agreement or is created, invented or developed other than in the course of performing the Project;

"**Confidential Information**" means any secret or commercially sensitive information which is disclosed by one party to the other in connection with the Project and is marked as confidential by the disclosing party at the time of disclosure;

"**Data**" means the raw data and information that is more particularly described in Schedule 1 to this Agreement and any additional Data agreed by the Provider and the University and which is disclosed by the Provider to the University. For the avoidance of doubt, per clause 3.1.1, the Data is confidential and Results do not form part of the Data;

“**Intellectual Property**” means all copyright, database rights, rights in designs, rights in trademarks and service marks, rights in inventions, rights to apply for patents, rights in patent applications and granted patents, rights in and in relation to petty patents, topography rights, semi-conductor rights, rights in plant varieties; and any rights of similar kind in any jurisdiction, in all cases whether registered or not, and whether or not capable of registration; all rights in relation to know-how, techniques and results;

“**Project**” means the research project titled ‘Sustainable Water Fund’ and detailed in Schedule 2.

“**Purpose**” means the use and analysis of the Data for the purposes of the Project and the use of the Results for further research and academic purposes including publication;

“**Results**” means any data or information derived from the analysis of the Data in the course of the Project or otherwise obtained in the course of performing the Project.

2. PROVIDER OBLIGATIONS

2.1 In return for the University fulfilling the University Obligations under clause 3, the Provider agrees that it will grant to the University a non-exclusive and non-transferable licence of the Data for the Purpose and that it will:

2.1.1 ensure that all Data:

a) has been obtained and processed in accordance with all laws and ethical standards applying in the countries of collection and processing of the Data at the relevant time;

b) does not (whether in its collection, transfer to the University or otherwise) infringe the intellectual property rights of any third party;

c) is in no way defamatory or of a form such that its collection or use may in any way damage the reputation of the University or the Project.

2.2 For the avoidance of doubt, in order to facilitate the operation of the Project, the University has the right to use, copy, modify, distribute, display, transfer, re-use, make extractions from and make derivative works of the Data in accordance with the terms of this Agreement and to make the Data available to any individuals and third parties as reasonably necessary for the performance of the Project.

3. UNIVERSITY OBLIGATIONS

3.1 In return for the Provider fulfilling the Provider Obligations under clause 2, the University agrees that it will:

3.1.1 treat the Data as Confidential Information;

3.1.2 take reasonable and appropriate technical and organisational measures against the unauthorised or unlawful processing of the Data and against the accidental loss or destruction of, or damage to, the Data;

3.1.3 ensure the Data is used only for the Purpose and in accordance with the provisions of this Agreement; and

3.1.4 acknowledge the Provider's contribution of the Data in any publication based on the Data or the Results in accordance with reasonable current practice consistent with the nature of the Data and of the publication in question.

4. DATA PROTECTION

4.1 Each Party shall comply with the obligations set out in Schedule 3 (Data Protection) to this Agreement.

5. INTELLECTUAL PROPERTY

5.1 Nothing in this Agreement does or is intended to grant either Party any right, title, interest in or authorisation to use the other's Background Intellectual Property save to the limited extent necessary for the performance of this Agreement and the Project.

5.2 The University recognises that the Data will remain in the ownership of the Provider and that the submission of the Data to the University will not transfer ownership of the Data to the University.

5.3 All Arising Intellectual Property and the Results shall vest in and be owned by the University. The University grants the Provider a non-exclusive, non-transferable, non-sublicensable, worldwide licence to use the Results subject to any appropriate form of acknowledgement (wording to be agreed between the Parties). Any use by the Provider of the Results is at its own risk; the University accepts no responsibility for any use which may be made of any work carried out under or pursuant to this Agreement, or of the Results by the Provider, nor for any reliance which may be placed on them, nor for advice or information given in connection with them.

6. PUBLICATION

6.1 The Project will form part of the actual carrying out of a primary charitable purpose of the University; that is, the advancement of education through teaching and research. There must therefore be some element of public benefit arising from the Project, and this is secured through the following sub-clauses:

6.1.1 Nothing in this Agreement shall prevent or hinder any registered student of the University from submitting for a degree of the University a thesis based on the results obtained during the course of work undertaken as part of the Project, the examination of such a thesis by examiners appointed by the University, or the deposit of such a thesis in accordance with the relevant procedures of the University.

6.1.2 In accordance with normal academic practice, all employees, students, agents or appointees of the University (including those who work on the Project) shall be permitted:-

a) to publish the Results obtained during the course of work undertaken as part of the Project; and

b) in pursuance of the University's academic functions, to discuss work undertaken as part of the Project in internal seminars, and to give instruction within the University on questions related to such work.

6.2 For the avoidance of doubt, the right to publish the Results as contained in clause 6.1 shall not extend to publication of the Data.

7. CONFIDENTIALITY

7.1 Subject to the following sub-clauses of this clause 7, each party will use all reasonable endeavours not to disclose any Confidential Information to any third party.

7.2 Neither party shall incur any obligation under clause 7 with respect to information which:

7.2.1 is known to the receiving party before its receipt, and not impressed already with any obligation of confidentiality to the disclosing party; or

7.2.2 is or becomes publicly known or available without any breach of this Agreement or of any other obligation to keep it confidential; or

7.2.3 is obtained by the receiving party from a third party in circumstances where the receiving party has no reason to believe that there has been a breach of an obligation of confidentiality owed to the disclosing party; or

7.2.4 is independently developed by the receiving party; or

7.2.5 is approved for release in writing by an authorised representative of the disclosing party; or

7.2.6 the receiving party is required to disclose by law or regulation (provided that, in the case of the Freedom of Information Act 2000 and the Environmental Information Regulations 2004, none of the exemptions in those Acts apply to the information disclosed) or by order of a competent authority (including any regulatory or governmental body or securities exchange); provided that, where practicable, the disclosing party is given reasonable advance notice of the intended disclosure and provided that the relaxation of the obligation of confidentiality shall only last for as long as necessary to comply with the relevant law, regulation or order and shall apply solely for the purposes of such compliance.

7.3 If the University receives a request under the Freedom of Information Act 2000 or Environmental Information Regulations 2004 to disclose any information which, under this Agreement, is the Data or the Provider's Confidential Information, it will notify the Provider and will consult with the Provider. The Provider will respond to the University within seven (7) days after receiving the University's notice if that notice requests the Provider to provide information to assist the University to determine whether or not an exemption in the Freedom of Information Act or the Environmental Information Regulations applies to the information requested under that Act.

8. LIMITATION OF LIABILITY

8.1 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, the Project or the Results will not extend to any indirect damages or losses, or to any loss of profits, loss of bargain, loss of revenue, loss of business, loss of contracts or opportunity, whether direct or indirect; even if, in any such case, the party bringing the claim has advised the other of the possibility of those losses or if they were within the other party's contemplation.

8.2 Subject to clause 8.4, the maximum aggregate liability of either Party under or otherwise in connection with this Agreement or its subject matter shall not exceed £100,000.

8.3 The Provider undertakes to make no claim in connection with this Agreement or its subject matter against any employee, student, agent or appointee of the University (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 the Provider may have to claim against the University. The benefit conferred by this clause is intended to be enforceable by the persons referred to in it.

8.4 Nothing in this Agreement limits or excludes either Party's liability for:

8.4.1 death or personal injury resulting from negligence; or

8.4.2 any fraud or for any sort of other liability which, by law, cannot be limited or excluded.

9. TERMINATION AND EXPIRY

9.1 This Agreement will continue in force until terminated by either Party on not less than three (3) months' prior written notice, expiring not earlier than the first anniversary of this Agreement.

9.2 Upon completion of the Project or the earlier termination of this Agreement, the University shall:

9.2.1 cease all use of the Provider's Data; and

9.2.2 within eight (8) days thereafter shall destroy or return to the Provider all Provider's Data in its possession, sending written confirmation of despatch or destruction to the Provider. The University may however retain for record purposes one copy of the Data in secure conditions in a law office or other non-technical files.

10. GENERAL

10.1 Each of the Parties warrants and undertakes to the other that it has full capacity, power and authority to enter into and perform this Agreement and that this Agreement constitutes valid and binding obligations on it in accordance with its terms.

10.2 For the avoidance of doubt, nothing in this Agreement shall constitute or create an agency, partnership, joint venture or employment or worker relationship between the Parties.

10.3 Each Party shall at all times act in good faith towards the other and undertakes not to do anything that would or may bring the other into disrepute or damage its reputation.

10.4 Neither Party shall be liable for any failure to fulfil its obligations under this Agreement caused by circumstances beyond its reasonable control, provided that the Party has made all reasonable efforts to fulfil its obligations under this Agreement.

10.5 This Agreement sets out the entire agreement and understanding between the Parties in respect of the subject matter of this Agreement. No other statements or representations made by either party have been relied upon by the other in entering into this Agreement.

10.6 This Agreement and any dispute or claim arising out of or in connection with it or its subject matter or formation (including non-contractual disputes or claims) shall be governed and construed in accordance with the law of England and Wales; and the parties irrevocably agree that the courts of England and Wales shall have exclusive jurisdiction to settle any dispute or claim that arises out of or in connection with this Agreement or its subject matter or formation (including non-contractual disputes or claims).

IN WITNESS of this Agreement, the Parties have executed this Agreement through their duly authorised representatives.

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

Eve Henshaw

____

Name: Eve Henshaw

Title: Senior Research Contracts Manager
University of Oxford

Date: 6/10/2020

SIGNED for and on behalf of **UDUMA**))

____

Name:

Title:

Date:

SCHEDULE 1 – The Data

The data will draw upon UDUMA's existing data management systems and reporting to iteratively create value in recording and analysing data.

1. Community waterpoints installed and managed by UDUMA
    a. Infrastructure
        i. Type, model and data of installation or rehabilitation;
        ii. Capex for each rehabilitated waterpoint;
        iii. Location - GPS location, local name and ID code;
        iv. Water quality test(s) – parameters and protocol;
        v. Ancillary data of other water infrastructure in service areas.
    b. Operation and Management
        i. Water volumes - daily/weekly data of water pumped;
        ii. Payment records by individual accounts, credit and usage patterns;
        iii. Operational costs in service areas managed by mechanics;
        iv. Maintenance records and repair events;
        v. Water quality testing.
    c. Ancillary data
        i. Other indicators as available and relevant.
2. Supporting documentation
    a. Government contracts and agreements;
    b. Community agreements, including appointment of caretakers and engagement with Water User Committees;
    c. Project design and financing;
    d. Baseline studies and data files, including pro-poor assessments and provision
    e. Donor reporting, including monitoring and evaluation
    f. Other documents and data, as available, including rainfall, groundwater, political or economic

SCHEDULE 2 – Sustainable Water Fund

The project will focus on the performance and evolution of the UDUMA model being applied in several countries in Africa. The project aligns to existing collaboration between UDUMA and the University of Oxford in the Uptime consortium and related initiatives.

The aim of this project is to understand how the UDUMA model can inform public policy and new investment approaches for sustainable funding for reliable water services to meet the SDG goal of safely-managed water by 2030, particularly for vulnerable people in rural areas of Africa.

We identify three objectives to guide future work to achieve the overall aim:

1. Sustainable Funding.
    a. To understand water user payment behaviours through analysis of water user and waterpoint data;
    b. To understand how a longer-term and more sustainable funding model can be designed and delivered at the national or regional level.
2. Digital innovation
    a. To understand the role and performance of UDUMA's digital measurement and payment systems;
    b. To understand how digital data may unlock more sustainable funding from government and non-traditional sectors.
3. Governance and Policy.
    a. To identify how legal and policy reform may achieve and sustain funding in different institutional environments to share risks and responsibilities between state, private and community partners.
    b. To identify measures for social protection and water services regulation in terms of affordability, social inclusion, gender equality, sector coordination and cooperation, water quality, and enforcement.

SCHEDULE 3

Data Protection

Definitions

Controller, processor, data subject, personal data, and **processing**: as set out in the Data Protection Legislation in force at the time.

Data Protection Legislation: any law, statute, declaration, decree, directive, legislative enactment, order, ordinance, regulation, rule or other binding restriction (as amended, consolidated or re-enacted from time to time) which relates to the protection of individuals with regards to the processing of personal data to which a party is subject, including (i) the Data Protection Act 1998, until the effective date of its repeal (ii) the General Data Protection Regulation (*(EU) 2016/679*) (**GDPR**) and any national implementing laws, regulations and secondary legislation, for so long as the GDPR is effective in the UK, and (iii) any successor legislation to the Data Protection Act 2018 and the GDPR.

Shared Personal Data: any personal data which may be shared or is shared between the parties pursuant to this agreement.

1. MUTUAL OBLIGATIONS

1.1 Each Party shall comply with and assist the other in complying with all applicable requirements of the Data Protection Legislation. In particular, each party shall:

(a) ensure that it has in place appropriate technical and organisational measures to protect against unauthorised or unlawful processing of personal data and against accidental loss or destruction of, or damage to, personal data;

(b) ensure that it has all necessary notices and consents in place to enable lawful transfer of the Shared Personal Data to the other party for such purposes as the parties have mutually agreed, and consult with the other Party about any notices given to data subjects in relation to the Shared Personal Data wherever possible;

(c) provide the other Party with reasonable assistance in complying with any data subject access request or deletion requests and queries or complaints made under Data Protection Legislation;

(d) provide the other Party with reasonable assistance in ensuring compliance with its obligations under the Data Protection Legislation with respect to security, breach notifications, impact assessments and consultations with supervisory authorities or regulators;

(e) notify the other party without undue delay on becoming aware of any breach of the Data Protection Legislation in relation to the Shared Personal Data and provide assistance to the other Party as is necessary upon reasonable request to facilitate the handling of any data security breach relating to the Shared Personal Data in an expeditious and compliant manner;

(f) maintain complete and accurate records and information to demonstrate compliance with this Agreement;

(g) ensure the reliability of any of its personnel who have access to personal data and ensure that such personnel have committed themselves to confidentiality or are under an appropriate statutory obligation of confidentiality

1.2 In instances where the parties are deemed to be joint data controllers with each other, the Parties shall co-operate to do all necessary things to enable performance of the above obligations. In particular, the Parties shall co-operate to provide sufficient information to data subjects when collecting the personal data to ensure that the data subjects understand how their personal data will be processed and used by each Party.

Appendix II – Guiding questions and lists of interviews

A) Questions for semi-structured interviews with water users

- Site name:
- Sex of respondent:

1. Current water-related practices (main waterpoint and its use).

1.1. Is the solar kiosk your main water source?

1.2. Why do you use this waterpoint?

1.3. For which purpose do you collect water here?

1.4. Is the waterpoint heavily used? Is there queuing in the morning/evening? And if yes, how long do people have to wait to fetch water?

1.5. How many jerry cans did you fetch yesterday?

1.6. Do you fetch less water from the waterpoint in the rainy season? If yes, why?

1.7. What other (alternative) sources do you use and for which purposes? Are these sources free of charge or do you have to pay, and if yes, how much?

2. Priorities and preferences regarding service provision (value of reliability).

2.1. What is the most important aspect for you regarding your water supply? (Give prompts)
   - Fast repairs in case of breakdowns (reliability)
   - Amount of water (quantity)
   - Proximity to household (convenience /distance)
   - Physical effort for fetching water (convenience/pumping)
   - Queuing time for fetching water (convenience/time)
   - Price of water (affordability)
   - Taste of water (Water quality)
   - Safety of water (Water quality)

3. Perception of UDUMA and solar kiosk (acceptance of PAYF at solar).

3.1. What do you like the most about UDUMA's service?

3.2. What do you dislike the most about UDUMA's service?

3.3. According to you, what is the biggest advantage of solar compared to a handpump?

3.4. According to you, what is the main disadvantage of solar compared to a handpump?

3.5. Why do you agree to pay a PAYF-tariff now?

4. Demand for further improvements (factors to stimulate demand)

4.1. According to you, what improvements of your waterpoint are necessary so it serves better your needs?

B) Questions for semi-structured interviews with sector experts from Mali

Background on research project

- Current state of rural water supply in sub-Saharan Africa

Rural water supply, especially when provided via handpumps in remote areas, is characterised by poor service levels. Generally, communities are managing waterpoints with limited success – roughly 25% to 30% of rural waterpoints in sub-Saharan Africa are non-functional.

In the context of reaching SDG 6.1 by 2030, new models for reliable rural water service provision are emerging – ensuring that waterpoints are properly operated and maintained. However, the challenge to fund these reliable services has yet to be addressed.

- The UDUMA model in Mali

Mali is advancing new models for rural water service provision at large scale including the UDUMA service model in Sikasso. UDUMA presents a new approach to water service delivery in rural settings by offering professional operation and maintenance services for about 1.400 waterpoints. UDUMA charges a tariff of 500 FCFA per m^3 (in line with national policy), and users are asked to pay according to volume abstracted. The UDUMA model offers hence a window of opportunity to explore use and payment behaviours related to reliable rural water services.

Aim of the interview: Contextualise the UDUMA model

Since the UDUMA model is altering customary patterns of rural water in Sikasso, it seems necessary to better understand the context of rural water supply in Mali. The interviews will help to situate the project in its larger context and provide insights into the history, current developments, and potential pathways of rural water supply in Mali – and elsewhere.

Questions:

I. Infrastructure

1.1 What are the prevalent infrastructure types in Mali for rural water supply?

1.2 Are there prioritised infrastructures for rural water supply to reach SDG 6.1 in Mali?

1.3 How do rural households generally satisfy their water needs?

1.4 Are there differences between different types of infrastructure (wells, handpumps, solar systems, piped systems, etc.) regarding sustainability, management approaches, etc.?

1.5 To what extent do use and payment patterns change regarding infrastructure design in Mali?

II. Institutions

2.1 How do rural users value water in Mali?

2.2 What are socio-cultural, spiritual, or traditional considerations related to water and payment?

2.3 Is water valued based on its quality or usage?

2.4 How is rural water supply traditionally managed?

2.5 What are dominant formal, informal, and traditional management arrangements for rural water supply in Mali?

2.6 Is there a guiding service delivery model for rural water supply in Mali? What are the most important features and challenges of this guiding model?

III. Investments

3.1 How is rural water supply currently financed? What costs are covered by tariffs, transfers, and taxes?

3.2 In Mali, what is considered an appropriate service level worth paying for?

3.3 Regarding the sustainable financing of reliable water supply in rural areas, what are essential parts missing in the actual sector set-up?

3.4 What is necessary, in your view, to attract financing for service delivery – aiming at covering recurring operation and maintenance costs (and eventually capital maintenance costs)?

IV. Innovations in policy

4.1 What was the main policy for rural water supply before the advent of SDGs?

4.2 Are you aware of policy or practical innovations related to the improvement of rural water services? How do these undertakings positively impact sustainability of rural water services?

4.3 Are there any limitations to these initiatives? What are potential gaps or challenges for a sound implementation?

4.4 According to you, are there institutional arrangements missing to provide enabling conditions for these innovations to be successful?

V. Information

Could you give me advice to whom else to talk to better understand challenges and solutions to rural water services in Mali and to refine my key research questions?

C) List of interviews with sector experts from Mali

This anonymised list presents the interviewees from various organisations intervening in the water sector in Mali. The 14 semi-structured online interviews were conducted in French and lasted for around 60 minutes each. In advance to the interview, the questionnaire (Appendix II – B)) was shared with the interviewees to allow for adequate preparation.

Date	Organisation	Position of interviewee
03/02/2021	UNICEF	WASH Specialist for Mali
05/02/2021	Protos	Country Director
10/02/2021	Malian Association of Municipalities	International Affairs Manager
10/02/2021	National Water Directorate (DNH)	Head of Division "Regulations and Standards"
11/02/2021	National Water Directorate (DNH)	Director
11/02/2021	Helvetas Swiss Intercooperation	Regional Policy Advisor WASH
12/02/2021	SNV	Advisor WASH
12/02/2021	AKVO	Advisor WASH
15/02/2021	USAID	Planning Officer Water and Irrigation
15/02/2021	WaterAid	Advisor WASH Policy and Advocacy
15/03/2021	CN-CIEPA WASH (Civil Society)	Advisor WASH-Advocacy
15/03/2021	National Water Directorate (DNH)	Head of Division "Rural Water Supply"
07/05/2021	STEFI operator (Private entity for Financial and Technical Monitoring of piped water schemes in rural Mali)	Director
10/06/2021	Urban Water Services Regulator (CREE)	Economist

D) Questions for semi-structured interviews with representatives from donor agencies

The interviews were tailored to unpack how different actors behave and cooperate in overcoming the limitations of an incomplete contract and what they learned from this process.

1. Process of contract renegotiation.

Renegotiation appears as a multi-actor process shaped by communication, reputation, and pragmatic interests (or informed by shared experience and interests). Hence, the following questions emerge: Who was involved in the renegotiation process? How and when did this occur? Why did the actors/parties agree to change the model?

- **Foundation:**

The foundation played a pivotal role in UDUMA's model by agreeing to fund the installation of ten solar kiosks as a pilot project in nine municipalities.

  - How did UDUMA convince you to fund the upgrades?
  - Why did you accept to fund?
  - What did you learn from the process?
  - What was your wider role besides providing funding for solar pilots?

- **RVO:**

RVO supports the UDUMA project in Mali through its Sustainable Water Fund since 2017.

- What was the initial motivation for granting funds to the UDUMA project in Mali?
- How did the transition from handpumps to solar come about?
  - Did RVO require a "proof-of-concept"? If yes, why?
  - What were the implications of the pilot funded by the foundation?
- What was convincing to agree to reallocate funds for solar?
- What did the process look like to reallocate the funds to solar kiosks?
- Where there any additional conditions for permitting the re-allocation of funding?

2. Wider learnings for designing contracts for drinking water services in rural Africa.

This report from RVO (2022) reflecting on the Water Fund is quite interesting, hence I am wondering whether there are specific insights emerging from your experience with the UDUMA model in Mali?

- Based on the Mali experience, what do you think are the wider learnings on how to design rural water service contracts?
  - What must be considered in contract design? Which learnings may have relevance for other contexts/countries?
  - What are the implications for funding innovative (but risky) projects?
  - Who should cover investment risks?
  - What is/should be the role of subsidies/income guarantees?

E) List of meetings with staff from UDUMA France

As part of the research project, the lead author conducted various in-person and online meetings with staff from UDUMA France to understand UDUMA's service model and stay informed of challenges in its implementation and potential evolutions. This anonymised overview list presents the type and content of meetings that were organised as part of the research during 2020 to 2023. In total, 6 in-person workshops and 13 online meetings with staff from UDUMA France were held throughout the research process, providing opportunities for regular updates from Mali and venues to share research findings and receive feedback. Discussions were generally conducted in French – unless specified otherwise. Notes were taken and short summaries of the exchanges were established.

Date	Type of meeting and short description	Participants from UDUMA
28/10/2020	**Online meeting** as kick-off of research collaboration, providing an overview on the service model, its assumptions, and available service data.	Managing Director, Chief of Operations for Mali, Data Officer
25/11/2020	**Online meeting**, focusing on implementation challenges of the service model in Mali.	Chief of Operations for Mali
25/01/2021	**Online meeting**, focusing on available service data and their collection.	Chief of Operations for Mali
21/02/2021	**In-person workshop** in Orléans at UDUMA's Head Quarter (HQ). Presentation of research design and preliminary findings of exploratory data analysis.	Managing Director, Project Manager, Finance Officer, Data Officer. Executive Director, Vergnet Hydro
16/03/2021	**Online meeting**, focusing on cost data	Project Manager, Finance Officer
18/05/2021	**In-person workshop**, Orléans. Presentation of revised contracts, installation of solar kiosks, and introduction of flat fees.	Managing Director, Project Manager, Data Officer.
19/07/2021	**In-person workshop**, Orléans. Overview of progress in Mali, up-date from the field, contextualisation of service adaptations.	Chief of Operations for Mali, Managing Director, Project Manager, Data Officer
24/09/2021	**Online meeting**, focusing on scale of operations in Mali and business opportunity in Côte d'Ivoire.	Project Manager, Data Officer
05/01/2022	**In-person workshop**, Orléans. Presentation and discussion of emerging results following the installation of solar kiosks.	Managing Director, Project Manager, Finance Officer, Data Officer. Executive Director, Vergnet Hydro
23/02/2022	**In-person workshop**, London (conducted in English). Discussion of results of solar kiosks, presentation of UDUMA's wider business strategy (Benin, Côte d'Ivoire).	Managing Director Executive Director, Vergnet Hydro
25/03/2022	**Online meeting**, focusing on preparation of fieldwork in Mali regarding site selection and data collection.	Chief of Operations for Mali, Project Manager

14/04/2022	**Online meeting**, focusing on preparation of fieldwork in Mali.	Chief of Operations for Mali
05/07/2022	**Online meeting** (conducted in English), focusing on recapitulation of and reflections on fieldwork, particularly on insights from user interviews.	Managing Director Executive Director, Vergnet Hydro
20/09/2022	**In-person workshop**, Orléans. Presentation and discussion of qualitative and quantitative findings from fieldwork and implications of service adaptations.	Chief of Operations for Mali, Managing Director, Project Manager, Data Officer
13/12/2022	**Online meeting**, focusing on updates from the field.	Chief of Operations for Mali
07/03/2023	**Online meeting,** focusing on updates from the field.	Chief of Operations for Mali, Project Manager
11/07/2023	**Online meeting,** focusing on updates from the field.	Chief of Operations for Mali
04/10/2023	**Online meeting**, focusing on reflections of UDUMA's service delivery model and its evolution over time.	Managing Director
28/11/2023	**Online meeting**, focusing on reflections of UDUMA's service delivery model and its evolution over time.	Chief of Operations for Mali

Appendix III – List of waterpoints and GPS coordinates

Nr	Municipality	Village	WP_ID	Latitude	Longitude	Type	Cohort
1	FAKOLA	DIONKONI	2233403024PEA	10.51829129	-6.993154585	Solar	1
2	KEBILA	BOUGOULA	2233406009PEA	11.2572731	-7.09724384	Solar	1
3	KEBILA	KEBILA	2233406036PEA	11.27577142	-7.04594373	Solar	1
4	KOUMANTOU	TIEFALA	2233214071PEA	11.4451881	-6.65892692	Solar	1
5	WOLA	DIONKALA	2233223016PEA	11.77244432	-6.716689328	Solar	1
6	SIDO	TINKOLE	2233220009PEA	11.66126034	-7.526896661	Solar	1
7	MERIDIELA	N'TENKONI	2233216008PEA	12.02572133	-7.333645178	Solar	1
8	SIBIRILA	FANGALA	2233219043PEA	10.46529113	-7.54426606	Solar	1
9	SERE MOUSSA ANI SAMOU	MORIBALA	2233610009PEA	11.34323417	-8.216362009	Solar	1
10	TAGANDOUGOU	BINKO	2233611003PEA	11.63902852	-8.244437864	Solar	1
11	GARALO	DIOLOGOLA (GARALO)	2233210004PEA	10.99737438	-7.438687356	Solar	2
12	GARALO	ZENA FARABALE	2233210018PEA	10.75684926	-7.263522595	Solar	2
13	GARALO	SIRAKOROBLE	2233210024PEA	10.79924342	-7.437427389	Solar	2
14	GARALO	MARKALA	2233210068PEA	10.99128719	-7.43500988	Solar	2
15	TIEMALA BANIMONOTIE	KOLOGO	2233222013PEA	11.28726167	-7.56936	Solar	2
16	DANOU	BERIAN	2233203006	11.42018302	-7.934935419	Handpump	NA
17	DANOU	BERIAN	2233203007	11.41923255	-7.9321837	Handpump	NA
18	DANOU	BERIAN	2233203009	11.42191638	-7.9310491	Handpump	NA
19	DANOU	BERIAN	2233203010	11.42122386	-7.93525754	Handpump	NA
20	DANOU	DIADOUBALA	2233203011	11.4408722	-7.95306662	Handpump	NA
21	DANOU	TORA TOMONI	2233203028	11.37054241	-8.04050119	Handpump	NA
22	DANOU	TORAKORO	2233203033	11.41860735	-7.997046327	Handpump	NA
23	DOGO	FIANA	2233206031	11.91076106	-7.397082439	Handpump	NA
24	DOMBA	FOURALA	2233207004	11.70622	-7.9124768	Handpump	NA
25	DOMBA	FOURALA	2233207005	11.81955183	-6.873715147	Handpump	NA
26	DOMBA	FALABADA	2233207006	11.8582582	-6.914838441	Handpump	NA
27	DOMBA	FALABADA	2233207007	11.86003433	-6.911769491	Handpump	NA
28	FARAGOUARAN	ZAMBOUGOU	2233209002	11.31537222	-7.728538765	Handpump	NA
29	FARAGOUARAN	ZAMBOUGOU	2233209003	11.31663881	-7.728373809	Handpump	NA
30	FARAGOUARAN	MAFELE	2233209008	11.2942334	-7.947615059	Handpump	NA
31	FARAGOUARAN	MAFELE	2233209009	11.29468451	-7.947817734	Handpump	NA
32	FARAGOUARAN	MAFELE	2233209010	11.29226554	-7.940519443	Handpump	NA
33	FARAGOUARAN	SIBIRILA	2233209011	11.4251726	-7.772189537	Handpump	NA
34	FARAGOUARAN	SIBIRILA	2233209012	11.4253956	-7.771516722	Handpump	NA
35	GARALO	TOUGOUMELA (GARALO)	2233210005	10.99373479	-7.437642217	Handpump	NA
36	GARALO	SIENROU	2233210007	11.0604156	-7.463755868	Handpump	NA
37	GARALO	SIENROU	2233210009	11.06032901	-7.466087127	Handpump	NA
38	GARALO	PAGNOLA	2233210014	10.7938842	-7.332030572	Handpump	NA
39	GARALO	ZENA FARABALE (HAMEAU)	2233210016	10.77614029	-7.294609481	Handpump	NA
40	GARALO	SIRAKOROBLE	2233210022	10.79943465	-7.43943586	Handpump	NA
41	GARALO	SIRAKOROBLE	2233210025	10.80035088	-7.437319513	Handpump	NA

42	GARALO	KOTIE	2233210060	11.04724042	-7.390806405	Handpump	NA
43	GARALO	KOTIE	2233210061	11.04735659	-7.392280949	Handpump	NA
44	GARALO	SENA	2233210066	10.98497688	-7.328851568	Handpump	NA
45	KELEYA	FAMANA	2233211003	11.87178181	-7.827585451	Handpump	NA
46	KELEYA	DIALAKORRO	2233211006	11.8029775	-7.859810097	Handpump	NA
47	KELEYA	OURE	2233211009	11.87733399	-7.712077294	Handpump	NA
48	KELEYA	BIKO	2233211012	11.89846623	-7.635733746	Handpump	NA
49	KELEYA	SEMANA	2233211013	11.849272	-7.593144039	Handpump	NA
50	KELEYA	KOLONDA	2233211019	11.79892761	-7.701300932	Handpump	NA
51	KELEYA	SIEMBOUGOU	2233211020	11.8292924	-7.722849883	Handpump	NA
52	KELEYA	SIEMBOUGOU	2233211021	11.83115553	-7.723046942	Handpump	NA
53	KOUMANTOU	SIOBOUGOU	2233214054	11.45231317	-6.70534113	Handpump	NA
54	KOUMANTOU	TEBEZANA	2233214055	11.42618972	-6.71005694	Handpump	NA
55	KOUMANTOU	TIEFALA	2233214070	11.44733858	-6.65800935	Handpump	NA
56	KOUMANTOU	TIEFALA	2233214072	11.44378131	-6.66058694	Handpump	NA
57	MERIDIELA	DONKERILA	2233216002	12.04448129	-7.259391071	Handpump	NA
58	MERIDIELA	WOSSA	2233216004	12.03426782	-7.291559223	Handpump	NA
59	MERIDIELA	FALADIE-DAMBELE	2233216015	12.18476925	-7.31112971	Handpump	NA
60	MERIDIELA	N'TONFALA	2233216022	12.21124676	-7.166960975	Handpump	NA
61	MERIDIELA	DOMBA-TIEMBA	2233216024	12.19688545	-7.201318899	Handpump	NA
62	MERIDIELA	DOMBA-TIEMBA	2233216026	12.14665497	-7.22493357	Handpump	NA
63	MERIDIELA	NEREKORO-DAMBELE	2233216029	12.11771624	-7.309585176	Handpump	NA
64	SIBIRILA	MANANKORO	2233219003	10.45897788	-7.448898694	Handpump	NA
65	SIBIRILA	MANANKORO	2233219005	10.45980484	-7.443439225	Handpump	NA
66	SIBIRILA	MANANKORO	2233219006	10.45821525	-7.444100557	Handpump	NA
67	SIBIRILA	MANANKORO	2233219007	10.45559188	-7.445989503	Handpump	NA
68	SIBIRILA	KONA-BADA	2233219012	10.26079306	-7.014952395	Handpump	NA
69	SIBIRILA	KONA-BADA	2233219013	10.26208597	-7.016407074	Handpump	NA
70	SIBIRILA	FARABALE	2233219023	10.49898047	-7.11750431	Handpump	NA
71	SIBIRILA	KOLE	2233219024	10.50941032	-7.085130382	Handpump	NA
72	SIBIRILA	DIENDIO	2233219031	10.58971931	-7.378500011	Handpump	NA
73	SIBIRILA	DIENDIO	2233219034	10.58969806	-7.380425669	Handpump	NA
74	SIBIRILA	NGOROLA	2233219040	10.51419396	-7.475574436	Handpump	NA
75	SIBIRILA	FANGALA	2233219042	10.46533023	-7.54623346	Handpump	NA
76	SIBIRILA	FANGALA	2233219045	10.46608615	-7.542367978	Handpump	NA
77	SIDO	BANANTOUMOU	2233220001	11.74013175	-7.691566441	Handpump	NA
78	SIDO	BANANTOUMOU	2233220002	11.74215715	-7.692328189	Handpump	NA
79	SIDO	FARABA	2233220004	11.78812925	-7.554434063	Handpump	NA
80	SIDO	DENDIALA	2233220006	11.7669486	-7.569977967	Handpump	NA
81	SIDO	FARABABOUGOU	2233220007	11.76985603	-7.599386964	Handpump	NA
82	SIDO	N'PIEBOUGOULA	2233220008	11.75322684	-7.59944329	Handpump	NA
83	SIDO	SIDO	2233220013	11.66724443	-7.600606531	Handpump	NA
84	SIDO	SIDO	2233220014	11.6652943	-7.601629375	Handpump	NA
85	TIEMALA BANIMONOTIE	SIDIOLE	2233222010	11.28792667	-7.567616667	Handpump	NA
86	TIEMALA BANIMONOTIE	SIDIOLE	2233222011	11.28726167	-7.56936	Handpump	NA
87	TIEMALA BANIMONOTIE	KOLOGO	2233222015	11.22102667	-7.495643333	Handpump	NA

88	WOLA	DJELE	2233223008	11.74280402	-6.580355577	Handpump	NA
89	WOLA	DIONKALA	2233223015	11.77155877	-6.718581794	Handpump	NA
90	WOLA	DIONKALA	2233223018	11.77076224	-6.71369154	Handpump	NA
91	ZANTIEBOUGOU	SOUNTOU	2233226004	11.29906339	-7.229525344	Handpump	NA
92	ZANTIEBOUGOU	MONZONDOUGOU-KOLONI	2233226011	11.29993967	-7.186464993	Handpump	NA
93	ZANTIEBOUGOU	MONZONDOUGOU-KOLONI	2233226014	11.33442538	-7.194165532	Handpump	NA
94	ZANTIEBOUGOU	BELEKONI	2233226015	11.34689237	-7.188317059	Handpump	NA
95	ZANTIEBOUGOU	BEKO-SOKORO	2233226024	11.31356186	-7.350712745	Handpump	NA
96	ZANTIEBOUGOU	BEKO-SOKORO	2233226026	11.31537122	-7.352228444	Handpump	NA
97	ZANTIEBOUGOU	ZANTOGOLA	2233226036	11.6078563	-7.190915868	Handpump	NA
98	ZANTIEBOUGOU	SALA	2233226045	11.59576134	-7.310629645	Handpump	NA
99	FAKOLA	DEMBASSO	2233403001	10.55463606	-6.848497018	Handpump	NA
100	FAKOLA	DEMBASSO	2233403002	10.55664545	-6.847234704	Handpump	NA
101	FAKOLA	WOMA	2233403005	10.5716628	-6.790883001	Handpump	NA
102	FAKOLA	SOCOURANI	2233403011	10.4465339	-6.929318765	Handpump	NA
103	FAKOLA	SOROMANA	2233403013	10.42329851	-6.891958863	Handpump	NA
104	FAKOLA	TOGODABA	2233403015	10.36506012	-6.917888867	Handpump	NA
105	FAKOLA	TOGODABA	2233403016	10.35555433	-6.917788954	Handpump	NA
106	FAKOLA	DIASSA	2233403017	10.33395509	-6.953942953	Handpump	NA
107	FAKOLA	DIASSA	2233403018	10.33538793	-6.9530968	Handpump	NA
108	FAKOLA	FLAKODA	2233403019	10.3087103	-6.970620761	Handpump	NA
109	FAKOLA	DIDIENI	2233403021	10.32682473	-6.993073281	Handpump	NA
110	FAKOLA	WORODA	2233403022	10.37046205	-6.940958379	Handpump	NA
111	FAKOLA	DIONKONI	2233403023	10.5194163	-6.988272378	Handpump	NA
112	FAKOLA	MPIESSANA	2233403027	10.57448151	-7.033841349	Handpump	NA
113	FAKOLA	MPIESSANA	2233403029	10.57291342	-7.028465448	Handpump	NA
114	FAKOLA	FAKOLA	2233403041	10.55078139	-6.917447979	Handpump	NA
115	FAKOLA	FAKOLA	2233403043	10.54957657	-6.915234486	Handpump	NA
116	KEBILA	BOUGOULA	2233406012	11.25651362	-7.0945587	Handpump	NA
117	KEBILA	DIAKA	2233406016	11.16386031	-7.13257251	Handpump	NA
118	KEBILA	DIAKA	2233406017	11.16390676	-7.13258902	Handpump	NA
119	KEBILA	DIAKA	2233406018	11.16949383	-7.13586521	Handpump	NA
120	KEBILA	GOUARAN	2233406035	11.23900364	-6.9459582	Handpump	NA
121	KEBILA	KEBILA	2233406038	11.27378995	-7.04340579	Handpump	NA
122	KEBILA	KOKOUNA BILABA	2233406041	11.2426546	-7.18880098	Handpump	NA
123	KEBILA	KOKOUNA BILABA	2233406042	11.24430132	-7.18689455	Handpump	NA
124	KEBILA	KONNA	2233406048	11.10783463	-7.09911472	Handpump	NA
125	KEBILA	DIALAKORONI	2233406051	11.11784534	-7.09429606	Handpump	NA
126	KEBILA	KORONI	2233406053	11.15182222	-7.02950589	Handpump	NA
127	KEBILA	MANTAGALA	2233406054	11.19457481	-7.02731621	Handpump	NA
128	KEBILA	MASSALA	2233406055	11.23038945	-6.96932746	Handpump	NA
129	KEBILA	N'TIOBALA	2233406061	11.10647027	-7.13220507	Handpump	NA
130	KEBILA	KONNA	2233406074	11.25918145	-7.023604196	Handpump	NA
131	KEBILA	N'TIOBALA	2233406075	11.11043574	-7.134119002	Handpump	NA
132	NANGALASSO	KAMASSO	2233410002	10.91220804	-6.347419219	Handpump	NA
133	NANGALASSO	KAMASSO	2233410003	10.90944633	-6.346740453	Handpump	NA

134	NANGALASSO	KAMASSO	2233410004	10.90762775	-6.34747169	Handpump	NA
135	NANGALASSO	NANGALASSO	2233410009	10.8726445	-6.313565718	Handpump	NA
136	NANGALASSO	NANGALASSO	2233410015	10.86874121	-6.31179437	Handpump	NA
137	WASSOULOU-BALLE	BALANFINA	2233601001	11.06415125	-7.888945509	Handpump	NA
138	WASSOULOU-BALLE	DJEGUENINA	2233601005	11.20913114	-7.99063283	Handpump	NA
139	WASSOULOU-BALLE	GOUALAFARA	2233601022	11.3002115	-8.163646292	Handpump	NA
140	WASSOULOU-BALLE	GOUALAFARA	2233601023	11.29744903	-8.163823569	Handpump	NA
141	WASSOULOU-BALLE	KOFOULATIE	2233601033	11.24787489	-8.091442231	Handpump	NA
142	DJALLON FOULA	GUELINKORO	2233604002	11.14858279	-8.522717804	Handpump	NA
143	DJALLON FOULA	TEKELINDOUGOU	2233604005	11.17324842	-8.491615579	Handpump	NA
144	DJALLON FOULA	TEKELINDOUGOU	2233604006	11.17345013	-8.495594133	Handpump	NA
145	DJALLON FOULA	SIRAKORO	2233604013	11.01593188	-8.64482847	Handpump	NA
146	DJALLON FOULA	SIRAKORO	2233604014	11.018606	-8.639407475	Handpump	NA
147	DJALLON FOULA	KABAYA	2233604017	11.11596612	-8.556253295	Handpump	NA
148	GOUANAN	SIRAKORO	2233606005	10.8173161	-8.060662206	Handpump	NA
149	GOUANAN	SIRAKORO	2233606006	10.81845507	-8.060824396	Handpump	NA
150	GOUANAN	GUELEKETIGUILA	2233606022	10.78982346	-7.840461396	Handpump	NA
151	GOUANAN	TABAKO	2233606030	10.98216492	-8.010182446	Handpump	NA
152	GOUANAN	TABAKO	2233606031	10.98181527	-8.007182982	Handpump	NA
153	GOUANAN	TABAKO	2233606032	10.97921579	-8.005626881	Handpump	NA
154	GOUANDIAKA	KALAKO	2233607010	10.81145811	-8.147589164	Handpump	NA
155	GOUANDIAKA	KALAKO	2233607011	10.81294611	-8.145447336	Handpump	NA
156	GOUANDIAKA	KALAKO	2233607012	10.81328964	-8.145827623	Handpump	NA
157	GOUANDIAKA	KALAKO	2233607013	10.81274771	-8.146437155	Handpump	NA
158	GOUANDIAKA	KALAKO	2233607014	10.81274478	-8.147931146	Handpump	NA
159	GOUANDIAKA	KALANNA	2233607015	10.78444416	-8.193246564	Handpump	NA
160	GOUANDIAKA	KALANNA	2233607019	10.78790191	-8.192914641	Handpump	NA
161	GOUANDIAKA	KALANNA	2233607020	10.78530503	-8.193824161	Handpump	NA
162	GOUANDIAKA	KALANNA	2233607022	10.78953831	-8.195327874	Handpump	NA
163	GOUANDIAKA	KALANNA	2233607025	10.78494603	-8.200705284	Handpump	NA
164	SANKARANI	MADIMADOU	2233609003	11.43442773	-8.482921449	Handpump	NA
165	SANKARANI	MADIMADOU	2233609004	11.4363391	-8.484998485	Handpump	NA
166	SANKARANI	MADIMADOU	2233609005	11.43180897	-8.484667735	Handpump	NA
167	SANKARANI	FARABA	2233609013	11.38256248	-8.312284341	Handpump	NA
168	SANKARANI	BAMBALA	2233609017	11.40134096	-8.312342763	Handpump	NA
169	SERE MOUSSA ANI SAMOU	ASSAMOROLA	2233610001	11.35877309	-8.237595716	Handpump	NA
170	SERE MOUSSA ANI SAMOU	MORIBALA	2233610008	11.34351455	-8.22260946	Handpump	NA
171	SERE MOUSSA ANI SAMOU	BANKOUMANA	2233610010	11.31059818	-8.274499141	Handpump	NA
172	SERE MOUSSA ANI SAMOU	BANKOUMANA	2233610011	11.30876196	-8.277319903	Handpump	NA
173	SERE MOUSSA ANI SAMOU	GANSEREFOUGA	2233610020	11.05226629	-8.328746986	Handpump	NA
174	SERE MOUSSA ANI SAMOU	SIEKOROLE	2233610021	11.32514527	-8.260167008	Handpump	NA
175	SERE MOUSSA ANI SAMOU	SIEKOROLE	2233610023	11.31983072	-8.258765806	Handpump	NA
176	TAGANDOUGOU	BINKO	2233611001	11.64178625	-8.244902389	Handpump	NA

177	TAGANDOUGOU	BINKO	2233611002	11.64033404	-8.243984738	Handpump	NA
178	TAGANDOUGOU	FARABACOURA	2233611008	11.64354372	-8.251535827	Handpump	NA
179	TAGANDOUGOU	FARABACOURA	2233611009	11.64250504	-8.252534196	Handpump	NA
180	TAGANDOUGOU	FARABACOURA	2233611010	11.64219738	-8.251127964	Handpump	NA
181	TAGANDOUGOU	FARABACOURA DOUGOUCORO	2233611011	11.59255162	-8.249573624	Handpump	NA
182	TAGANDOUGOU	BALAMA	2233611013	11.58503812	-8.298979914	Handpump	NA
183	TAGANDOUGOU	BALAMA	2233611014	11.58728158	-8.298567608	Handpump	NA
184	TAGANDOUGOU	BALAMA	2233611015	11.58830329	-8.298979159	Handpump	NA
185	TAGANDOUGOU	FARABACORO	2233611017	11.59625856	-8.338438813	Handpump	NA
186	TAGANDOUGOU	FARABACORO	2233611019	11.5966261	-8.336901823	Handpump	NA
187	TAGANDOUGOU	TIERANY	2233611020	11.62075165	-8.357342351	Handpump	NA
188	TAGANDOUGOU	GUELEBA1	2233611021	11.63433658	-8.320156038	Handpump	NA
189	TAGANDOUGOU	BEKO	2233611022	11.55208392	-8.363178503	Handpump	NA
190	TAGANDOUGOU	TIEGOUEKOUROUNI	2233611025	11.51923432	-8.336797217	Handpump	NA
191	TAGANDOUGOU	BOKO	2233611034	11.46887898	-8.421861548	Handpump	NA
192	TAGANDOUGOU	BIDABA	2233611036	11.51322437	-8.389705885	Handpump	NA