Improving the reliability of water service delivery in rural Kenya through professionalized maintenance: a system dynamics perspective

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Abstract

Reliable water service delivery continues to be a complex global issue that is particularly challenging in rural communities. Despite billions of dollars of infrastructure interventions, sustainable water services remain out of reach for millions of people. Professionalized maintenance services have emerged as a service provision strategy to supplement the community-based rural water management approach. This study applies system dynamics modeling to assess the potential impact of scaling up professionalized maintenance services on piped water systems in Kitui County, Kenya. The study results show that over a 10-year simulation, calibrated with 21 months of empirical data and based on a range of key

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assumptions, delivery of professionalized maintenance services across the county may increase county-wide functionality rates from 54% to over 83%, leading to a 67% increase in water production. Furthermore, the increase in preventive maintenance activities and proactive repairs can lead to less frequent major breakdowns, and reduction in county government spending on major repairs by over 60%. However, current service fee income from communities accounts for 8% of the total cost of service, necessitating substantial sustained external financing or government subsidies to be financially viable at scale.

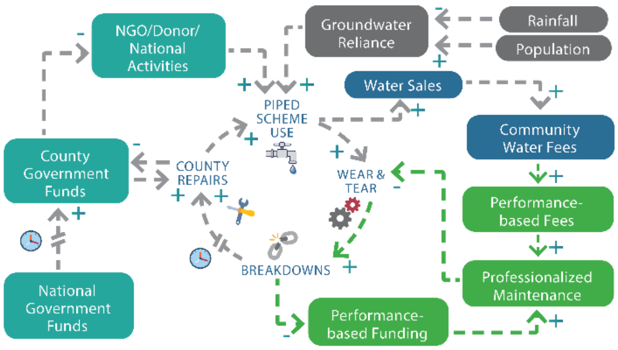
Keywords

Rural, water, maintenance, system dynamics, modeling, functionality, finances, sustainability

Synopsis

The effects of professionalized maintenance on rural water services are not well understood. This study finds that professionalized maintenance can increase pump functionality rates and water volumes while reducing repair costs.

Graphical Abstract



Introduction

The United Nations Sustainable Development Goals (SDGs) emphasize the complex global challenges facing humanity along the path towards a sustainable future. Reliable water access is one of those challenges, with 771 million people still lacking access to basic water services, 80% of whom live in rural communities[1]. To achieve SDG 6 (universal and equitable access to safe and affordable water) by 2030, the disparity between rural and urban areas must be addressed. Decades of engineered water infrastructure solutions have improved water access in rural communities of low- and middle-income countries; however, poor planning and implementation strategies have left nearly a quarter of these water schemes non-functional[2]. The complexity of achieving reliable rural water access stems from interconnections of technical, social, economic, and environmental factors all working in dynamic concert to promote or inhibit sustainable service delivery outcomes[3–7].

Over the last decade, service delivery models have emerged in the rural water sector in under-resourced contexts, with research suggesting a shift away from infrastructure interventions that lack post-construction support[8,9]. A variety of studies have identified factors that influence the reliability of rural water service delivery, including the role of supply chains to facilitate the availability of spare parts[10], the availability of skilled technicians to conduct maintenance and repairs[11,12], and the role of government in mobilizing finances[13]. Investigations into sustainability factors have highlighted the need for professionalized maintenance services, where skilled technicians operate within established institutional arrangements and align with local policy frameworks. Innovative models for maintenance service provision have emerged, seeking to provide reliable rural water service delivery[14,15]. However, implementing professionalized maintenance requires consideration of robust institutional arrangements, regulatory frameworks and sustainable financing[16]. Considering the nascency of many of these maintenance models, there is little understanding of how they disrupt the existing complex system of interacting factors that affect service reliability. Furthermore, the specific effects of implementing a professionalized maintenance approach on water point functionality throughout a geographical region, as well as the financial implications of providing the service in terms of costs and savings, are not well understood. To explore these knowledge gaps, this study investigates the financial and functionality effects of implementing a professionalized maintenance service in Kitui County, Kenya, through development, calibration and simulations of a system dynamics model.

Study Context

In Kenya, roughly 50% of the rural population has access to basic drinking water services and over 27% rely on untreated surface water[1]. This is in stark contrast to the urban population, of which nearly 90% have access to at least basic water services and only 5% rely on surface water[1]. The Constitution of Kenya (2010) stipulates that clean and safe water is a basic right of every person, and that the responsibility of water service delivery is devolved to the county government level[17]. However, county-level water service providers often fail to reach rural areas which remain largely underserved, and community-based management with delayed government intervention continues to be the status quo[18]. In 2010, safe drinking water became a constitutional right for every Kenyan; yet, a decade later in the census of 2019, over one in five Kenyans stated their main drinking water supply was surface water, such as a river or a stream[19].

The failure to match policy aspirations with service realities is not unique to Kenya though leaves Kenya's 47 county governments with the difficult challenge of delivering sustainable drinking water in rural areas where progress has been slowest.

Sustainability studies have recently placed emphasis on transdisciplinary, pluralist approaches to sustainable interventions which integrate multiple kinds of knowledge with a particular focus on action-oriented research[20]. Caniglia et al. (2021) suggest that research conducting sustainability experiments in real-world "laboratories" should be "1) intentionally designed for transformational change towards sustainability, 2) involve shared agency of multiple actors, and 3) materialize through contextual realization of constantly evolving and emergent settings"[20]. FundiFix[21] is a professional maintenance approach that has evolved through such pluralistic approaches in pursuit of sustainable rural water service outcomes, and is being applied to a subset of handpumps and piped schemes in Kitui County, Kenya. Kitui County is one of 29 counties in Kenya classified as Arid and Semi-Arid Land (ASAL). Nearly half of Kitui's population live in absolute poverty[22], and approximately half the population of Kitui lacks access to improved water sources[23].

Communities enrolled with FundiFix services sign annual contracts and pay monthly fees based on pumped water volumes in exchange for routine preventive maintenance of water infrastructure and guaranteed repairs within 3 to 5 days of breakdowns. FundiFix has been supported by a trust fund since 2016 to provide a targeted subsidy to ensure service delivery is maintained to honour the contractual guarantee of payments from participating communities and schools. The Kitui Water Services Maintenance Trust Fund is a legally registered entity with a mandate to support the maintenance of rural water infrastructure. Since 2016, the source of funds has evolved from relying on research or development grants to securing a majority of funds from Kenyan and international companies based on performance based contracts in 2021. Two objectives of the fund are to ensure funding stability and to test a performance based contractual model with FundiFix.

The intentional design of the FundiFix approach extends beyond service provision to a number of other co-developed activities intended to improve rural water sustainability in the county, including facilitating quarterly forums with relevant actors to improve rural water sector coordination, collecting and sharing county-wide infrastructure data through an online database to improve monitoring, and supporting the development of a water bill and policy that promotes consideration for funding for the aforementioned forums and database, as well as creating a pathway for the viability of maintenance services in the county.

What is not well understood is how FundiFix, or similar professionalized maintenance approaches, will affect financial and functionality outcomes when operated at scale. We define financial impacts by repair and maintenance costs, and generated income, functionality impacts by functionality rates and volume of water produced, and scaling is considered by increasing the proportion of schemes receiving maintenance services in the county. FundiFix currently serves ~5% of piped schemes in Kitui County, and the implications of expanding services are not known. This provides an opportunity to investigate the effects of expanded professionalized maintenance provision through the use of modeling. In this study, we apply system dynamics modeling to understand the potential financial and functionality impacts of scaling the FundiFix professionalized maintenance service on piped water systems within Kitui County, Kenya. The study focuses on piped schemes because they serve a larger population per pump, are an infrastructure priority for the Kitui County government, and a key component of FundiFix's growth strategy. Specifically, we seek to understand the effect of scaling FundiFix service coverage across Kitui County on 1) the county-wide functionality rates of rural piped schemes, 2) the volume of water produced by rural piped schemes across the county, 3) the amount of money spent by the county government on repairs, and 4) the income generated by community water committees from piped scheme water sales. We also seek to understand the cost of scaling FundiFix services across Kitui County and the extent to which potential savings in county government repair spending could offset this cost. The goal of this research is to contribute to an improved understanding of how intentionally professionalized maintenance services can affect rural water service delivery outcomes.

Methods

System dynamics modeling is a tool to understand the unpredictable and dynamic ways complex system behavior changes over time, through the identification, parameterization, and simulation of feedback mechanisms, delays, and non-linearities of the system[24]. System dynamics models are explanatory models developed to create an improved understanding of how complex systems, composed of interacting factors and feedback loops, behave under different policies or courses of action[25]. As noted by McAlister et al. (2022), linear-thinking approaches fail to address the complex nature of global challenges, which require participatory, systems-based approaches[26]. Thomas and Brown (2021) note the particular importance of feedback through developed partnerships and advanced monitoring to improve environmental interventions[27]. Aligning with the aforementioned contemporary pluralist approaches to sustainability studies, system dynamics modeling was selected for this research because it is an action-oriented approach that explores the interconnected factors and feedback loops that comprise the system, enables shared agency through collaborative production and emergent understanding of counterintuitive system behavior, and can inform and optimize the intentional design of effective interventions. There are also many unknowns regarding the shift from community-based management approaches to professionalized maintenance services, and while the availability of quantitative analyses to aid policy makers' with such decisions is often limited, system dynamics modeling is an approach that leverages data to explore the costs and benefits of doing so.

To conduct the analysis, we used a mixed methods approach that 1) incorporated semi-structured interviews with relevant sector actors in Kitui County to understand the factors that affect rural water service delivery; 2) developed causal loop diagrams to hypothesize the interactions of factors and feedback loops that drive system behavior within the reference mode of status quo community-based management with government intervention for rural water services; 3) compiled quantitative data on different factors; 4) developed stock-flow models; and 5) ran simulations to test scenarios for the implementation and scale-up of the professionalized maintenance service. These steps are outlined in Figure 1 and discussed in further detail in this section.

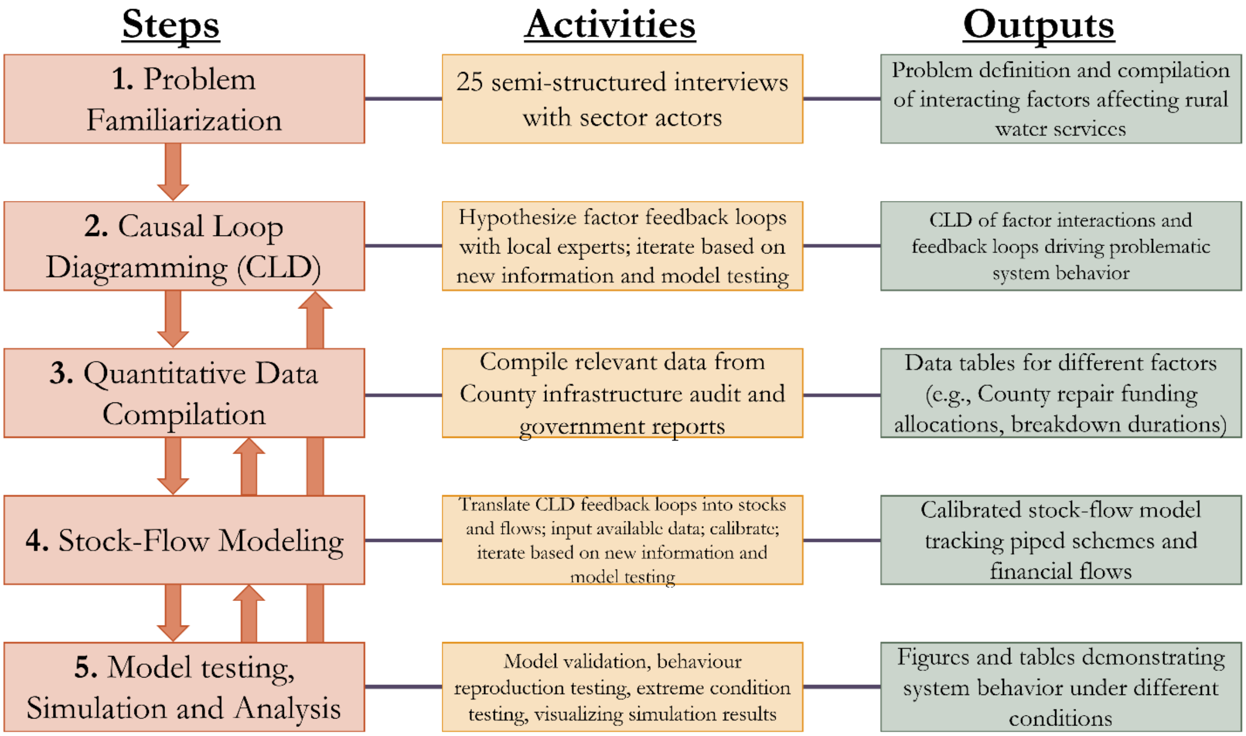


Figure 1: Research steps, activities and associated outputs. Semi-structured interviews with relevant rural water sector actors informed problem definition and the factors that affect service delivery. The factors were used to hypothesize feedback loops that drive problematic system behavior and inform data compilation and stock-flow model structure. The process was iterative and knowledge gained from simulation and analysis enabled re-evaluation of stock-flow models, required data and hypothesized factor interactions in CLDs.

Data Collection

Semi-structured interviews with government officials, NGOs, donor organizations and other relevant actors in the local water sector provided qualitative data on the factors affecting rural water service delivery in Kitui County. The interviews identified the successes and challenges affecting sustainable service delivery. A social network mapping activity described elsewhere[28], preceded the interviews and provided a tangible approach to elucidate respondents' knowledge of their interactions with other actors within the rural water sector. The collective responses from interviewees representing 25 organizations in the county informed the factors within the modeled system. Details on the interviewees, semi-structured interview process and qualitative data analysis have been reported elsewhere[28], and are summarized in Supporting Information. Qualitative data collection was approved under the University of Colorado Boulder Institutional Review Board (IRB) protocol # 18-0314, and research was conducted under the Kenya National Commission for Science, Technology and Innovation (NACOSTI) permit # P/19/42437/30344. Valcourt and Walters (2021) investigated the shift in these stakeholders' understanding throughout the implementation of the professionalized maintenance service and noted "over the course of the project, stakeholders increasingly conceptualized more factors that influence service delivery and interactions between them, demonstrating a greater understanding of the complexity and nuance of water, sanitation, and hygiene (WASH) systems. In addition, the study showed that systems approaches can shift stakeholder understanding of factor interactions that align with key tenets of sustainable service delivery, in particular the linkages between operations and maintenance, service performance, private sector engagement, and a decreased dependence on community-based management approaches"[29].

Quantitative data were collected from a county-wide audit of water infrastructure[18], government reports and operational data from the professional maintenance service, FundiFix. These data included national and county-level budget allocations to the water department, the number of piped schemes in each sub-county, target installation and repair rates, seasonal daily pump use averages, breakdown frequencies, breakdown durations, and tariff collection by water committees. A comprehensive list of model factors and data sources is provided in Table S1 in Supporting Information.

Model Development

Development of the system dynamics model began with a compilation of interacting factors identified through data collection interviews, which were then used to develop a conceptual framework for how factors interact known as a causal loop diagram (CLD). Table S2 in Supporting Information indicates the boundaries of the model by categorizing the variables as endogenous (internal, affected by other variables), exogenous (external, affect endogenous variables but are not affected) and excluded variables. Variables that were expected to affect service delivery outcomes, or were described as doing so in data collection interviews, were included. . To develop the CLD, the interactions between variables were assessed based on whether a change in one variable is hypothesized to impact the magnitude of another in the same or opposite direction, and were assigned polarities of + or –, accordingly. The feedback loops created by + or - connections were then characterized as reinforcing (an even sum of - polarities in the loop) or balancing (an odd sum of - polarities in the loop). The hypothesized feedback loops indicated the possible variable interactions that drive the changes in piped scheme functionality seen over time in the region. The variable interactions from the CLDs were then used to develop stock-flow models, which allowed for the quantification of variables, their interactions, and how they change over time. Stock-flow models also enabled testing and re-evaluation of the hypothesized feedback loops identified within the CLDs. Stock-flow models are comprised of stocks, which represent the state of factors at a given time (e.g., infrastructure repair funds) and flows, which are occurrences that change stocks over time (e.g., repair spending driven by breakdown rates). In stock-flow models, stocks are typically represented visually as boxes and flows as large arrows that connect to stocks. STELLA Architect software from isee systems (https://www.iseesystems.com/) was used to develop the CLDs and stock-flow models in this analysis. Through data collection and stock-flow model development, and testing, the factors and feedback loops of the CLD also evolved. The system dynamics model development process was intended to follow methodologies described by Sterman (2000)[30] and Ford (2010)[31], through co-development and iteration. Bi-weekly meetings with a local expert (co-author, Nyaga) on FundiFix operations and Kitui's rural water sector took place throughout model building, enabling the structure of the CLDs and stock-flow models to be co-developed and evolved iteratively through regular feedback and re-evaluation of factor connections, polarities, data needs and simulation outputs. The details of the specific stock-flow model components and their interactions are provided with screenshots in Supporting Information. In addition to quantitative model testing and validation activities, such as extreme condition and behaviour reproduction testing, this form of participatory model development methodology sought to bring about meaningful insights towards sustainable service delivery outcomes by integrating different forms of knowledge, including 1) co-produced knowledge to inform relevant factors in the CLD, 2) generative knowledge to inform how factors interact, and 3) the iterative development of the model structure utilizing emergent knowledge, where insights were gained through exploration, reflection and evaluation of simulated system behavior in-relation to the real-world experiences of local experts[20].

The stock-flow model was calibrated and tested using 42 months (July 2017 to December 2020) of metered volumetric flow readings from 924 observations of 24 different piped schemes served by FundiFix. Half of this data was used for model calibration and the other half was used for model testing. The variables included in model calibration were identified through a sensitivity analysis of 58 variables, adjusted across ranges of +/- 50% of their initial estimates, using 100 simulation runs. The most sensitive variables were identified as average daily pump use, per capita daily water demand, and spare parts/technician delays. The average monthly volumetric flow per scheme is calculated in the model using average daily pumping hours which vary seasonally and average production capacities of pumps (volume per unit time) that were compiled from the county infrastructure audit data. Although seasonal variation in pump use appeared in the calibration dataset, climate variability data was not available to be directly incorporated into the model. The calculated values for average monthly volumetric flow inform the driving factors within the model as breakdown rates are a function of pump use. The optimization function in STELLA Architect was used for conducting the calibration, which minimizes the mean squared error between calibration data and the simulation output. In model testing, the simulated output had a root-mean squared error of 68.4 m^3/month and R^2 of 0.44. The model structure was also tested with indirect extreme condition tests[32] and model behaviour tests. The plot showing calibration, testing and simulation results (Figure S14) and details on sensitivity analysis, calibration and model testing are included in Supporting Information.

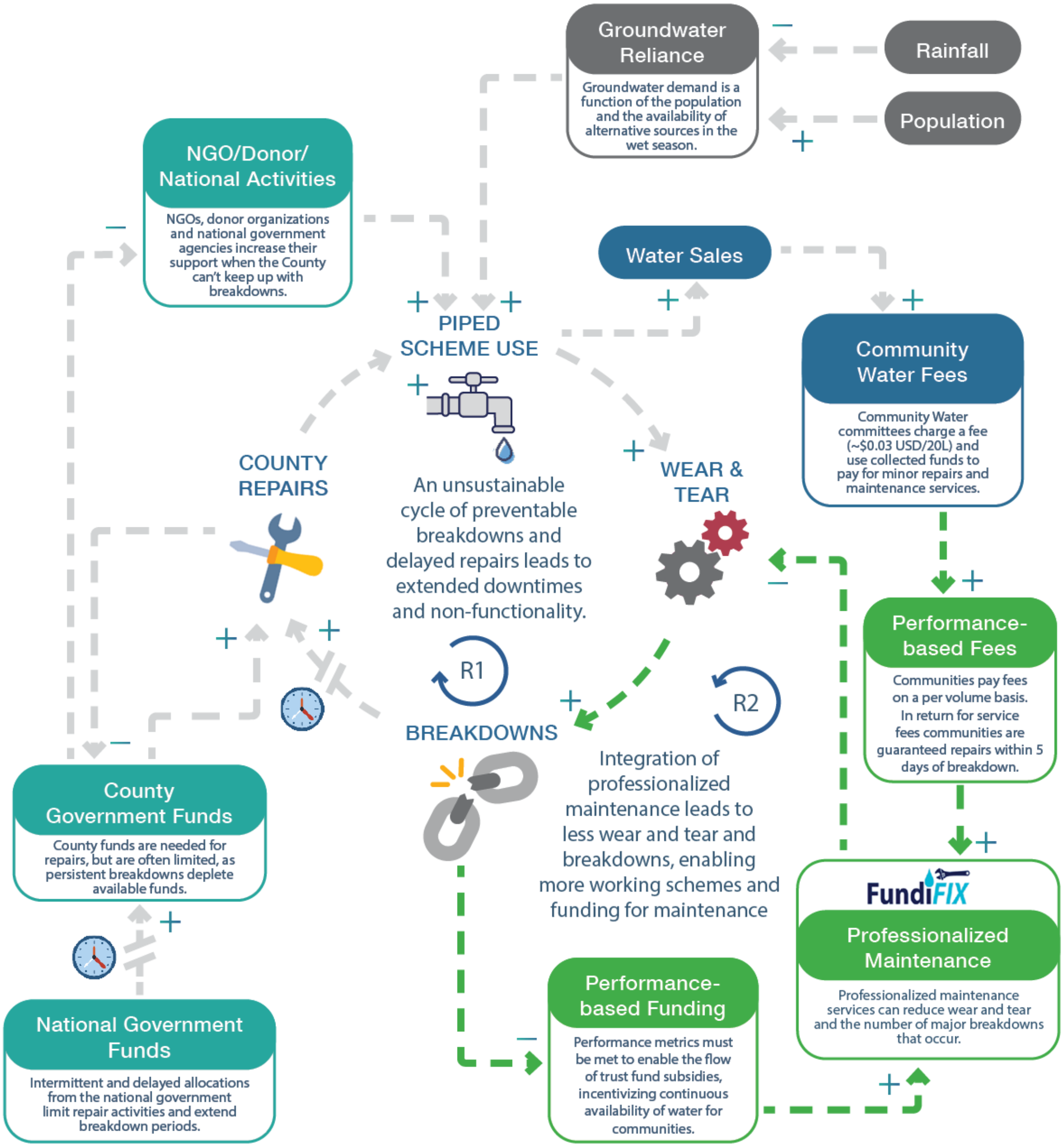
Results and Discussion

System dynamics modeling, as a co-developed analysis methodology, provided a platform for collaborative and emergent understanding of complex system behavior. By investigating the scalability of the FundiFix professionalized maintenance service through iterative model development, the analysis approach paralleled the co-developed, intentional design of sustainability interventions and action-oriented research described by Caniglia et al. (2021)[20], such as the development of the FundiFix approach itself. The sections below discuss the outcomes of model development, and model simulation results pertaining to the impact of

FundiFix services on county-wide piped scheme functionality rates, along with the implications and costs of scaling the service.

System Factor Interactions and Projected Functionality

The compilation of factors obtained from qualitative analysis of the semi-structured interviews with local rural water sector actors was used to hypothesize system behavior through the development of an initial CLD. A loop analysis of the stock-flow model, corroborated by stakeholder input, identified two key feedback loops driving system behavior, shown below in an illustrative CLD (Figure 2). The complete and final CLD (Figure S2) with more detailed descriptions of the feedback loops is provided in Supporting Information. This CLD shows the key driver of service delivery outcomes is an unsustainable cycle of infrastructure breakdowns that depend on government intervention for repairs. Donor programs that focus primarily on infrastructure access contribute to this cycle by prioritizing new installations over rehabilitations and maintenance of existing schemes. Intermittent and irregular financial flows from the national government limit county activities, causing delayed repairs and increased dependence on external support. Pump use is driven by groundwater reliance which increases in the dry season when there are limited surface water alternatives. The two key feedback loops interact through the integration of FundiFix services, which provide preventive maintenance to reduce the number of major breakdowns that occur, alleviating pressure on county government funds to conduct repairs. The maintenance service enables pump use and community water sales to create an income stream for per volume service fees, which dampen the effects of wear and tear by funding preventive maintenance. Performance-based funding supplements community fees and incentivizes short breakdown durations and continuous availability of water.



Groundwater demand is a function of the population and the availability of alternative sources in the wet season.

NGOs, donor organizations and national government agencies increase their support when the County can't keep up with breakdowns.

Community Water committees charge a fee (~$0.03 USD/20L) and use collected funds to pay for minor repairs and maintenance services.

An unsustainable cycle of preventable breakdowns and delayed repairs leads to extended downtimes and non-functionality.

Communities pay fees on a per volume basis. In return for service fees communities are guaranteed repairs within 5 days of breakdown.

Integration of professionalized maintenance leads to less wear and tear and breakdowns, enabling more working schemes and funding for maintenance

County funds are needed for repairs, but are often limited, as persistent breakdowns deplete available funds.

Professionalized maintenance services can reduce wear and tear and the number of major breakdowns that occur.

Performance metrics must be met to enable the flow of trust fund subsidies, incentivizing continuous availability of water for communities.

Intermittent and delayed allocations from the national government limit repair activities and extend breakdown periods.

Figure 2: Illustrative causal loop diagram highlighting the key feedback loops driving system behavior. Grey arrows indicate the status quo, while green arrows indicate the integration of professionalized maintenance services.

A stock-flow model was created based on the interactions and feedback mechanisms identified in the CLD. The model structure is divided into sectors which are connected through interacting factors. A detailed overview of the stock-flow model, including a complete set of screenshots of all model components (Figures S3-S13), descriptions of stock, flow and converter interactions as well as a table of all model factors, equations and data sources (Table S1) is provided in Supporting Information. A simplified overview of the key model sectors, stocks (accumulation or state of a parameter, shown as boxes) and flows (occurrences that change a stock over time, shown as arrows) used in the model is illustrated in Figure 3, which indicates the connections between finances and functionality outcomes. Specifically, two key feedback loops in the CLD (Figure 2) that inform the connections in the stock-flow model are, R1, a reinforcing loop where the intermittent national allocations that lead to periodic depletion of government repair funds (Government finances sector), result in delayed repairs (Gov’t schemes sector), and overuse of working schemes, and R2, a reinforcing loop where the integration of a professionalized maintenance service which takes on responsibility for a portion of schemes (Uptake between Gov’t schemes and FundiFix schemes sector), leads to reduced wear and tear and rapid repairs, reducing breakdowns and increasing the number of working schemes, leading to increased water sales income to local water committees as well performance-based subsidies, generating funds to pay service fees and continue maintenance provision. FundiFix service fees are set on a per volume basis at roughly 30-50% of the fees water committees charge users at the point of collection, with operating costs offset by trust fund subsidy. In the model we assume installation, repair and maintenance activities are contingent on the availability of sufficient funds to cover their costs. National government funding determines county budget availability for water department spending. The availability of funds and cost of new infrastructure installations and piped scheme repairs determine whether or not target installation and repair rates are achieved. To simplify the nature of breakdowns, which can be caused by a number of factors for which data was not collected, such as corrosivity of water, quality of parts, technical specification, etc., we model pump breakdowns as a function of pump use. Cumulative pumping hours lead to breakdowns after an assigned threshold is crossed, and thresholds are determined through calibration of model parameters using 21 months of pump use and functionality data averaged from 924 site observations. Breakdowns cause piped schemes to transition from states (stocks) of *Working* to *Broken*. Repairs, based on the availability of funds, enable the transition from *Broken* to *Repaired* and *Working*. Functionality is calculated as the proportion of *Working* to total piped schemes at any given time. These findings are consistent with recent studies applying system dynamics modeling to investigate rural water supplies in Indonesia, Bolivia and Columbia which also noted the reinforcing loop between breakdowns, repairs and the critical role of finances[4,7].

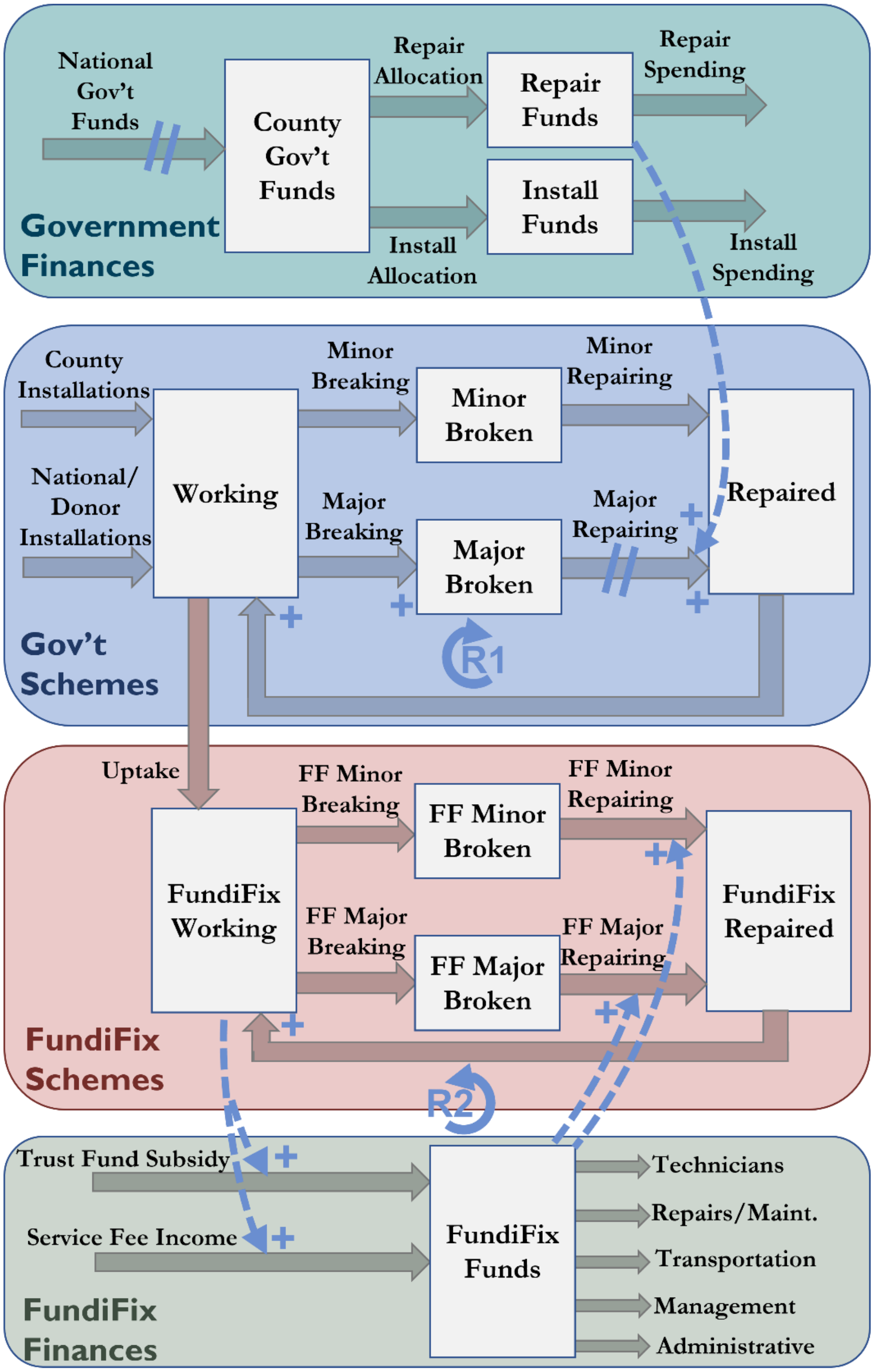
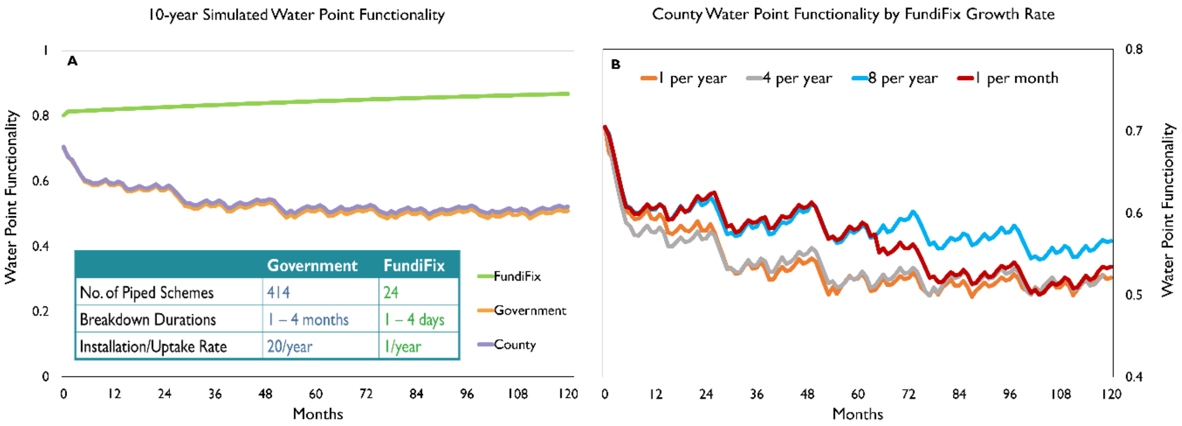


Figure 3: Illustrative stock-flow model depicting the interactions between sectors for government finances, the functionality of government-managed piped schemes, and the uptake and functionality of schemes served by FundiFix and FundiFix finances.

Stock-flow model simulations were run for 10-year durations. Breakdown frequencies as a function of borehole use-hours and breakdown durations for both government-supported schemes and FundiFix schemes were informed by available data and disaggregated by breakdown types (minor vs. major vs. full rehabilitation) based on cost and complexity of the repair. Preventive maintenance performed on FundiFix schemes led to less frequent major breakdowns, enabling shorter average downtimes and sustained functionality rates. FundiFix repair rates were calculated based on availability of funds, average repair costs and technician availability to conduct one repair/technician/day, the established norm for FundiFix technicians. County government repair rates were calculated based on average repair costs, the availability of funds, and yearly repair targets stated in government planning reports. As shown in Figure 2, external donor and national government activities increase when county government funds are depleted to avoid continuous decline in water point functionality. Predicted functionality rates (Figure 4A) from the stock-flow model show marked differences in functionality between piped schemes served by FundiFix (24 piped schemes) vs. the government approach (414 piped schemes). Two reinforcing feedback loops cause this behaviour in the system. Preventive maintenance reduces wear and tear and thereby the frequency and severity of breakdowns, leading to more working schemes. Simultaneously the guaranteed-service model incentivizes rapid repairs in the order of days rather than months. The resulting increase in working schemes leads to more pump use, and the per volume fee structure ensures that more working schemes provide more income to the maintenance service. Over a 10-year simulation FundiFix is able to maintain relatively high functionality rates, but the overall county-wide impact is relatively low because only ~5% of schemes are being served. Figure 4B shows how increasing the uptake rate, transitioning schemes from the status quo approach to FundiFix, does improve county-wide functionality outcomes. The findings are consistent with Cannon et al. (2022) who note through system dynamics modeling that the application of maintenance provision, specifically preventive maintenance, leads to drastically improved water system performance[7]. Increasing FundiFix uptake rates from the current rate of 1 new scheme per year to 8 per year with no change to resource levels increases county-wide functionality by 5%, on average. However, increasing uptake too quickly (e.g., 1 new scheme per month) without additional resources appears to be unsustainable for FundiFix. In the model, provision of maintenance services is a function of the number of technicians, so raising the number of schemes served while keeping technician numbers stagnant leads to an accumulation of broken schemes. Figure 4B shows that at this uptake rate of 1 new scheme per month, repair rates were sustained until a tipping point was reached. Taking on additional schemes beyond this without additional resources revealed that technicians could no longer keep up with breakdown rates leading to a decline in county-wide functionality back to status quo levels. Details of this dynamic are provided in Supporting Information and Figure S15. County-wide functionality at this scale remains dependent on the dynamics of the status quo government approach, where functionality is driven by the availability of intermittent repair funds, leading to the periodic pattern observed in Figure 4B.



	Government	FundiFix
No. of Piped Schemes	414	24
Breakdown Durations	1 – 4 months	1 – 4 days
Installation/Uptake Rate	20/year	1/year

Figure 4: A) Simulated functionality of schemes served by FundiFix (green) achieving relatively high functionality compared to those served by the status quo government/CBM approach (blue) and the entire county (orange); B) Scaling up FundiFix services does improve county-wide functionality rates but, without increasing the number of technicians, a tipping point occurs at a rate of 1 new scheme per month where repairs can no longer keep up with breakdown rates. Plots show average values from multiple simulation runs.

Implications of Scale-Up

To test the county-wide implications of scaling up FundiFix coverage, simulations were run for 10-year periods at coverage levels of 5% (current), 25%, 50%, 75% and 90%, accounting for growth in total number of schemes in the county due to new installations at current rates. The model results (Figure 5) showed that increased coverage levels led to increasing functionality rates, eventually leading to functionality rates currently observed in schemes served by FundiFix (>80%). This appears to be the maximum functionality achieved by the maintenance service, based on how the model's functionality metric is calculated. While professionalized maintenance reduces the frequency and duration of major breakdowns, as well as the duration of minor breakdowns, the minor breakdowns are still reported at roughly the same rate as the status quo condition. Since there is no point in the model when no pumps are being run, there are always some broken pumps at any point in the model simulation. This peak functionality is achieved at the 75% coverage level, at which point county funds are able to adequately support the remaining 25% of schemes. The details of this dynamic are described further at the end of this section and in Figure S1. As stated earlier, we define functionality here as the proportion of working to total piped schemes at any given time, recognizing that there are multiple and competing definitions of functionality[33]. A result of increased functionality was that over a 10-year period the total volume of water produced also increased, growing by 67% between current

(5%) and 90% coverage levels. While significantly increasing the amount of available water to meet per capita demand, this increased production amounts to less than 2% of Kenya's safe groundwater abstraction rate[34]. Based on average community tariffs of $0.03 USD/20 L jerry can (2021), the increased volume produced could lead to growth in income to community water committees, accounting for rural population growth and assuming no change in per capita water demand. The model results suggest this amounts to approximately $48M USD in added revenue at the community level over a 10-year period at 90% coverage.

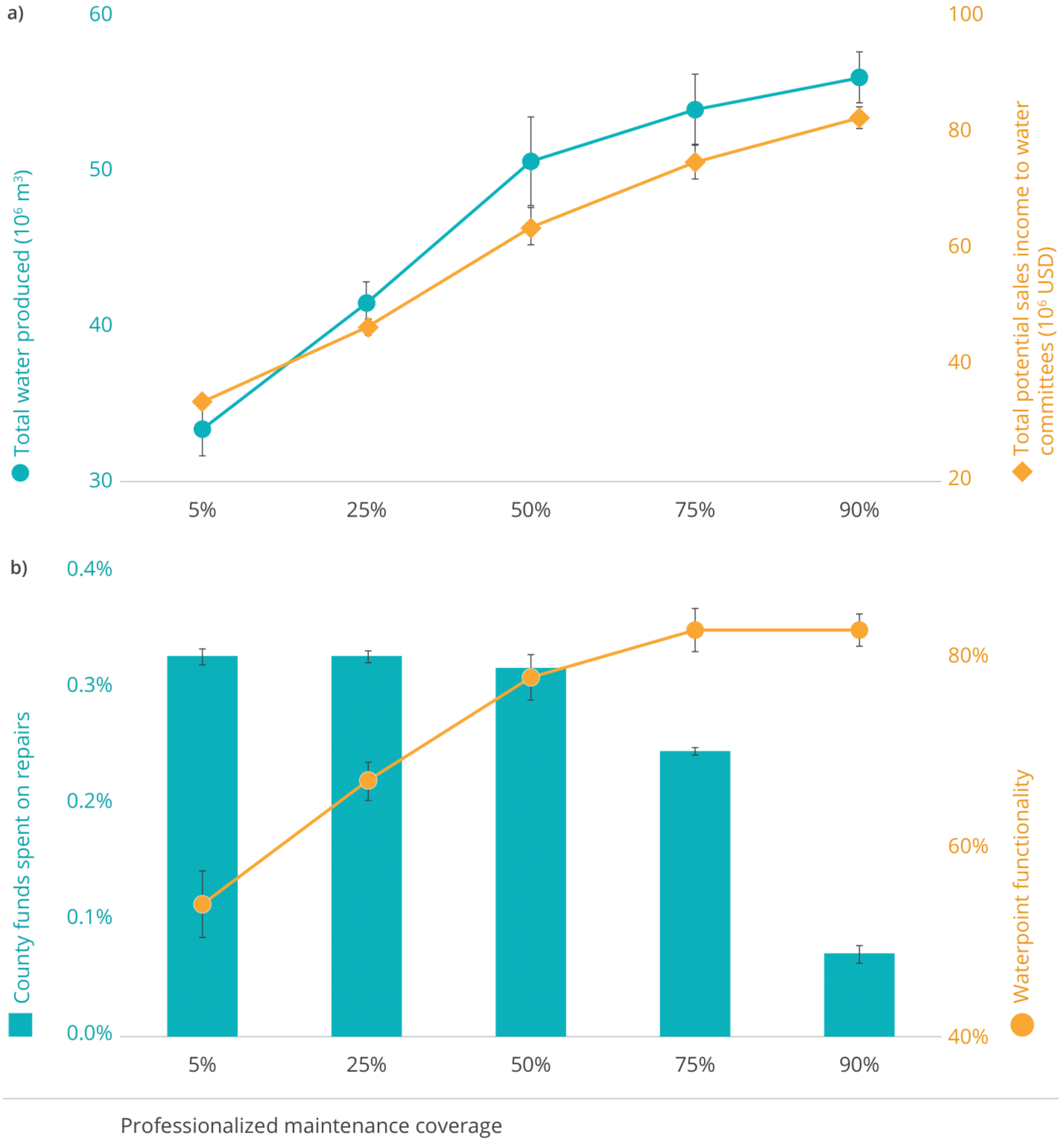


Figure 5: (a) Projected total volume of water produced by piped schemes across the county increases by 67% with professionalized maintenance coverage (teal) increased from 5% to 90% coverage. Assuming no change in per capita water demand, this results in an additional $40M USD over 10-years to water committees from per volume tariffs (orange); (b) As professionalized maintenance coverage increases, projected county-wide functionality rates increase to over 80% (orange). Less frequent major breakdowns and a shift in repair responsibility lead to a 77%

reduction in projected government repair spending when coverage is increased from 5% to 90% (teal). Data points are mean values from multiple simulation runs, with error bars representing standard deviations.

The model results suggest that an additional outcome of increased FundiFix coverage is the reduction in major repair spending by the county government. As schemes transition out of county government responsibility and into FundiFix service provision, preventive maintenance reduces the total number of major breakdowns that occur and the county spends less money on repairs over a 10-year period (Figure 5B), with reductions reaching 77% at 90% FundiFix coverage.

Irregular and intermittent transfers from the national government to the county affect county-level budgets for various activities including the proportions allocated to the water department and thereby water infrastructure repairs. When funds are depleted, a backlog of breakdowns build up, and funds that become available are quickly depleted again. The inability for the model to reach a steady-state between breakdowns and repairs means that allocating county budget to lower administrative levels fails to achieve the desired financial buffering capacity, and that sub-county level funds are still dependent on national government financial flows. Figure S1 in Supporting Information shows that as FundiFix takes on a higher proportion of schemes in the county, the shift in repair responsibility and reduction in major repairs allows county repair budgets to fluctuate without total depletion, funding repair activities without being impacted by the intermittency of national government allocations. At lower FundiFix coverage levels, the back-log of needed repairs accumulates leading to spikes in spending when a national government allocation comes to the county.

Resource Requirements for Scale-up

Achieving 90% coverage levels required building a growth strategy into the model. The uptake rate (addition of schemes into the FundiFix service) determines how quickly a 90% coverage can be achieved. However, increasing coverage levels also affects how quickly major expenditures, like personnel hiring and vehicle purchases, occur. The model results showed that as uptake rates increase, available FundiFix funds initially decline at greater rates. In the model, all repair and maintenance activities are contingent on the availability of funds to conduct them and therefore, rapid scale-up triggers rapid expenditure, and the decline of available maintenance funds. This in turn leads to a temporary reduction in functionality rates until a greater influx of external subsidy funds can occur. An uptake rate of 8 schemes per month achieved 90% coverage after 65 months of operation with less than 3% reduction from peak functionality (~80%). Details of modeling parameters to simulate scale-up are discussed in Supporting Information. Figure 6 shows the cost breakdown of achieving 90% coverage in 65 months and sustaining that coverage level for a 10-year period.

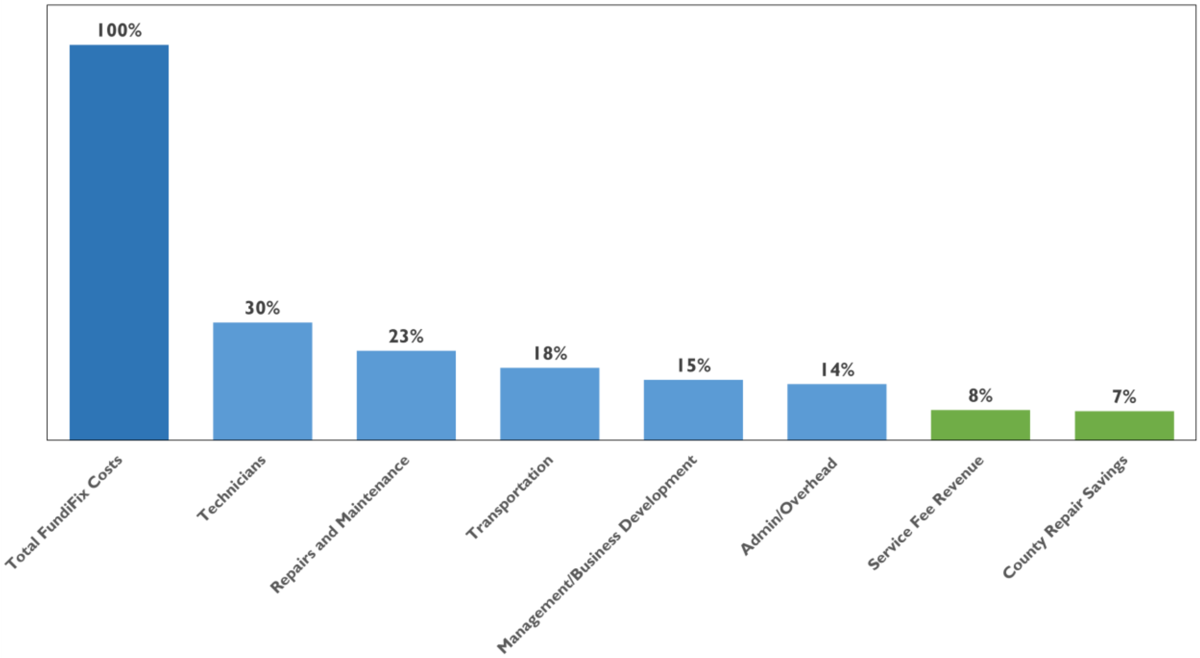


Figure 6: Projected relative costs of achieving and sustaining 90% FundiFix coverage across Kitui County (blue) and corresponding service fee income and county repair savings across the same time period (green). Data are mean values from multiple simulation runs with <1% standard deviation.

Over the 185-month simulation, the total cost of FundiFix service provision amounts to roughly \$29,000,000 USD, which includes both the 65-month growth period to reach 90% coverage and 120-month simulation at that scale. The cost to operate at 90% coverage and maintain over 80% functionality is roughly \$0.20 USD/person served/month. Income from service fees in this time period cover 8% of these costs, requiring 92% external subsidy. County repair spending is reduced by 66% when comparing the 185-month FundiFix scale-up simulation to 185 months of operation at current scale, resulting in over 200,000,000 KES (~\$1,770,000 USD, 2021) in cost savings. If invested in the FundiFix service, those cost savings would reduce the required external subsidy to 85% of total costs.

Achieving financial sustainability is a global challenge with urban utilities requiring in the order of \$300 billion USD per year for operational costs, without including costs for China or India[35]. In the rural sector data are limited, though longitudinal data from over 2,000 schemes in four countries in Africa indicate water users will pay around one third of local operational costs based on a performance contract guaranteeing rapid repairs[36], while the working ratio for FundiFix at the current scale is roughly 16-21%[16]. The implication is that the projected costs can be reduced if the service level is high enough to unlock user payments. The findings from this study demonstrate that professionalized maintenance can provide an improved level of service, and similarities in system structure with other contexts[4,7] indicate the broader applicability of these findings beyond the Kenyan context. As many professionalized maintenance services are still in their nascency and providing services to a limited number of schemes, the results demonstrate the potential benefits from scaling up. There will remain a significant dependence on subsidy, and though the project efficiencies from reallocating county budgets will address some but not all of these costs, the stability of subsidy flows will certainly affect outcomes. It is likely that stronger coordination with donor and NGO projects would close the funding gap. Ultimately, the challenge may be more political and institutional than financial in achieving coordination and compliance to long term local goals over short term project objectives, as previous research has demonstrated the potential value of reprioritizing funding allocations from the installation of new schemes towards maintenance provision[3].

The application of system dynamics modeling as a collaborative analysis tool provided a platform for emergent understanding of complex system behavior, and may be particularly valuable for investigating the effects of sustainability interventions. The interviewees who informed model parameters experienced greater understanding of the complexity of rural water service delivery in Kitui over time[29], as did the researchers who co-developed the model. The collaborative model development process facilitated reciprocal and emergent learning about the rural water sector, limitations of the status quo approach and opportunities for the implementation of professionalized maintenance. Specifically, the process allowed implementers to develop a growth strategy and informed discussions with government on funding requirements and potential implications on service quality. By investigating the scalability of the FundiFix professionalized maintenance service through iterative model development, the analysis approach paralleled the co-developed, intentional design of sustainability interventions themselves, and in this study, elucidated unique insights about the financial and functionality implications of implementing professionalized rural water maintenance services.

Limitations

Many assumptions had to be made during model development. While the subset of schemes used for model calibration showed indications of seasonal variability, the data did not fully capture the variation in water use that is observed over dry and wet seasons and how these patterns have changed over longer periods due to climate variation[37]. The calibration of the model to volumetric flow data from meter readings of schemes served by FundiFix assumes that the production capacity of these 24 schemes is representative of the schemes throughout the county. This is a conservative estimate, as infrastructure audit data indicates higher average production capacities amongst schemes not currently served by FundiFix. In the model, we assume that differences in schemes not currently served by FundiFix do not affect their ability to provide maintenance services after accounting for the costs of acquiring the necessary equipment and personnel to manage scale-up. In the case of increased production capacities, the implication is that service fee income would likely be higher following scale-up than what simulation results show. Service fee collection rates are assumed to be 50% of what is owed based on volume flows and fees. This estimate is based on current collection efficiency levels over the past two years, but studies on willingness-to-pay indicate that improved service reliability increases likelihood of payment[38]. Changes to collection efficiency as a function of water availability has not been incorporated into the model. The overuse of pumps beyond design capacities and differences in pump breakdown rates based on aging vs. new infrastructure was not incorporated in the model. Many of the results at scaled service-levels, such as water production and community water income, assume no change to per capita water demand. Population growth and urbanization rates are used to estimate future rural population levels over simulation timelines, but dynamics around how increased functionality rates and water availability may shift per capita water demand are not accounted for. In the model we apply the 5-year average inflation rate of 6% to all costs, and increase FundiFix service fees at the same rate to keep up with inflation; however, strategic approaches to service pricing are complicated and can vary based on the complexity of the schemes being served. We assume a flat per volume price for all schemes receiving FundiFix service. Lastly, while we strive towards universal access to safe and clean water for all, the provision of professionalized maintenance services is only a step towards that. This model did not include the important costs of water quality analysis and/or treatment, which need to be considered in future analyses.

Supporting Information

County repair spending; qualitative data collection and analysis; description of modeling of scale-up of services; causal loop diagram and description; stock-flow model and descriptions; model calibration and testing details; FundiFix scale-up dynamics; table of model parameters, equations and units; boundary table of endogenous, exogenous and excluded variables.

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