Turn up the Dial: System Dynamics Modeling of Resource Allocations toward Rural Water Supply Maintenance in East Africa

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Abstract: Water stress is increasingly affecting hundreds of millions of people around the world. In East Africa, severe and persistent drought periods negatively impact health and livelihoods. Drought increases reliance on mechanized boreholes to extract groundwater. However, without adequate resource allocations, effective monitoring of borehole functionality, and reliable maintenance service, breakdown rates increase and downtimes last many months. Our study applies system dynamics modeling to investigate the effects of allocating resources to borehole maintenance and repair in the Afar Region in Ethiopia and Turkana County in Kenya. We inform model calibration with runtime and functionality estimates derived from sensors installed on 245 boreholes and apply sensitivity analyses varying budget allocations to optimize for functionality. We conclude that increasing the borehole repair and maintenance budgets in Turkana from the current 30% to 85% of available budgets could result in an additional 83 working boreholes and 95% functionality in 2030. In Afar, increasing maintenance budgets from 38% to 79% could result in functionality levels of 75% by 2030, well above currently projected levels of 54%. **DOI: 10.1061/(ASCE)EE.1943-7870.0001982.** *This work is made available under the terms of the Creative Commons Attribution 4.0 International license, https://creativecommons.org/licenses/by/4.0/.*

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Introduction

Climate change is expected to exacerbate drought in East Africa, with the wet season experiencing rainfall reductions in recent years (Funk et al. 2015; Nicholson 2014). Drought conditions increase reliance on deep mechanized boreholes when surface water alternatives are depleted, while reducing these same aquifers' recharge (Thomas et al. 2019). Changing precipitation patterns also include flooding, which damages the infrastructure needed to extract groundwater during droughts. Without adequate resource allocations, both financial and in-kind resources such as spare parts and vehicles, repairs of essential infrastructure are delayed, reducing capacity to sustain reliable water access for millions of people.

Within the last ten years, the focus of the rural water sector has shifted from the delivery of infrastructure to the delivery of services (Schouten and Smits 2015). With this shift, a renewed focus on understanding the factors that influence sustainability as part of an interconnected system has emerged. Studies investigating sustainability factors for rural water services delivery have identified various interacting parameters, ranging from government structures and funding mechanisms (Pories et al. 2019) to local spare parts supplies and technician availability (Harvey and Reed 2006; Klug et al. 2018; Whaley and Cleaver 2017), leading to the emergence of professionalized maintenance services (Lockwood 2019; Lockwood and Le Gouais 2015) in some contexts. However, these services are still nascent and not widely available.

In arid, low-income contexts, such as our study regions of Afar Region, Ethiopia, and Turkana County, Kenya, the responsibility of rural water service delivery is devolved to local governments and the communities themselves. In Turkana County, the Turkana Water Act of 2019 stipulates that the County Water Department is responsible for overseeing water supply provision and management (County Assembly of Turkana 2019). Six sub-county water officers and their respective repair and maintenance teams manage water schemes across the seven sub-counties. The Diocese of Lodwar has also been an active maintenance service provider in the area since 2004, currently supporting ∼7% of mechanized boreholes in the County, in addition to ∼100 hand pumps each year (R. Musyoki, personal communication, October 8, 2020). National government allocations to the County are intermittent and often delayed, with months passing without financial flow (County Executive Committee, Turkana County Government, 2019).

In the Afar National Regional State of Ethiopia, the dominant model of water supply management is community-based, with woreda (district) water offices expected to support communities in the event of a significant breakdown (Behailu et al. 2016). In practice, pump caretakers and Water and Sanitation Volunteer Committees collect little to no tariffs from water users, so all maintenance activities require outside support from the woreda or regional water office (Adank and Hailegiorgis 2018).

In both regions, the availability of resources such as vehicles, fuel, spare parts, and/or skilled technicians is typically a function of allocating regional government finances for the rehabilitation

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of schemes. However, irregular and delayed funding halts the progress of various local government activities, including rural water infrastructure repairs, leading to downtimes that can last months. Addressing this challenge requires adequate resource allocations, but the effects of distributing those resources within a complex rural water sector with various interacting parameters are not well understood, making system dynamics modeling an appropriate choice to simulate outcomes over time.

Literature Review

System dynamics modeling is a tool that can be used to examine the complex ways interconnected factors behave and can be helpful in identifying leverage points to develop policies that shift system behavior towards the desired outcomes (Richardson 2019). The merits of system dynamics for complex system modeling include assessing how system behavior changes over time due to changes in parameters and their interactions, and accounting for feedback mechanisms, delays, and nonlinearities of the system (Amadei 2020). System dynamics is well-suited for modeling interactions between the natural and social sciences in disciplines such as water resources planning and management and is often applied alongside other modeling techniques (Mashaly and Fernald 2020; Zomorodian et al. 2018). Although system dynamics modeling has been underapplied to understand the effectiveness of environmental health interventions, there is a growing interest in systems approaches in the water, sanitation, and hygiene (WASH) sector (Currie et al. 2018; Valcourt et al. 2020).

The value of system dynamics models is in their ability to reveal system structure and thereby the factors contributing to system behavior, rather than their predictive strength. Olaya (2019) argues that unlike scientific models designed to replicate and predict phenomena, system dynamics models are engineering models that are designed to achieve a variety of goals, including the creation of shared understandings and the design of policies, plans, and courses of action (Olaya 2019). System dynamics modeling has historically been applied to model interactions of variables to map causal influences and better understand complex systems' counterintuitive behavior; however, recently, there has been more frequent integration of larger quantitative data sets (Lin et al. 2020).

Study Objective

In this study, we sought to model the potential impacts of government resource allocation (specifically, financial allocations towards repairs) on mechanized borehole functionality while incorporating parameters affecting financial flows, pumping rates, water usage, and breakdown response times, using system dynamics models for the Afar Region, Ethiopia, and Turkana County, Kenya. The two regions were chosen for the availability of data to calibrate the models from satellite and cellular-connected sensors that are monitoring pumping rates for 245 boreholes serving over a million people (Thomas et al. 2021). The two study regions also share a similar climate, area, and access to improved sources. These characteristics and the sensor locations can be found in the Supplemental Materials (Fig. S1).

Our goal is to explore optimal financial resource allocations that improve rural water supply scheme functionality and access. With access to borehole use data and an understanding of the system, government and donor decision-makers can prioritize more effective interventions. Interaction with a systems simulation can also improve user understanding of the system's complexity and, therefore, the importance of leverage points for investment, including long-term support for maintenance activities. To achieve this, we translate the model into a user-friendly interface that enables resource allocation adjustments and shows corresponding effects on functionality.

Methods

Data Collection

Data collection was conducted by observing government water office staff, and semi-structured interviews of NGO implementing partners, government staff, and other experts on the rural water sector in the two regions. These observations and interviews took place over 2–3 months in 2019, as well as in follow-up email communications. Government and NGO partner budgets and expenditure reports were examined for financial allocations to different departments and costs of repairs and rehabilitations. Throughout model development, water technicians and monitoring specialists working with implementing organizations within the USAID-funded Ethiopia Lowland WASH (Afar) and Kenya RAPID (Turkana) programs were consulted using surveys and email communication to ground-truth estimates and assumptions around model components.

Borehole time series runtime data were supplied through the USAID Lowland WASH Activity and Kenya RAPID, and through technology provided by SweetSense. The data were analyzed in R according to asset inventory data available from the two regions and accessed via the mWater application. The asset inventory data include borehole characteristics and historical breakdowns, and repairs. The data sources are listed in Table 1 and a full list of model variables and sources are included in the Supplemental Materials Table S1.

Model Development

System model development began with a compilation of parameters identified during data collection interviews, which were then used to develop causal loop diagrams. In a causal loop diagram (CLD), relationships between factors are assigned polarities of $+$ or $-$, depending on whether a change in one factor or variable positively or negatively impacts another (e.g., $+$ indicates that more of A leads to more of B, while $-$ indicates that more of A leads to less of B). The loop created by $+$ or $-$ connections can then be characterized as reinforcing or balancing, based on whether the resulting effect on the initiating factor perpetuates or dampens the initiating

Table 1. Data sources

Category	Description	Source
Borehole characteristics	Type of scheme, power source number of users, yield (L/s), location, and distance to the government water office	mWater Asset Inventories
Sensor statistics	Historical pump runtime, downtime, failure events	SweetSense dashboard and sensor metadata
Borehole status reports	Borehole breakdown and repair events from 2017 to 2020, classified into minor and major	mWater Surveys and Issues
Government water office operations & finances	Disbursement of funds, repairs, replacements, associated costs, and logistics	Budget tracking, annual reports, issues feature in mWater, informal interviewing of the water office staff

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behavior. The CLDs consist of feedback loops that drive the changes in borehole functionality seen over time in the region.

The causal connections identified in the CLDs inform the development of stock-flow models, which enable quantifying the parameters, their interactions, and how these change over time. Stock-flow models consist of stocks, which represent the size or state of parameters at a given time (e.g., the volume of water or number of boreholes); and flows, which are events or activities that cause stocks to change over time (e.g., pumping water or boreholes breaking). Our stock-flow models were developed with the STELLA version 2.0.3 Architect software from isee systems and integrate quantitative data, parameter estimates, and time.

CLDs and stock-flow models capture the most influential factors for borehole functionality from two perspectives: repair response times and borehole failure rates. Borehole functionality is defined in the model as the percentage of working over the total number of boreholes in the region/county at a given time. Factors influencing repair times include funding for operations and maintenance (O&M), availability of spare parts and vehicles, travel time to the site, delays in information sharing, and the priority assigned to the repair based on breakdown type (major/minor). Seasonality was captured in the models based on historical wet and dry seasons, and informed the probability of flooding events, which affect repair rates. New construction increases the number of working boreholes and is based on capital expenditure allocations and water access coverage targets under the United Nation's Sustainable Development Goals (SDGs) (United Nations 2015).

The stock-flow model simulation begins in the past to calibrate to historical data from January 1, 2018, and then runs for a simulated 12 years (629 weeks by one week time steps), ending at the end of 2029. This time frame was chosen to observe values for 2030, the end of the SDGs.

At each stage of the modeling process (Fig. 1), we re-evaluated the dynamic hypothesis, model structure, and parameter values to correspond with an evolving understanding of the system. Sterman (2000) and Ford (2009) have laid out iterative processes for system dynamics modeling that we have adapted to incorporate time-series data, calibration, and interface development (Ford 2009; Sterman 2000). Full details on parameters and calculations are available in the Supplemental Materials (Table S1).

System Dynamics Model Components

Borehole status, functionality, and runtime: The model is structured to track the transition of boreholes through the states of Working, Broken, and Repaired. The availability of allocated government budget and target installation rates from both government and donor organizations determines the rate at which new schemes enter the Working stock. The breakdown rates are a function of pump usage, with minor and major breakdowns occurring every time a certain usage threshold in hours is passed. Borehole weekly pumping hours (runtime) were imported into the model directly for the calibration timeframe and then repeated for the remainder of the simulation. Broken boreholes are fixed based on response times,

Fig. 1. Model development process: observations and interviews (top-right) led to an understanding of the system's parameters and constraints, enabling problem definition and model formulation. Parameters were estimated, and sensor data were input to calibrate and validate the model, followed by sensitivity analyses to identify optimal conditions for borehole functionality. An interface was published to inform implementer understanding of the system. From problem familiarization to sensitivity analysis, each step provided insights to revisit previous steps and proceed iteratively.

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which are a function of the varying vehicle, spare parts, and technician availability. The remoteness or distance of a borehole site from the Water Department office is also a factor affecting response time and is a graphical distribution fit to existing distances.

Borehole functionality is a simulated calculation calibrated to historical data. Sensor-supplied borehole runtime data from 2018 to 2021 was accessed from Sweetsense Inc. and averaged every week to determine the regional/county functionality levels using R.

Borehole runtime, or hours of pumping per week, was also aggregated weekly from the historical sensor data. Actual borehole pumping ranges from 0 to 133 h per week in Afar and 0 to 63 h per week in Turkana. The weekly pumping data was imported directly into STELLA to account for the high variability in runtime between sites observed and a graphical distribution was fit to the data for the remainder of the simulation.

Water demand and storage: The breakdown rates are informed by borehole usage, based on cumulative hours pumped. The water storage stock was set based on current reservoir capacities in cubic meters and the water demand was calculated from average per capita water use, population estimates based on growth rates, and water access levels. When all reservoirs are empty, groundwater use goes to zero until stored water becomes available again.

Breakdowns: Borehole runtime affects the breakdown rates via thresholds of pumping hours after which a minor or a major breakdown is expected, according to the historical fraction of minor to major breakdowns. This breakdown threshold parameter for the calibration was set at a minimum of 1,000 h and a maximum of 20,000 h. Each time the number of cumulative pumped hours crossed a multiple of the specified breakdown threshold, an additional breakdown was tallied. The breakdowns per week are the number of boreholes over the threshold of pumping hours, and those boreholes then change status from Working to Broken. We used Monte Carlo distributions to specify the probability of a major breakdown (20% of breakdowns in Turkana and 70% of breakdowns in Afar), based on self-reported breakdown histories from the government maintenance staff.

Maintenance response times: The maintenance response times are a sum of the average time taken to identify a breakdown (monitoring), to access vehicles (rented or owned), to access spare parts (immediate or time to procure), and the time to deploy staff to the field. Delays due to conflict were assessed to have a 10% risk, while inaccessibility to sites due to flooding or other disasters was estimated as a 5%–15% risk in Turkana and Afar, respectively, during the wet season, based on historical inaccessibility (e.g., flooded roads) by repair teams. Response delays were calculated for minor and major breakdowns separately, as major repairs are prioritized over minor ones.

Spare parts: Spare parts costs include inflation and are based on whether the maintenance performed is categorized as minor or major. When a part is used, a procurement order is placed to replace it depending on the availability of funds and can take between a month and two years to fulfill. Spare parts costs for major and minor repairs are average costs of the following types of maintenance activities:

- Minor: sensor replacement, generator repair, switchboard repair or replacement, reservoir repair, other repair or replacement (requiring a light vehicle, 80 km/hr average driving speed).
- Major: submersible pump repair or replacement, generator replacement, borehole cleaning, structural repair to pump house, total rehabilitation (requiring a heavy vehicle, 50km/hr average driving speed).

Vehicle availability: Vehicle availability is the sum of rented and owned vehicles not currently in use. Both regions owned two light vehicles in 2017 and the Afar Water Bureau owned two pieces of heavy equipment (drilling rigs and cranes required for major repairs and rehabilitations). When owned light vehicles are unavailable or if a major breakdown requires an advance site visit to assess the repair needs, a vehicle will be rented. Deployment rates of light and heavy vehicles were determined based on the number of technicians available to drive and the length of time needed for the repair, based on the driving distance to the site. Both regions have a stated goal to purchase one new vehicle a year, so rentals and repair delays reduce as new vehicles are purchased.

Technicians/Contractors availability: The availability of a technician for a repair is determined by the total number of staff, the number already deployed, and their daily expenses (per diem and salary). The technician demand at any time is two persons per broken borehole; however, there must be sufficient repair funds to actually conduct the repair. In the case of Turkana, contractors are hired for major rehabilitation works, which constitute approximately 10% of significant breakdowns, for an all-inclusive cost for parts, equipment, vehicles, and per diems.

Government funds: All funds in the model start from national government allocations to the regional/county governments, which are then allocated to the water departments. The water department then determines what fraction of the total budget will go towards capital expenditure, capital maintenance expenditure (major repairs and rehabilitations), operations and maintenance (minor repairs), and monitoring (also called direct support). Certain expenses, like administration and overhead, are fixed. In Afar, the use of funds for monitoring is based on the number of sensors, and the use of funds for repairs is based on the numbers and types of repairs conducted in a calendar year. In Turkana, the water department has not allocated funds for sensor-based monitoring, as this is currently covered through outside aid. New construction spending is based on borehole unit costs, target installation rates by the local government, an estimated maximum capacity of one new borehole per week, and a universal access target in 2030.

The components previously described are interconnected throughout the model. Pump use rates based on groundwater demand and population growth determine breakdown frequencies, informing the rate at which schemes transition from stocks of Working to Broken. Maintenance response times are a function of the availability of spare parts, vehicles and skilled technicians, as well as rates of flooding and insecurity, informing the rate at which schemes transition from Broken to Repaired. Resources for maintenance activities are contingent on the availability of budgeted funds, as well as procurement times. Lastly, the availability of funds is based on the government allocations towards repair and maintenance activities. Complete details of every model parameter, including equations used for calculations and data sources, are provided in Table S1.

A number of assumptions were made throughout model development. Data on government budget allocations, installation and target repair rates were obtained from annual government reports and were assumed to be representative of future allocations, adjusting for inflation. The inflation rate is an average of the past five years. The model assumes pump use is the primary factor contributing to wear and tear and breakdowns, and does not take into account the effects of environmental conditions, groundwater quality, system age, or other factors that are likely to affect breakdown frequency. Cost estimates for vehicles, spare parts, and contractors are assumed to follow historical prices observed by regional repair teams, adjusted for inflation. Similarly, time delays associated with procurement and contracting are also assumed to follow historical averages.

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Stock-flow Model Calibration and Validation

Model calibration fit simulated stock-flow values to time series data, using STELLA Architect payoff optimization (goodness-of-fit optimization) to iteratively refine parameter values (isee systems, n.d.). The calibration dataset consists of daily estimated percentages of functional schemes calculated from the sensor expert status classifier and corrected for sensor specificity and sensitivity (Thomas et al. 2021). The calibration data runs from 2018 to 2021 for 185 boreholes in Ethiopia and 60 boreholes in Kenya. Periods of missing data due to sensor malfunction, replacement, or cellular network outages, are interpolated backward from the available data.

We re-evaluated model structure and components with help from local experts when calibrated parameters were unexpectedly sensitive or out of a reasonable range. Parameter estimates were reviewed by regional experts throughout model development, from initialization to final sensitivity analysis interpretation, with the support of individuals working with the two regional water offices. The borehole breakdown threshold (the average hours of use per pump before a breakdown) was selected as the functionality calibration variable. The calibration sets the thresholds for pumping hours before a breakdown to match the simulated functionality with imported functionality data. Calibration quality was measured using the mean squared error of the modeled functionality against the imported functionality in STELLA Architect.

Model Outputs: Sensitivity Analysis and Optimization

Following model calibration, we tested model performance under a wide range of parameter inputs using sensitivity analysis, selecting input values iteratively. The input variables are different fractional allocations of the water office's budget to different uses. In the case of Afar, the budget is divided into capital expenditure (CapEx), O&M, monitoring, capital maintenance (CapManEx), and other water expenditure. In Turkana, the budget is divided into allocations for borehole maintenance and new installations, with the proportion for all other water expenditures (e.g., rain/surface water storage, water testing) considered constant. The measured output variables from the sensitivity analysis are the values for functionality and the number of working boreholes at the end of the simulation in 2030.

Within each sensitivity analysis model run, we performed a multicriteria optimization of factors to meet two goals: reduce the maintenance response time delay, therefore increasing the repair rate, and maximizing the overall functionality. Multicriteria optimization in STELLA Architect selects a set of model parameters where the tradeoff between payoff goals can be analyzed. The optimized factors are O&M team operations that determine operational efficiency at conducting repairs. These include the target purchase rates of spare parts per week and vehicles per year, the target for new installations per year, and the average driving distance per day. We chose to optimize the allocation of resources for maintenance between capital maintenance expenditures (vehicles and spare parts), and operational maintenance expenditures (travel and technicians) to simulate best practices for decision-making in a maintenance service provider financial department.

The impacts of the different sensitivity analysis runs are translated into the number of working boreholes and estimated number of households served under the current budget allocation, the sensitivity-analysis-identified optimal allocation, and a scenario where the optimal allocation is applied to a doubled total water department budget. Household size estimates are from asset inventory surveys done in each region, cross-verified against national and regional census data.

Model Dissemination: Interface Development

A web interface was developed for demonstration purposes to allow users to interact with the model by adjusting key financing factors, such as budget allocations and external donor funds, and view the resulting simulated outcomes for borehole functionality and water access. Targeted users include the Region and County water department O&M teams and NGO implementers installing infrastructure in Ethiopia and Kenya; however, the interface is broadly applicable for the effects of funding repairs for mechanized borehole schemes in rural areas.

The model interface is itself an intervention, as we hypothesize that interacting with a systems model can illustrate counterintuitive and less predictable outcomes in complex systems and change mental models of rural water maintenance systems. The maintenance model outputs and the user interface were presented to ten NGO staff working in the two regions, followed by a short survey to gather feedback on the utility and interpretation of simulation outputs and interactivity.

Results and Discussion

Causal Loop Diagrams

The CLDs developed for Afar and Turkana highlight the critical relationships derived between rural water operation factors and reveal the underlying balancing and reinforcing feedback loops present in the rural water systems. The CLDs do not include every variable present in the stock-flow models.

The CLD developed for Afar shown in Fig. 2 includes 35 factors that affect borehole functionality problems in the region. The critical feedback loops are as follows:

- Maintenance underinvestment (reinforcing loop): The accumulation of broken or abandoned pumps and the subsequent unmet demand for maintenance services, as well as pressures of donor funding priorities, low existing coverage levels, and population growth, reinforce the preference for new construction. This continues the cycle of lower allocations for O&M and CapManEx, and therefore insufficient repair funds to conduct timely repairs, leading to more broken pumps.
- Maintenance team capacity (reinforcing loop): Limited maintenance capacity leads to longer response times as fewer pumps can be under repair at any one time, and each repair takes longer to conduct. Additional regional repair funds do not immediately lead to shorter repair response times, as there is limited financial absorption capacity under current procurement and hiring methods.
- Limits to growth (balancing loop): As coverage of the population with reliable and safe water services and the number of working pumps increases, groundwater demand per capita rises, which increases the use of existing pumps. This leads to more wear and tear and a decline in working pumps, which diminishes coverage.
- Groundwater demand (reinforcing loop): Pump usage leads to more stored water available in reservoirs, leading to higher reliability of access and more demand for groundwater. This dynamic is complicated by aquifer depletion, which at much higher groundwater abstraction levels than currently seen, would increase groundwater scarcity and possibly reduce demand in favor of other sources.
- Breakdown rates (balancing loop): Pump usage leads to wear and tear, which causes breakdowns, which decrease use.

In Turkana, a total of 29 parameters were identified to affect borehole functionality. Similar feedback loops were observed in

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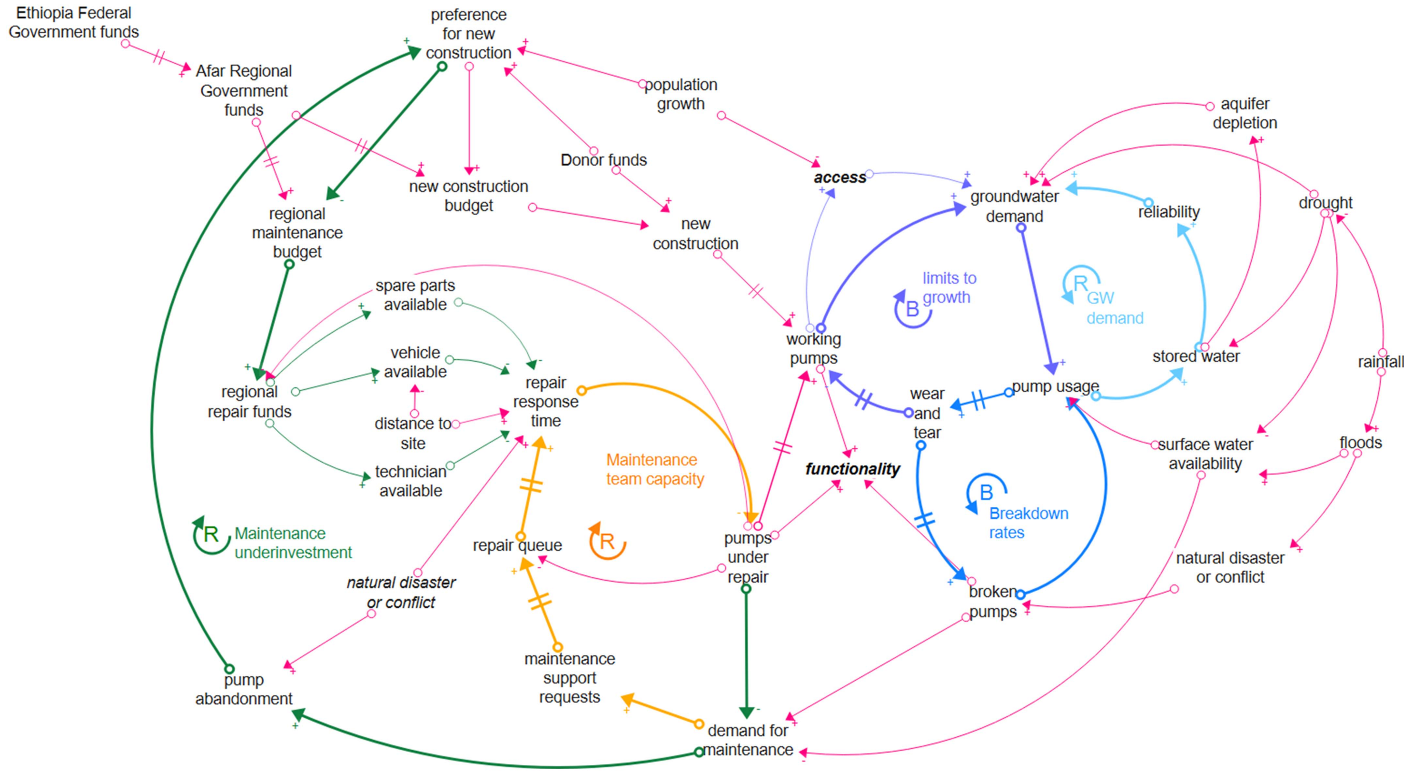

Fig. 2. CLD of the Afar rural water supply and maintenance system. The CLD highlights the sources and uses of finance for water supply operations and maintenance and the drivers of water pump use and pump breakdowns. Output variables, in bold, are functionality (percentage of working boreholes) and access (coverage of the population with working boreholes).

Turkana, as seen in the Afar CLD. Intermittent and delayed funding allocations from the national government affect county-level budgets and resource allocation to the installation and repair of water infrastructure. Groundwater demand is a function of free surface water availability, which informs pumping rates that lead to wear and tear and eventual breakdowns. As breakdowns increase, so does the backlog of needed repairs, affecting response times. Response times depend on various parameters, including spare parts procurement, vehicle hiring or purchasing, and technician contracting. Without sufficient resource allocation, delays in spare parts procurement, vehicle availability, and contracting can significantly extend downtimes. The Turkana CLD can be seen in the Supplemental Materials (Fig. S2).

Stock Flow Model Calibration for Borehole Functionality

Stock and flow model calibration was performed to specify breakdown rates that best fit the observed borehole functionality trends in the two regions. The modeled breakdown rates in Table 2 show the average cumulative hours of pump use before a breakdown occurs (breakdown threshold). Based on average weekly use hours, these correspond to 9 years of service in Afar and 5.3 years in Turkana. These numbers are consistent with stakeholder-reported breakdown frequency of about 1–2 breakdowns per week in each region. Calibration accuracy is measured via minimization of the mean squared error (MSE).

Breakdowns are characterized as minor and major, each with differing spare parts costs and response times, where Monte Carlo distributions specify the probability of a major breakdown (20% of breakdowns in Turkana and 70% of breakdowns in Afar), based on self-reported breakdown histories from the government maintenance staff.

In Afar, the calibration data starts at 73% functionality in January 2018 and ends at 68% functionality in February 2021, as shown in Fig. 3. There is significant functionality variation year-to-year, mainly attributable to variations in rainfall and drought conditions (Thomas et al. 2019). The modeled functionality values capture some of the amplitude of these yearly swings in functionality, with an overall downward trend to 53% functionality by the end of 2029. The annual cycle in the Afar model is mainly due to the timing of

Table 2. Calibration data and modeled borehole breakdown rates

	Calibration data (January 1, 2018 to February 22, 2021)			Calibration results (simulation from January 1, 2018 to December 31, 2029)			
Case	# of sensors	Weekly mean pumping	Weekly functionality	Breakdown threshold (hours of total use)	Breakdown threshold (days of average use)	Simulated functionality in 2030	Functionality calibration MSE
Afar, Ethiopia	185	17–37 h, mean = 29 h	62%–98%, mean = 79%	13,803	3,332 days (9 years)	53%	86.0
Turkana, Kenya	60	29–70 h, mean = 47 h	70%– 100%, mean = 86%	12,874	1,917 days (5.3 years)	59%	12.0

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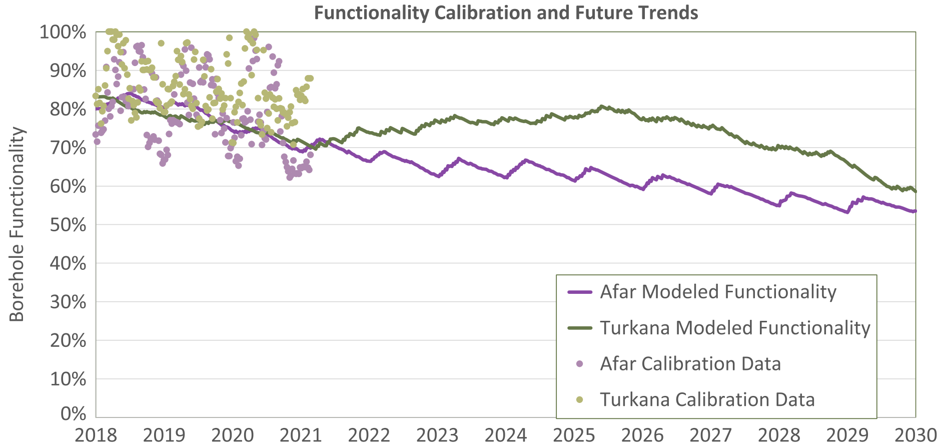

Fig. 3. Functionality trends (darker lines) and calibration data points for Afar and Turkana.

budget disbursements from the regional government, as the O&M team typically depletes their budget for repairs within the first few months of the year and cannot send out repair teams after that.

In the Turkana model, Fig. 3 shows the calibration data began at 83% functionality in January 2018 and ended at 88% in January 2021, with similar variability in weekly functionality rates to the Afar model. The simulation also shows a similar downward trend in functionality to 59% by the end of 2029. Unlike in Afar, the simulated repair funds in Turkana are not fully depleted by the end of a fiscal year but are insufficient to support all required repair activities. The decline in functionality rates is tempered by installing new schemes until accumulated repair funds are available. The yearly numbers of breakdowns and repairs with the total numbers of Working and Broken boreholes in both regions can be seen in Fig. 4.

Repair rates vary due to breakdown type and resources available. In Afar, repair teams fix between 52% and 92% of breakdowns in a calendar year, with an average of 73% of breakdowns repaired. In Turkana, between 20% and 96% of breakdowns are repaired in a year, with an average of 64% and a higher magnitude and variability in both repairs and breakdowns compared to Afar.

These models suggest that although the two cases were initially characterized by similarities in the number of schemes, available government budgets, initial functionality, and water usage levels, subtle differences in operation, mainly in how maintenance teams batch repairs or rules governing contracting and procurement, have significant effects on borehole functionality over the simulation time.

Sensitivity Analyses and Optimization

Fig. 5 shows the percentage increase in functionality and the number of working boreholes from changes in proportions of funding allocations towards new installations and maintenance of existing schemes. The sensitivity analysis not only adjusted budget allocations but included multicriteria optimization to maximize functionality and working boreholes in each run (as described in the section "Model Outputs: Sensitivity Analysis and Optimization"), except for the current allocation proportions, in order to compare current scenarios to optimal conditions. Each run represents simulated conditions at the end of 2029.

The results of 48 different combinations of budget allocations for Turkana are shown in Fig. 5(a) as a stacked bar chart for the different sensitivity analysis runs. The results show a general improvement in functionality and the number of working boreholes at higher proportions of maintenance allocations. The current allocation of 30% to maintenance (O&M and CapManEx) and 70% to new installations has a predicted functionality of 59% and 409 working boreholes by 2030. The optimal condition indicates 95%

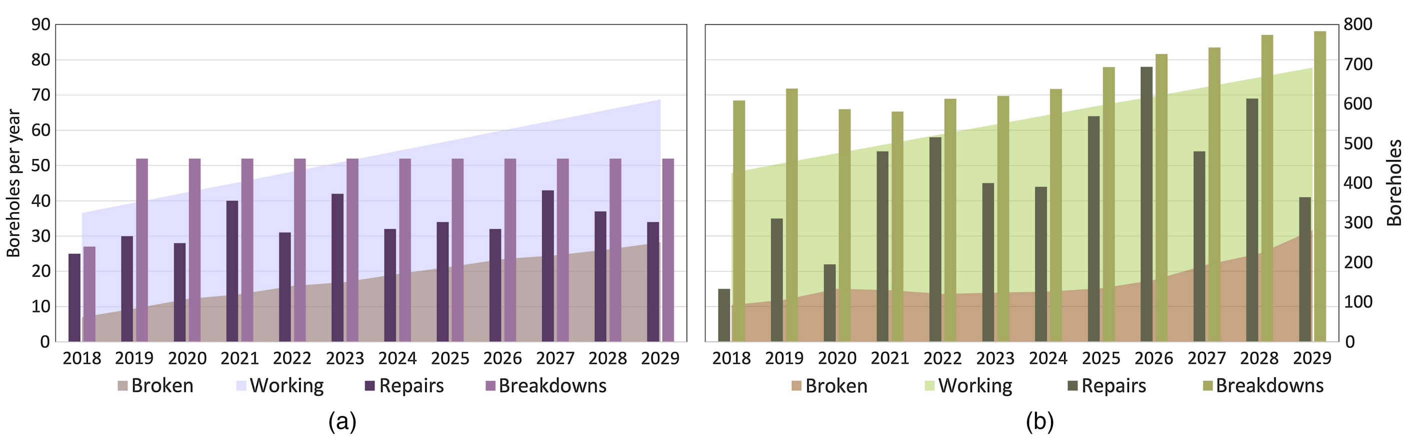

Fig. 4. Simulated numbers of breakdowns and repairs occurring each year in (a) Afar Region, Ethiopia; and (b) Turkana County, Kenya. The number of breakdowns and repair activities are represented as bars on the left axis, and the total numbers of broken and working boreholes are the shaded areas and are counted on the right axis.

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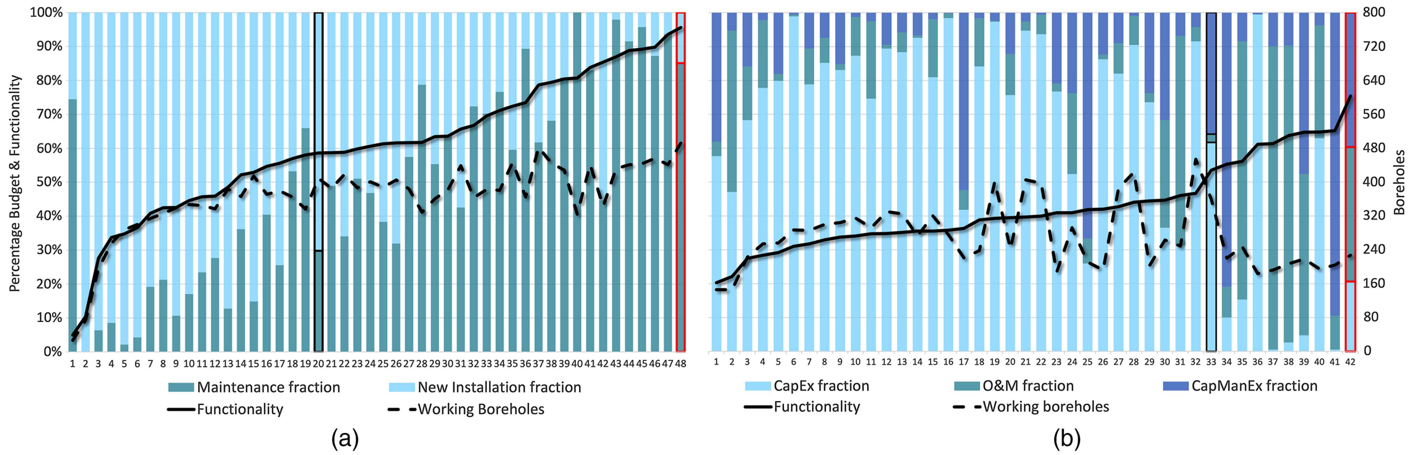

Fig. 5. (a) Sensitivity analysis outcomes for Turkana County. The optimal point is at run 48, where the available budget is 15% new installations and 85% maintenance. The current budget allocation is outlined (run 20). (b) Sensitivity analysis outcomes for Afar Region. The higher percentages of budgets allocated for CapEx on the left are associated with lower levels of borehole functionality and numbers of working boreholes. In contrast, increased allocations to O&M and CapManEx on the right side are associated with functionality levels above 50%. The current budget allocation is outlined at run 33, where 58% is CapEx, 2.3% is O&M, and 34% is CapManEx. The optimized allocation in run 42 corresponds to 21% for CapEx, 37.5% for O&M, and 37.5% for CapManEx.

functionality and 492 working boreholes based on an allocation of 85% to maintenance and 15% to new installations.

What is seen from left to right in the Afar sensitivity analysis outputs in Fig. 5(b) is the importance of balancing CapManEx, O&M, and CapEx under a constrained budget. There is only one allocation of the regional funding for water supply under business-as-usual conditions (4% annual budget growth) that can increase borehole functionality above 75% by 2030. Because of high prices for new construction, the region rarely builds new boreholes out of pocket, so the addition of new schemes does not outpace the rate of breakdowns, and functionality declines. As they also do not typically take on maintenance responsibilities for newly constructed donor-funded schemes and the actual construction numbers are unknown, additional funding for CapEx at the expense of CapManEx and O&M neither increases the number of total boreholes in the region nor their functionality. The optimal allocation identified in the sensitivity analysis is Run 42 [last on the right in Fig. 5(b)], where 37.5% of the budget is dedicated to O&M, 37.5% goes to CapManEx, and 21% goes to CapEx, resulting in a functionality level of 75% and 227 working boreholes in the region by 2030.

Optimal resource allocations indicated by the sensitivity analysis can be distilled into more tangible outcomes based on households served by mechanized boreholes in these regions. Table 3 indicates that increasing repair and maintenance budget allocations in Turkana to optimal levels results in an additional 83 working boreholes, providing water access to an additional 16,680 households in the area (assuming ~200 households served per borehole). The repair costs per borehole are calculated by dividing the total water department budget allocated to repairs in each scenario by the total number of boreholes. We see that achieving optimal functionality rates requires raising per borehole repair budgets from $990 to $3,800. Although the shift in allocations means less money for new installations, the overall number of working boreholes increases.

In Afar, optimal budget allocations to raise functionality to 75% show a decline in the number of working and total boreholes, reducing access. This trend appears to be due to a limitation of total funding allocations to the water department, as we see that doubling the water budget with the same optimal allocation proportions to CapEx, CapManEx, and O&M alleviates this constraint, increasing functionalities, the number of working schemes, and the estimated number of households with water access.

Model Interface and Dissemination

The model interface was developed with adjustable dials that enable users to test different allocations of the water department budget and increase financial flows through external donor funds. The interface shows the resulting number of working boreholes and functionality. The interface is available at https://exchange.iseesystems.com/public/alibey/kenya-ethiopia-maintenance/index.html#page1. Although not a fully developed aid for decision-making, feedback from several implementers of water supply

Table 3. Optimization outcomes for resource allocation in Turkana and Afar

Case	Budget condition	Maintenance budget fraction (%)	New installations budget fraction (%)	Projected functionality in 2030 (%)	Working boreholes in 2030	USD/ borehole/year for maintenance	Additional households served
Turkana	Current	30	70	59	409	990	—
	Optimal	85	15	96	492	3,800	16,680
	Doubled	85	15	96	603	13,400	38,800
Afar	Current	38	62	54	326	4,900	—
	Optimal	79	21	75	227	20,700	−22,629
	Doubled	79	21	95	569	22,000	55,543

projects in the case study regions indicates that such a system dynamics interface could be helpful for the development of costing plans for long-term goals for universal water access. In the interface, adjusting the allocation of existing resources from new construction towards maintenance programs in regional governments leads to improvements for borehole functionality and water access over current projected levels. However, breakthroughs in coverage with safely managed services do not appear without larger simulated investments into the rural water supply sectors in the model.

Conclusion

Our study finds that increasing repair and maintenance funds leads to higher borehole functionality and water access rates in the drought-prone regions of Turkana, Kenya and Afar, Ethiopia by 2030 in simulated outcomes. To the authors' knowledge, the work presented here is one of the first applications of system dynamics modeling to integrate and calibrate model parameters to regional scale time-series data in the WASH sector.

Many assumptions had to be made during model development. Where possible, we tried to have these assumptions match hypothesized and validated causal relationships or trends, but there are some areas where further inquiry or more data are needed. The model assumes breakdowns are primarily a function of pump use and does not account for other factors such as age or complexity of the scheme, environmental conditions, or groundwater quality. Instead, the model calibrates pump use hours to match observed functionality rates over a data collection period of over two years.

Anecdotal evidence suggests that inefficiencies and mismanagement of funds affect government spending, but information on the extent to which this occurs was not available for this study. Another potential error source lies in accounting for the preference for (free) surface water sources when available after heavy rains in these arid regions. This preference is documented in Thomas et al. (2019), and the imported pumping data includes historical trends, but without data on how the pump operators respond to changes in water demand we assume that weekly mean pumping rates in the model are only affected by the number of working boreholes.

Our follow-up studies will build from this work and apply system dynamics modeling to investigate the impacts of new institutional arrangements to support the professionalization of water management and infrastructure maintenance in East Africa. In one study, the financial and functional implications of implementing and scaling guaranteed-service maintenance provision are modeled for a county in Kenya, and in another, SD policy analysis is used to probe the impacts of new regulation for post-construction support in Ethiopia.

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Data Availability Statement

Some data, models, or code generated or used during the study are available in a repository or online in accordance with funder data retention policies [found in Libey (2021) and Sweetsense, Inc. (n.d.)]. Some data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request (STELLA Architect Model files).

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Supplemental Materials

Figs. S1–S3 and Table S1 are available online in the ASCE Library (www.ascelibrary.org).

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