PLOS Water

RESEARCH ARTICLE

Connecting narratives and numbers to investigate the interaction of social, physical and technical determinants of rural water supply performance

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Abstract

The performance of rural water supply infrastructure in Africa remains a considerable challenge. Performance is determined by interactions between social, technical and physical factors (the socio-material interface). Here we examine how breakdown, downtime, timeliness of repair, and socio-material factors, dynamically interact and mutually shape each other. We conducted interdisciplinary fieldwork at 145 hand-pumped boreholes across Ethiopia, Malawi and Uganda. Using regression analysis, we find that the probability of any failure occurring in the last year is dominated by physical and technical factors (handpump condition, water level, transmissivity, borehole construction and configuration), while the cumulative downtime in the previous year is dominated by social factors (demand, access to spares, finances). Cumulative failure is influenced by complex combinations of social and technical factors (finances, motivation, support, handpump condition, water level, transmissivity). Downtime duration from previous failure is influenced by skills and leadership in the community, and transmissivity and cylinder position in the borehole which in combination influence the risk of the handpump running dry. We find that ineffective finance and external support systems are worse than having no formal systems at all.

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In-depth narratives from nine sites showed that interactions between socio-material factors and performance and response outcomes are complex and multidimensional, shaping each other in counterintuitive ways. We find examples where external support providers are reluctant to conduct repairs, because they lack adequate equipment, creating tensions with communities. We find cases with perverse outcomes, for example well performing handpumps in locations with good hydrogeology allowing management and financial arrangements to evolve in ways that risk equitable water access. Similarly, capture of management arrangements by sections of the community resulting in poorly sited boreholes, inequitable skill development and poor performance outcomes. Recognising, understanding and working with these dynamic and multidirectional interactions can help ensure effective management and improved rural water supply performance.

1. Introduction

The performance of rural water supply infrastructure in Sub-Saharan Africa has been a persistent challenge over many decades. Considerable effort has been made to understand the factors that affect performance outcomes [1–6]. Many of these studies use physical and social data in their analysis with different approaches used to analyse these inter-disciplinary datasets. Many studies use regression or linear analysis [3,4,6,7]. Other studies use systems dynamics approaches [5,8–11] or other methods [2]. However, many of these studies have been restricted by the availability and quality of data to parameterise and test the models, often reducing the number of contributing factors that can be confidently tested. Even where data are available, the reductive analysis required cannot capture the richness of the complex interactions that constitute the socio-material interface. Only a few studies recognise the feedback mechanisms that exist between rural water supply performance outcomes and underlying determing factors [11,12].

In parallel, there have been various attempts to understand access to rural water supplies by employing more qualitative and critical social science approaches (e.g., [13]. Many of these studies have focussed on assessing the role of different management models for rural water supply sustainability and performance using a range of methods to assess their effectiveness [14–16] often focussing on Community Based Management (CBM). However, few studies have attempted to bring these apparently disparate disciplinary approaches together to benefit from both the broad quantitative insights that statistical and systems thinking methods allow, with the deeper insights that critical social science research offers.

Our intention in this article is to use both broad statistical methods and in-depth qualitative social science research (i.e., connecting narratives and numbers) to better understand the interplay of factors that influence rural water supply outcomes. To do this, we focus on the diversity of real-world water management arrangements rather than on the hypothetical policy model of CBM, which often deviates considerably in its practical application in many of the locations in which our research was conducted

[17]. We focus specifically on handpumped boreholes (HPBs) across rural Ethiopia, Malawi and Uganda, using data collected during the second survey phase of the FCDO/NERC/ESRC funded project 'Hidden Crisis: Unravelling Current Failures for Future Success in Rural Groundwater Supply' [18,19].

In this study, we focus on HPBs because they continue to play a crucial role in water supply across Sub-Saharan Africa, providing water daily for up to 200 million people [20,21] while underpinning water supply resilience in many drought prone areas [22,23] and often outperforming piped water supplies in terms of functionality [24,25]. Thus, there is a strong need to better understand the factors that determine the performance of rural HPBs across Africa. Building on previous work, which examined the role of physical factors in functionality outcomes [26] and the relationship between functionality and the capacity of communities to manage their water supplies [27], we investigate broader performance outcomes and their relationship to the dynamic interactions between social, physical, and technical (hereon 'socio-material') factors.

Our aim is to better understand the socio-material interface that underpins the performance of rural groundwater supply in sub-Saharan Africa [13]. To achieve this, we used a detailed dataset collected across Ethiopia, Malawi and Uganda to conduct an interdisciplinary analysis of HPB performance, in terms of downtime, breakdowns and timeliness of repair. Our analysis had three objectives: 1) assess HPB performance using quantitative indicators of downtime, breakdown, and repair; 2) analyse the status and role of social factors in HPB performance, and 3) investigate how social and material factors, individually and collectively, influence performance outcomes and ultimately the ability to deliver water for rural communities.

By investigating the socio-material interface, we contribute to a growing body of literature that explores water supply and use by drawing from conceptual developments in Science and Technology Studies (STS). At the heart of this literature is a concern with the ways in which the social and material dimensions of water supply are 'co-constituted' – how they mutually shape each other. This framing has been taken up most by studies of the piped networks that supply water to cities [28–31] and the irrigation systems that supply water for agriculture [32–35]. Far fewer studies have shared our concern: water supply from handpumped boreholes.

We begin with an overview of the methodology used to collect and analyse the physical, technical and social science data. Then we present the results, starting with a performance assessment of HPBs, a quantitative analysis of the social context, the regression results, and the narrative results of our qualitative interface analysis. Finally, we discuss our main findings and implications for the performance of rural water supplies in Sub-Saharan Africa.

2. Methodology

The socio-material interface (Fig 1) encompasses the dynamic relationship between social, physical and technical factors and performance and response outcomes for rural water supplies. Critically our conceptual model of the socio-material interface recognises the multidirectional relationship between outcomes and determining factors and how they mutually shape each other in a dynamic way (Fig 1). Our focus in this study is on rural HPBs and Fig 1 illustrates the key factors relevant to this technology. Our conceptual model of the socio-material interface informs our methodological approach, including a reductive analysis using logistic regression and a rich qualitative narrative analysis (Fig 3), which we describe in detail below. We begin with a description of the field methodology, then we describe the construction of performance, response, physical and social indicators used in the regression analysis (Fig 3a). Finally, we describe our approach to the in-depth qualitative analysis of a small sub-set of sites (Fig 3b). In the discussion we seek to frame our broad and in-depth findings within the wider socio-political context (Fig 1 and Fig 3b). While data was collected from Ethiopia, Malawi and Uganda our intention is not to compare performance outcomes in these countries, but rather to increase the depth and richness of our exploratory analysis, and to draw out nuances and features of our data that are only possible using a comparative analysis.

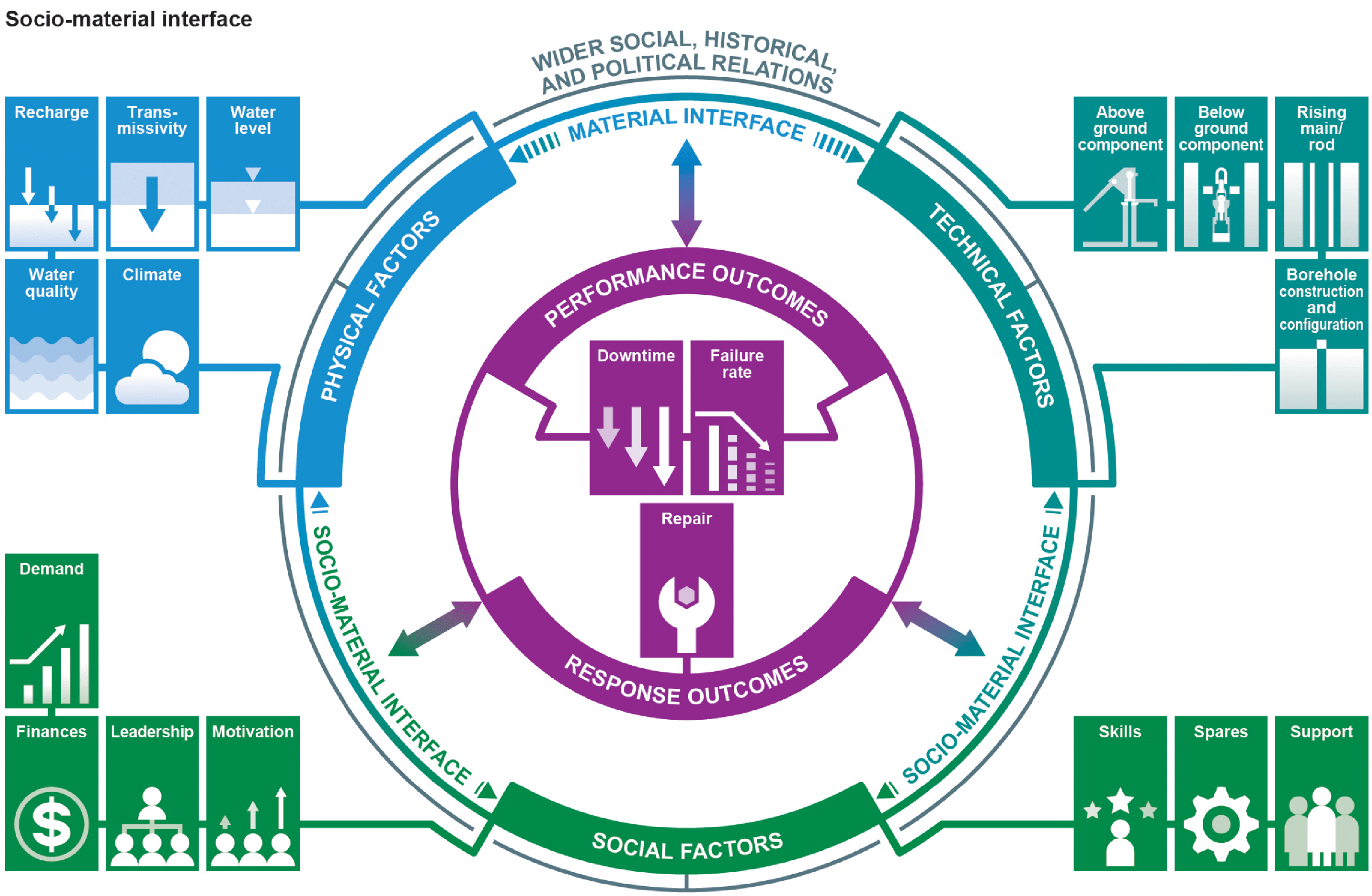

Fig 1. A conceptual model of the social, physical, and technical factors that comprise the socio-material interface as it relates to rural handpumped boreholes. The different factors interact with one another within and between the three categories. Factors included here are those we hypothesise have the most direct influence on performance and response outcomes, although we consider water quality, recharge and climate elsewhere [36,37]. Importantly there is a multidirectional relationship between outcomes and each of the influencing factors. Our model also recognises that the socio-material interface sits within wider environmental, social, historical and political contexts.

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2.1. Overview of interdisciplinary fieldwork

In the first phase of the FCDO/NERC/ESRC funded project 'Hidden Crisis: Unravelling Current Failures for Future Success in Rural Groundwater Supply', 200 sites were selected in each country using a stratified, randomised sampling design (see [37]). Based on the investigations at these 600 sites [38], the status of each HPB was then classified as one of six possible functionality categories [26,39]. Using these classifications, up to 50 sites in each country were then purposively selected to represent the six functionality categories in the second phase of the Hidden Crisis project [18,19]. Thus, the sites selected for the second phase, and our focus here, were not chosen to be representative of overall HPB status across each of the three countries. Rather sites were chosen to represent the full spectrum of functionality outcomes defined in the first phase of investigations. The functionality classification was the only criteria used for selecting sites in the second survey stage. Following site selection, it was possible to conduct fieldwork and recruit study participants at 45 sites in Ethiopia between 11/4/2017 and 14/8/2017, 50 sites in Malawi between 20/9/2017 and 23/3/2018 and 50 sites in Uganda between 20/6/2017 and 27/11/2017 (Fig 2). At each site the physical and social science research teams worked alongside each other to develop a shared understanding of the material and social dynamics of HPB performance.

2.1.1. Hydrogeological and climatic context. Ethiopia's igneous aquifers (Fig 2a) have moderate to high transmissivity and low groundwater storage capacity [40,42]. Mean annual rainfall is c.1280 mm/year [26]. In Uganda, most rural groundwater supplies abstract from fractured crystalline basement aquifers (Fig 2c) with low storage and transmissivity [43,44]. Mean rainfall is c.1290 mm/year [26]. The study sites in Malawi were in areas underlain by basement and unconsolidated sedimentary aquifers (Fig 2b); [45,46]. Basement aquifers in Malawi have low storage and transmissivity. Sedimentary aquifers have higher transmissivity and storage capacity. Mean annual rainfall is c.880 mm/year.

2.1.2. Physical science surveys. The physical science surveys began by conducting systematic observations and taking photographs of the HP, its components and the surrounding environment. Then the HP was systematically dismantled and observations (including photographs) of the condition, and extent of corrosion, of the below-ground components were recorded. Measurements were also made of the galvanising and pipe wall thickness. Once the HP was dismantled and all components removed from the borehole a submersible pump was lowered into it and a two-hour pumping test was conducted at 1 l/s (where possible). After two hours, the water level was allowed to recover. The drawdown and recovery were monitored throughout using groundwater level loggers and manual dips. Pumping test results were interpreted to estimate aquifer transmissivity using BGSPT which numerically solves the generalised well function equations [47–49]. Water chemistry and environmental tracers were sampled during the last hour of the pumping

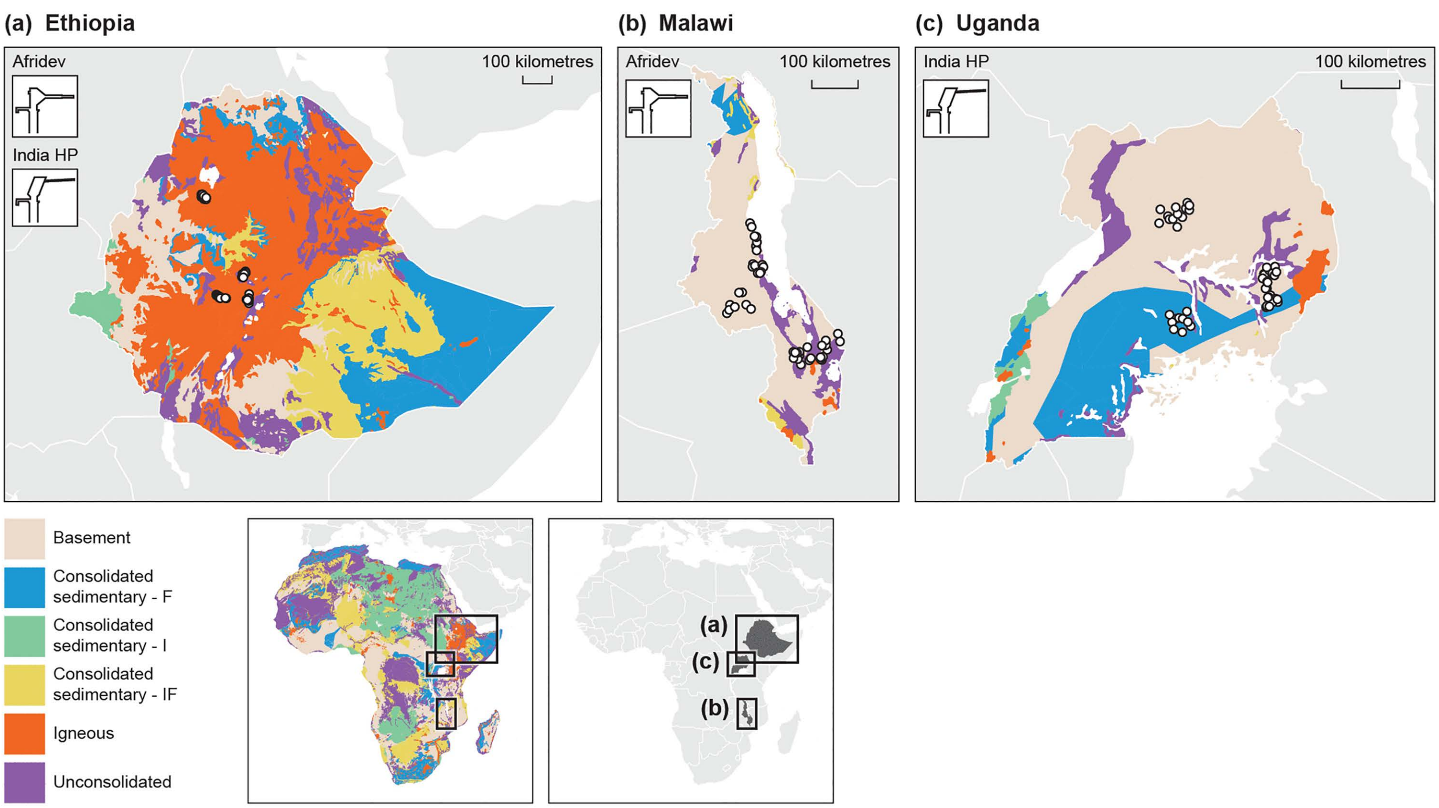

Fig 2. Location of the HPB sites and hydrogeology of each country [40,41]. (a) Hydrogeological map and site locations in Ethiopia. **(b)** Hydrogeological map and site locations in Malawi. **(c)** Hydrogeological map and site locations in Uganda.

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test, with results reported by Banks et al. [36]. The borehole was then examined using downhole CCTV. A thorough description of the physical survey investigations can be found in MacAllister et al. [26].

2.1.3. Social science surveys, ethics statement and participant consent. The social science methodology was carried out by in-country social science researchers who had received training in the project research methods from the relevant project leads. Ethics approval was gained from the Sheffield University Research Ethics Committee (UREC, approval number 007218). Participants were recruited between 11/4/2017 and 23/3/2018. Formal consent was gained from all participants using an information and consent form that was signed or agreed to verbally depending on literacy and disabilities. It was read out to participants who could not read, and verbal consent was witnessed by at least one other member of the research team and documented on the consent form.

Three main methods were used over two days at each of the field sites. Firstly, the team conducted participatory mapping with 6 – 12 community members to gain an understanding of the village and surrounding area, identify any relevant groups and organisations that exist in the community and discuss the use patterns of different types of water sources. Next, a transect walk (typically between two water sources in the village) was conducted, with the research team accompanied by one or more community members. The purpose of the transect walk was to witness first-hand aspects of the village and surrounding areas that were drawn and discussed during the participatory mapping session; to ask questions about life in the village; and to further explore water management, access, and use. Finally, using purposive sampling, focus group discussions were conducted (6 – 12 people in a group) with local authority figures, the water point committee, and water users (in the case of the latter, groups typically comprised only women). Where possible, additional data was gathered through ad-hoc interviews and informal discussions (with participant consent gained as described above).

2.2. Indicators of HPB performance – downtime, breakdown and repair

Instead of employing the overarching concept of functionality as defined in our previous work [26,39], we chose to focus on the performance indicators: downtime; failure rate; and timeliness of repair. While our definitions of functionality include measures of performance (i.e., a handpump is defined as unreliable if it has had more than 30 days downtime in a year) it does not allow a more detailed investigation of the factors that affect downtime duration and rate of failure. Focusing on these performance indicators allowed for a more nuanced analysis enabling us to examine the link between breakdowns and repair. While we choose to focus on failure, downtime and repair we also recognise that handpump borehole performance can incorporate information about handpump yield and water quality, and we deal with these issues elsewhere [26,37]. We include repair as a specific outcome, because research demonstrates the importance of rapid repairs for community health outcomes [50–52] and because of the importance of operation and maintenance to rural water supply outcomes (e.g., [15,16,53]).

Failure rate is defined as the number of times the handpump has broken down in the last year. We also examined the factors that influence the probability of *any failure* occurring in the previous year. *Downtime* is the total duration a handpump remains out of action over the course of a predetermined period. We examine downtime in two ways firstly, the duration of the most recent downtime prior to our field team visiting and secondly examining the total duration of downtime in the previous year. We also examine the factors that influence the likelihood of a repair being conducted on a broken down handpump in the year prior to our field team visiting (i.e., the timeliness of repair). Note that not all sites had data for each of the variables considered in the analysis, sample sizes for each indicator analysed are provided in the results section, but this means it is not possible to directly compare across indictors (for example it is not possible to compare sites with no breakdowns and sites that did not require repair).

All HPB performance metrics were based on community responses to structured questionnaires (with consent gained as described above) collected by the physical science team. Respondents were asked questions with pre-prepared multiple-choice answers on HPB downtime, breakdown frequency, and repairs. Respondents were provided with four or five options to choose from, and enumerators could ask the respondent for further information. Percentage stacked bar charts were used to examine the distribution of the performance indicators across the three countries. These multiple-choice answers were then used to construct the dependent variables for the regression analysis described below.

2.3. Construction of physical and social indicators

Physical and technical indicators were based on those used in the analysis of HPB functionality conducted by MacAllister et al. [26]. In that study, 22 individual physical and technical factors were combined into 10 independent variables by summing individual physical and technical factors and then dividing by the numbers of factors which constitute each of the 10 variables. Each of the 22 individual variables were assigned scores between zero and one based on our domain knowledge (e.g., [54] show that HP's generally require a transmissivity of 1.4 m^2/d to deliver their design yield), the physical condition of a component (i.e., assigning a binary score if a component is damaged or corroded), normalisation of a continuous variable (i.e., total length of screened section in a borehole) or by fractionization (i.e., position of the pump cylinder in the borehole). Here we further reduce and combine these 10 variables, using the same approach as the previous study, into four independent variables for use in a socio-material regression analysis (details of which are provided in Table A.1 S1 Text section A). Table 1 summarises the factors that were used to create the combined variables used in this study. Variables were combined to represent an overall condition or state of the four key physical and technical components of the handpump system, these being hydrogeology, the borehole, the handpump itself, and the rising main and rods. The overall condition or state of each of the four key components is represented by a combined score between zero and one, where zero indicates the state or condition of a component is suboptimal and one indicates it is optimal. It was important to reduce the number of variables for the regression models to avoid overfitting, unnecessary complexity, reduction of statistical power and to aid interpretation of the results [55]. The physical indicator used in the analysis was hydrogeology (water level and transmissivity). The three technical indicators used were borehole construction and configuration (which is made up of pump position and a combined screen and uncased position and length indicator), handpump (made up of above and below ground component condition indicators) and a combined rising main and rod indicator. More details about the construction of the physical and technical indicators can be found in S1 Text (section A).

We examined seven social dimensions of a community's water management arrangement. These dimensions were developed from a review of the literature which aimed to understand the most relevant features and categories of waterpoint governance and management. An initial set of indicators was further refined during team meetings and discussions involving experts on this topic. The final set of seven indicators are: 1) demand on the HPB, relating to the number of users; their dependency on the waterpoint in question; frequency, duration and quantity of use; and the activities for which water was being withdrawn [39,56], 2) motivation to repair, which depends on many factors including: the availability of alternative water sources; the communities perception of yield and water quality of the waterpoint; the time of year; and the accountability of the management arrangement to the people it serves. Motivation also relates to questions of trust between managers and users [10,57], 3) leadership and organising capacity, which need not relate only to members of a waterpoint committee but can be from any source of authority in the community. This includes questions of accountability, and the ability to make and enforce decisions and to mobilise and organise relevant persons to ensure the ongoing functioning and effective operation of the waterpoint [13,24,58], 4) finances, which relates to having sufficient access to funds and to how those funds are then managed and administered locally [12,59–61], 5) availability of spare parts, within reasonable proximity of communities or relevant service providers [4,12,62], 6) technical skills and tools within the community, in order for community technicians or others to undertake maintenance and repair work [12,24,63], and 7) access to external support with the necessary skills and means to undertake repair work in an effective and timely manner, while being accountable to the community being served [64,65].

For each site, social indicators were assessed and weighed based on the research teams experience and by analysing the qualitative datasets generated by the methods listed above, to arrive at a quantitative score. Social indicators were

Table 1. Summary of (a) the physical, technical and (b) social indicators used in the regression analysis. A more detailed summary of the physical indicators, including a detailed description of the methods used to combine indicators, is provided in S1 Text (section A).

(a)Physical and technical indicators				
Combined physical and technical indicators	Individual components used to form combined indicator			
Hydrogeology	Hydrogeology of the site consisting of: • Transmissivity (a description of the ability of water to move through the aquifer towards the borehole when pumped) • Groundwater level			
Borehole	Borehole construction and configuration, consisting of: • Total screen or uncased section length • Pump position in the borehole • Water column length			
Rising main and rod	Condition of (whether corroded or damaged): • Rising main • Rod			
Handpump	Condition (whether corroded, damaged or missing) of the following handpump components:			
	• Body • Handle • Flange	• Chain • Hanger • Fulcrum	• Bearings • Cylinder • Plunger	• Valves • Seals
(b) Social Indicators				
Social indicators	Factors used to inform creation of indicator			
Demand	The size of the user group and the amount of water people use influences the performance of the waterpoint. This relates to: • Who can access the waterpoint, • When it is accessed (time of day, year, and so forth), and • How much water is used/what the water is used for			
Finances	Funds to cover spare parts and the costs incurred by service providers are crucial. Funding arrangements include: • A bank account or savings system with finances already set aside, or • Funds raised in direct response to a breakdown User fees can cause conflicts and mistrust between users and the people who are collecting and managing funds. This may lead to users not paying monthly fees or not contributing when the waterpoint breaks down. Users may also feel they are not able to afford to contribute.			
Leadership	When the waterpoint breaks down, the capability for certain individuals to take a lead, mobilise community members, and, if necessary, engage with external service providers is crucial. Leadership may be considered fair and legitimate, or as unfair and self-serving.			
Motivation	User motivation is an essential pre-requisite for the waterpoint to be repaired when it breaks down, unless the repair service is undertaken entirely by an external service provider. Community motivation to repair the waterpoint depends on many factors, including:			
	• Availability and accessibility of alternative sources • Yield and water quality of the waterpoint • Reliability of the waterpoint		• Time of year (e.g., in relation to income, seasonal activities, or temperature) • Spiritual and religious beliefs, and • The trust people have in the management arrangement.	
Skills	Skills and tools need to be possessed by community technicians or others who attempt pump repairs. Without these, even a very minor breakdown will mean having to rely on external support, which may be easy or hard to come by depending on the circumstances of the case.			
Spares	The availability of quality spare parts within reasonable distance of communities. When spare parts outlets are far away this results in high time and travel costs.			

(Continued)

Table 1. (Continued)

(b) Social Indicators	
Support	If a repair is beyond the capability or capacity of the community, outside help is needed. Communities will only call for assistance if (a) they are motivated to fix the waterpoint and (b) if they believe the local Government, private entity (including area mechanics), or an NGO to whom they report will respond. They also need to know who to contact. When a service provider does respond, it is still important to understand if they have the skills, tools, and capacity to do an effective repair job. Finally, external support may depend on the proximity of a service provider to the community. Support from an area mechanic or district water office can be more forthcoming if it is located near to the community. Remote communities may struggle to access external support.

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constructed to be consistent with the construction of physical science indicators, with zero indicating the factor is sub-optimal and one indicating that the factor is optimal. Each country social scientist was trained in the approach to develop scores. Training included comparing and discussing the scores for a case derived by both the lead and country social scientists. For quality control, after deriving the initial set of scores the lead scientist then analysed a selection of cases for each country and compared their scoring to that of the country social scientist. Notable differences or discrepancies were worked through and resulted in another round of calibration across the country dataset.

Percentage stacked bar charts were used to examine the status of individual social science indicators. The social indicators were also combined to examine the overall status by summing each of the seven individual scores for each site. The social and physical science indicators were used as the independent variables for the regression analysis described below. More details on the social indicators can be found in Tabe 1.

2.4. Logistic regression

Taking a reductive quantitative approach and utilising the maximum available data (Fig 3a), regression analysis was used to assess the role of the physical, technical and social factors on downtime, breakdown and repair outcomes of HPBs. The statistical approach used in our analysis was designed for exploratory purposes, the models described here were not intended to be used as predictive tools. The intention was to identify factors that had explanatory power. Therefore, we did not split input data into testing, validation and training datasets. Furthermore, our models were designed to draw out common factors across all three countries. Thus, we only present results from models that utilise the whole dataset. Country specific models lacked statistical power and reliability due to very small sample sizes.

To ensure independence of our independent variables for the regression analysis we examined the correlation and variance inflation factors. A correlation matrix of the individual independent variables (available in S1 Text Fig C.1 section C) shows little correlation between most variables (for ten out of eleven variables correlation coefficients range between 0.52, for leadership and finances, and −0.45, for support and skills). There is a relatively high correlation between leadership and motivation (0.73), but we decided to include all variables in our regression analysis as they form a key part of our conceptualisation of the socio-material interface. Furthermore, all the factors in our model have a variance inflation factor less than five, confirming the absence of multicollinearity and the independence of the input variables.

Logistic regression was used to examine binary downtime and breakdown outcomes [66]. We created binary dependent variables by splitting the downtime and breakdown data, originally collected as ordinal categories, into a binary logistic variable. To do this we examined the count of each observation within the respective ordinal categories and split the categories into two binary categories to ensure model stability and to create binary categories that made conceptual sense, more details on how binary categories were created are shown in S1 Text section B (Fig B.1 – B.3). For annual cumulative downtime ($n = 70$), we looked at the difference between downtime less than or equal to four weeks and downtime greater than four weeks [39]. For previous downtime ($n = 92$) we examined the factors that influence the probability of downtime being more than one week. For breakdown we examined the probability of more than one failure within a

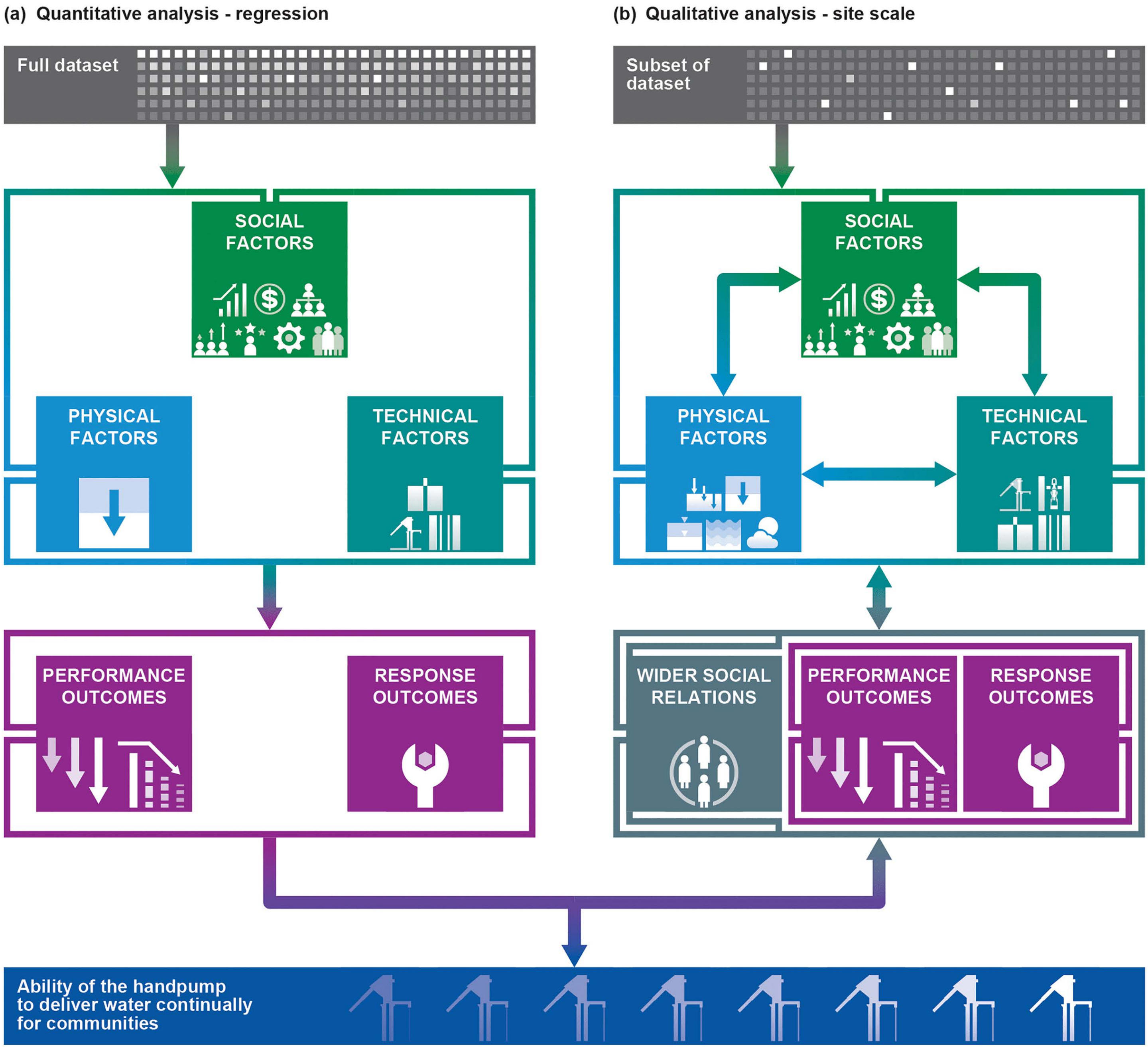

Fig 3. Flow diagram illustrating our approach to the socio-material analysis. (a) The maximum amount of available data was used to conduct logistic regression analysis with a small set of factors investigated. **(b)** Sites were specifically selected for in-depth qualitative analysis. The analysis aimed to examine the relationship and interaction between the social, physical and technical factors and the performance and response outcomes. The findings were then framed in the context of the local, and wider, socio-political and cultural dynamics.

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year (n = 100) and the likelihood of any failure occurring in a year (n = 100), for the latter we used Firth's penalized logistic regression to deal with sparsity and separation in the data [67], thus these results are presented differently from the other regression models, but are included for their explanatory power.

Logistic regression was also used to assess the influence of each of the physical and social factors on the timeliness of repairs being conducted on HPBs. Two possible outcomes (n = 69) were examined: HPBs that required repair in the last year, but repairs were not conducted; and HPBs that required repairs that were conducted within the previous year.

A fundamental assumption of logistic regression models is that continuous independent variables have a linear relationship with the log-odds of the dependent variable. However, real-world phenomena often exhibit more complex, non-linear relationships. To account for this, we systematically assessed the linearity assumption for each continuous predictor in our model by conducting a Likelihood Ratio Test. For each continuous predictor, this involved comparing a model where the predictor was represented linearly against a model where it was represented by a non-linear term (a natural spline with two degrees of freedom), while holding all other predictors constant [67]. Where we found a statistically significant improvement in our model fit by including a non-linear term, this variable was then included in our final logistic regression models.

All regression models were conducted using a backwards and forwards stepwise approach [66]. The stepwise method iterated through all possible combinations of independent variables and sought to minimise the Akaike Information Criteria (AIC) and optimise the set of independent variables used in the models. The stepwise approach aims to simplify each of the regression's models without undue negative impact on model performance. Finally, where combined physical variables show statistical significance in the regression models (social variables were not combined), we split that indicator in a subsequent model run to understand which component of that indicator is having most influence over the regression results [68].

2.5. Site scale qualitative interface analysis

To use the full richness of the dataset we then purposively selected a subset of sites (Fig 3b) to analyse the relationship between community management and use dynamics and the performance of the HPB (in terms of breakdown frequency, downtime, and repair outcomes). The intention was to provide greater understanding of real-world socio-material dynamics based on qualitative social science data, providing insights that are not captured by the logistic regression analysis. This qualitative analysis adds depth to the broader quantitative analysis described above but due to the deep dive required for each site was conducted only on a small number of sites. The nine sites were selected using an iterative process designed to reflect the range of performance outcomes observed across the three countries. Site selection was based on the dependent variables constructed for the logistic regression analysis described above. Firstly, sites with adequate physical and technical data (e.g., sufficient information on all component conditions, borehole configuration and construction, transmissivity, and water level data) to allow in-depth investigation were extracted from the overall dataset (67 sites had adequate data for each performance indicator). Then downtime and failure rate scores were assigned based on the ordinal categories used in the questionnaires described in section 2.2 and 2.4 (more breakdowns and longer downtimes were awarded a poor score and vice-versa). Scores were then summed for each performance outcome (i.e., for downtime and failure rate) and a total performance score for each of the 67 sites was calculated. Sites were then selected based on their scores, in each country one site with a poor score, one site with an intermediate score, and one site with a good score were selected. In Ethiopia, where a mix of India Mark II (IM2) and Afridev handpumps (HP) are used, one site with each type of pump was also selected. Once an initial selection of sites was made it was necessary to check the richness of the social science data associated with each site. If necessary, sites were switched where social science data were lacking to alternative sites with similar overall qualitative scores. The nine final sites included in the qualitative analysis represents approximately 13% of sites with sufficient performance indicator data. Following this method, one site was selected in Luwero (ULU) and two sites in Oyam (UOY) districts of Uganda, two sites in Abeshege (EAE), two sites in Mecha (EME) and one site in Sodo (ESD) woredas of Ethiopia, and one site in Machinga (MMA) district of Malawi. For each site, qualitative data pertaining to the socio-material factors influencing borehole performance were analysed and a picture of relevant dynamics was constructed. This narrative was used to discuss themes based on an STS framing of the results of the regression analysis, and of the physical and social science indicators as outlined above.

3. Results

We begin by summarising the performance indicators across each of the three countries. The results reported for downtime, failure and repair are based only on sites from which this data is available. After summarising the performance indicators for the three countries (objective 1), we then summarise the social science indicator results (objective 2). Approximately 58% of sites have one breakdown or less in the previous year (33% had no breakdowns in the previous year) and approximately 50% of sites have downtime greater than four weeks (less than 10% of sites had zero downtime). Then we present the results of the regression analysis and, finally, the site-based qualitative interface analysis for nine individual sites which allow us to examine how factors individually and collectively influence HPB performance outcomes (objective 3). The regression analysis indicates that transmissivity and pump cylinder position are critical to performance outcomes, and that all social factors influence performance outcomes with demand, finance and external support having complex non-linear relationships with performance outcomes. The qualitative interface analysis was used to construct performance narratives and to examine how factors identified in the regression analysis, and other factors, manifest at a site scale. The dynamic interaction of factors is then examined further in the discussion section.

3.1. Indicators of HPB performance

The results reported in this section address the first of our study objective and represent an assessment of overall HPB performance in each of our three study countries using quantitative indicators of breakdown (section 3.1.1), downtime (section 3.1.2) and repair (section 3.1.3). Our purpose here is not to compare the three countries in terms of outcomes, because of their different social, environmental and political contexts, but rather to draw out differences to facilitate our overall exploratory analysis.

3.1.1. Breakdown. The annual cumulative number of breakdowns in the last year is shown in Fig 4. Malawi had the highest proportion of sites with no reported breakdowns in the last year (45%). In Uganda, most sites reported one breakdown in the last year (42%). In all three countries, most sites had less than two breakdowns in the last year (57%, 54% and 62% in Ethiopia, Malawi and Uganda respectively). Ethiopia had the highest number of sites with

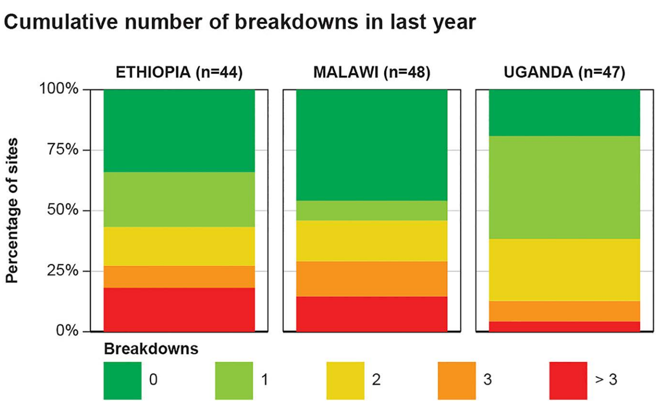

Fig 4. Summary of breakdowns across the sites in Ethiopia, Malawi and Uganda.

https://doi.org/10.1371/journal.pwat.0000486.g004

more than three breakdowns (18%). In Uganda, only a small proportion of sites had more than three breakdowns in the last year (4%).

3.1.2. Downtime. We examined cumulative downtime in the year before our survey (Fig 5a) and the downtime following the most recent breakdown (Fig 5b). When considering the cumulative downtime in the last year Ethiopia appears distinct because it has a larger number of sites with reported downtime of less than one day (21%) and the largest number of sites with reported downtimes > 4 weeks (55%). In Malawi and Uganda, a significant proportion of sites have a total cumulative downtime in the last year < 1 week (25% and 35% respectively). However, similarly to Ethiopia, the largest proportion of sites in Malawi and Uganda have cumulative downtimes in the last year of > 4 weeks (46% and 48% respectively). Only Uganda has no sites with reported downtime of less than a day in the last year.

Overall, the duration of the most recent downtimes (Fig 5b) was longest in Ethiopia, with 72% of sites having downtimes of 1 – 2 weeks or greater. Uganda had the largest number of sites with reported downtimes > 4 weeks (40%) and was the only country where all sites were reported to have at least some downtime (note that the number of sites with reported downtimes was less than the number of sites with reported breakdowns, which is why some sites in Uganda reported no breakdowns, but all sites reported some downtime). However, a significant number of sites in Uganda were also reported to have downtimes of < 1 week (37%). In Malawi for 67% of sites the most recent downtime duration was < 1 week and it was the only country where < 1 week was the most common duration (76% of sites had downtimes < 4 weeks).

3.1.3. Repair. We examined timeliness of repair and found that 12% of broken down HPBs were repaired within a week in Malawi, the only country where HPBs were reported to be repaired within that period (Fig 6). Likewise, Malawi also experienced the highest proportion of required repairs being conducted within a period of one month, 38% of repairs were conducted within this time frame. Overall, in Malawi 50% of HPBs that needed to be repaired were repaired within one month. In Uganda and Ethiopia, the number of HPBs with problems that were not repaired within one month is 64% and 65% respectively (Fig 6). However, over the course of the previous year Uganda had the highest proportion of broken down HPBs repaired (87%).

3.2. Social dimensions of handpump performance

The results reported in this section address our second study objective representing an assessment of the status and role of social factors in overall HPB performance.

Of the seven social indicators the least problematic appears to be access to spare parts with 75%, 62% and 68% of sites in Ethiopia, Malawi and Uganda respectively having no problems (Fig 7a). For most social factors in Ethiopia and

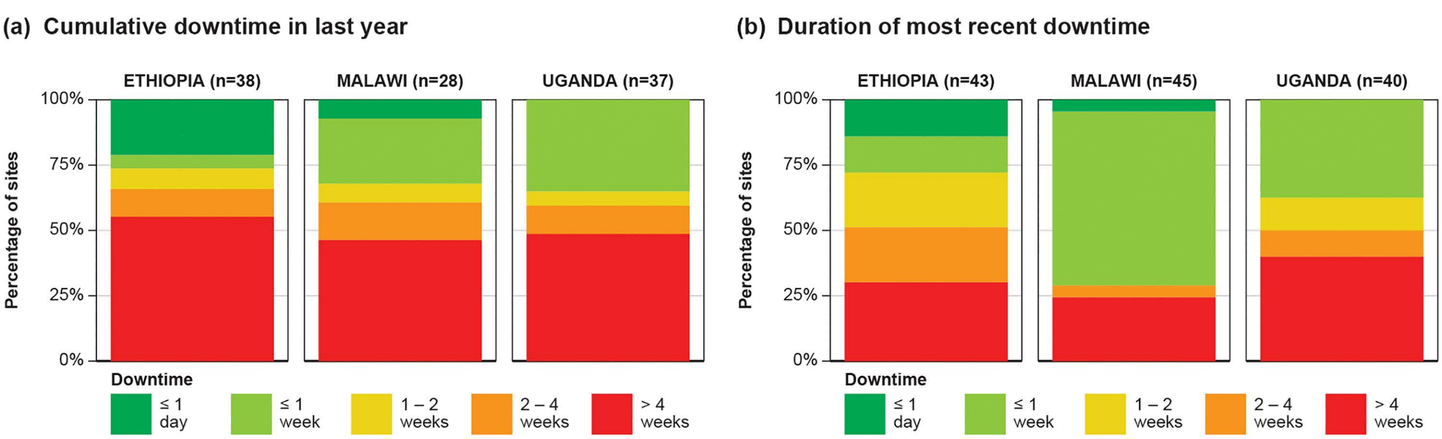

Fig 5. Summary of downtime across the sites in Ethiopia, Malawi and Uganda.

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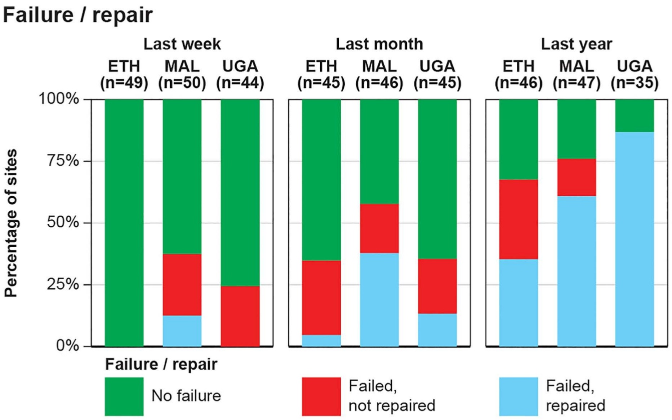

Fig 6. Summary of timeliness of repair across the sites in Ethiopia, Malawi and Uganda.

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Uganda a small majority of sites are reported as having no issues. However, access to external support is a problem at most sites in all three countries and finance is a problem at 68% of sites in Uganda (major problem at 23% of Ugandan sites). In Ethiopia and Uganda access to external support is a problem at 80% and 83% of sites respectively (major problem at 43% and 34% respectively, Fig 7a). In Malawi, most social factors are reported as being minor or moderate problems. However, finances and demand on the HPB are particularly problematic with these factors reported as a major problem at 31% and 33% of sites respectively (Fig 7a).

3.3. Regression results

The results reported in this section address our third study objective, highlighting the role of individual social and physical factors in handpump borehole performance. The regression analysis does not indicate how these factors interact to produce HPB performance outcomes, this is dealt with by our qualitative narrative analysis which is presented in the next section and in the discussion.

The regression results (Fig 8) illustrate that different combinations of factors influence different outcomes (i.e., downtime, breakdown or repair). The detailed results of the logistic regressions conducted can be found in the S1 Text section D (Fig D.1 – D.12 and Table D.1 – D.15), including measures of goodness of fit which indicate that our models provide moderate to excellent explanatory power. A mix of social, physical and technical factors occur across all models. However, it is notable that the probability of any failure occurring in the past year is dominated by physical and technical factors (i.e., borehole, handpump and hydrogeology) and that annual cumulative downtime is dominated by social factors (i.e., demand, finances and spares).

Of the social factor demand occurs most frequently, influencing the probability of failure in the previous year and the cumulative annual and previous downtimes. Crucially however, the effect is non-linear with both low and high values of demand being associated with a higher probability of any failure occurring and longer downtimes. This suggests that when demand on the handpump is very high or very low the probability of any failure having occurred in the previous year increases and longer periods of downtime also become more likely.

Finance influences the annual number of breakdowns (Fig 8a), although the relationship is non-linear, with both low and high values of finance being associated with a lower probability of higher rates of failure (high finance values result in the lowest rates of failure). This suggests that where finance systems are in place, they must be accessible, efficient and transparent, otherwise higher rates of failure are more likely, even than in cases where there is no formal finance system in place. Furthermore, as finance becomes more of a problem the annual cumulative downtime of handpumped boreholes

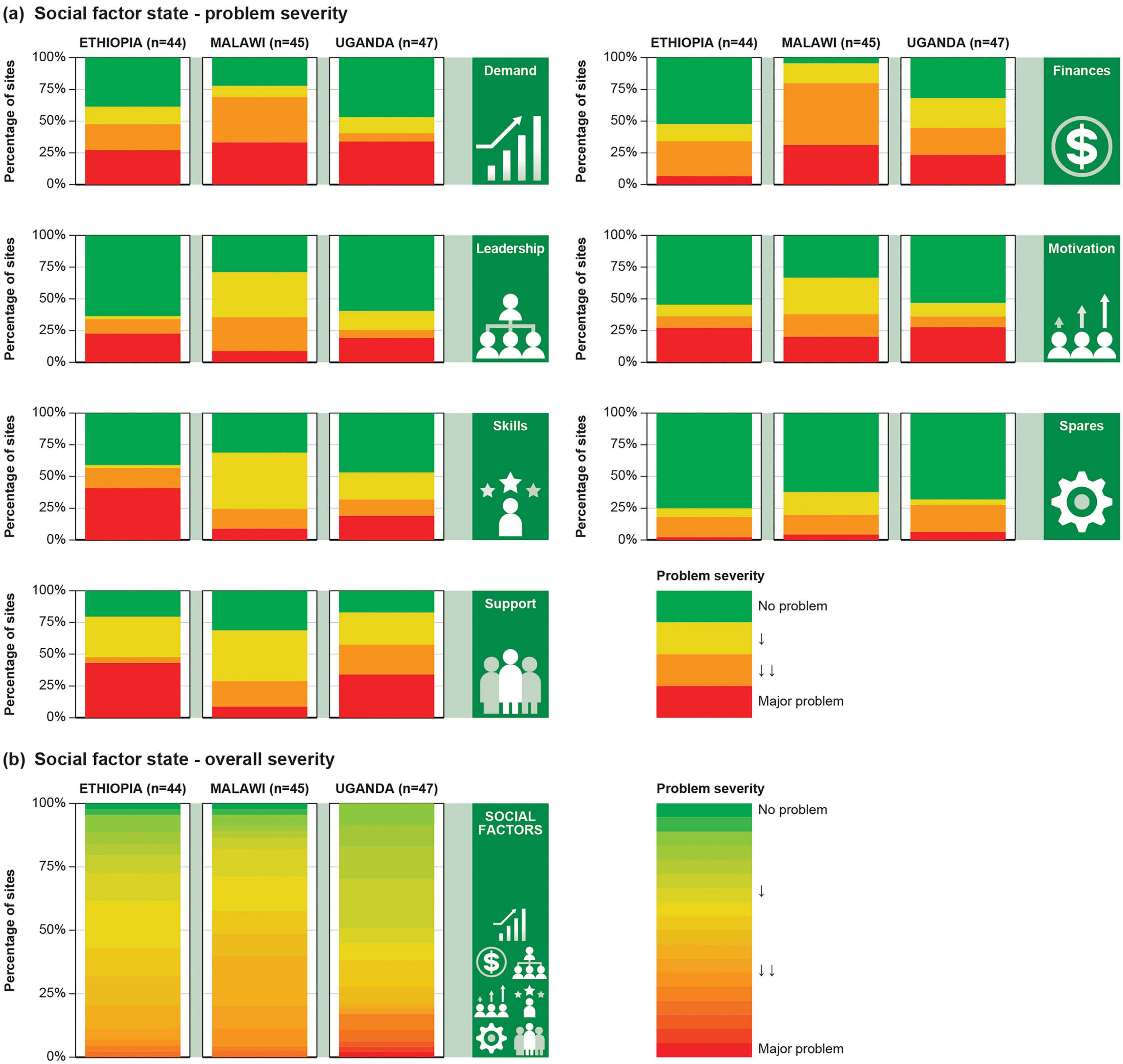

Fig 7. Summary of social science indicators across the sites in Ethiopia, Malawi and Uganda. (a) Indicator summary for each social factor considered. **(b)** Overall summary of social factors.

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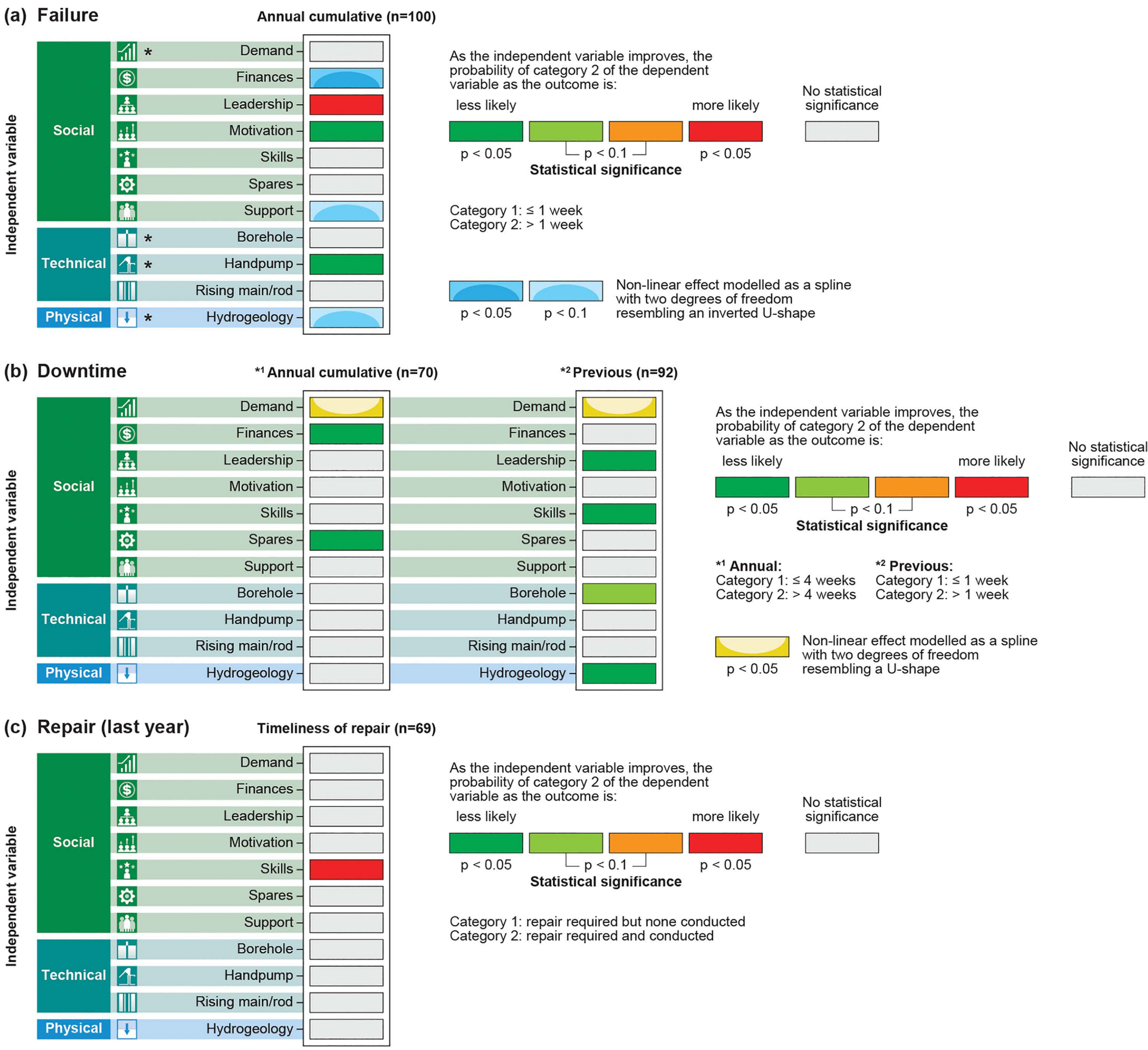

Fig 8. Summary of regression results. (a) Logistic regression results for annual cumulative rate of failure, the asterisk (*) indicates variables that were found to be important for the probability of any failure occurring in the last year using Firth's penalized logistic regression. **(b)** Logistic regression results for annual cumulative and previous downtime. **(d)** Logistic regression results for timeliness of handpump repair in the last year.

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increases (Fig 8b), which may indicate a negative feedback loop of more and longer failures inevitably placing further strain on finances.

With regards to the other social factors, availability of skills within the community is the key factor influencing the likelihood of repairs being conducted on handpumps requiring repairs in the last year (Fig 8c). Access to skills and effective leadership are important for reducing the length of most recent downtime (Fig 8b). Better leadership is also statistically associated with annual cumulative rates of failure, but counterintuitively better leadership appears to be associated with higher rates of failure. However, this may indicate that improved leadership is a response to higher rates of failure rather than a cause. Motivation is important for reducing the annual cumulative number of failures in the previous year (Fig 8a). For the 25% to 32% of sites where problematic access to spares is reported (Fig 7) the results of the regression analysis indicate that it increases the total annual cumulative downtime (Fig 8b). If parts are not readily available, then the likelihood of a longer period of downtime is almost certainly higher.

External support appears to have a weak non-linear relationship with annual cumulative failures (Fig 8a). Both low and high values of external support are associated with a lower probability of higher rates of failure, this suggests that in communities with no or very poor external support, water users may be less inclined to report problems and/or may be more likely to fix minor problems quickly themselves. In communities with very good external support lower rates of failure are more likely. In communities where there is some form of external support, if it is not effective, then higher rates of failure are most likely.

Of the physical factors hydrogeology appears most frequently. Better hydrogeology results in a lower probability of any failure having occurred in the past year (Fig 8a) and it reduces the duration of the previous downtime (Fig 8b). Transmissivity appears to be the key factor when it comes to the duration of the previous downtime with higher transmissivity leading to shorter downtime. Hydrogeology has a non-linear relationship with the annual cumulative number of failures (Fig 8a), both low and high values of hydrogeology are associated with a lower probability of higher rates of failure. Unsurprisingly, at sites where transmissivity and water level are low or very high, the cumulative rate of failure is lower. However, at sites with low transmissivity and or deep water levels communities may have learned to manage handpump use to reduce the probability of failure.

Construction and configuration of the borehole appears to influence the duration of the most recent downtime (Fig 8b) and the likelihood of any failures in the last year (Fig 8a). Further investigation indicates that poor positioning of the cylinder is the key borehole configuration factor influencing the duration of the previous downtime (e.g., a cylinder placed very close to the rest water level, or to shallow in a deep borehole). Poor positioning of the cylinder can be resolved by addition of new rods and rising main sections.

Handpumps in poorer condition increase both the probability of any failure occurring and the annual cumulative numbers of breakdowns in the previous year (Fig 8a). The condition of the rising main and rod doesn't appear to substantially influence failure rate or downtime. However, the length of rising main represented by the position of the cylinder, which might be altered by repairs in response to previous issues such as corrosion of individual rising main sections, was shown to be significant in the borehole configuration.

3.4. Site scale qualitative interface analysis

The results reported in this section address all three of our study objectives at a site scale. We examine the physical condition (objective 1) and social status (objective 2) of factors influencing performance outcomes at nine sites systematically selected to represent a range of performance outcomes. We also provide the context for comprehensive site narratives, which follow in the discussion section, examining how these factors interact to produce observed performance outcomes at each site (objective 3).

A summary of the social, physical and technical factors for each of the nine sites selected for the qualitative analysis is presented in Fig 9. In the discussion we consider the dynamic interactions between these factors at each of the nine sites (section 4.3). Of the nine sites selected, five were in Ethiopia, three in Uganda and one in Malawi. Afridev handpumps were installed at one site in Malawi and three sites in Ethiopia, while India Mark II handpumps were installed at the remaining sites. Across the nine sites, borehole depths ranged from 27.8 m (UOY19) to 70.3 m (EAE01), water level ranged from 2.42 (EME07) to 24.2 m (EAE01), and transmissivity values ranged from 0.62 m^2/d (MMA12) to 579.6 m^2/d

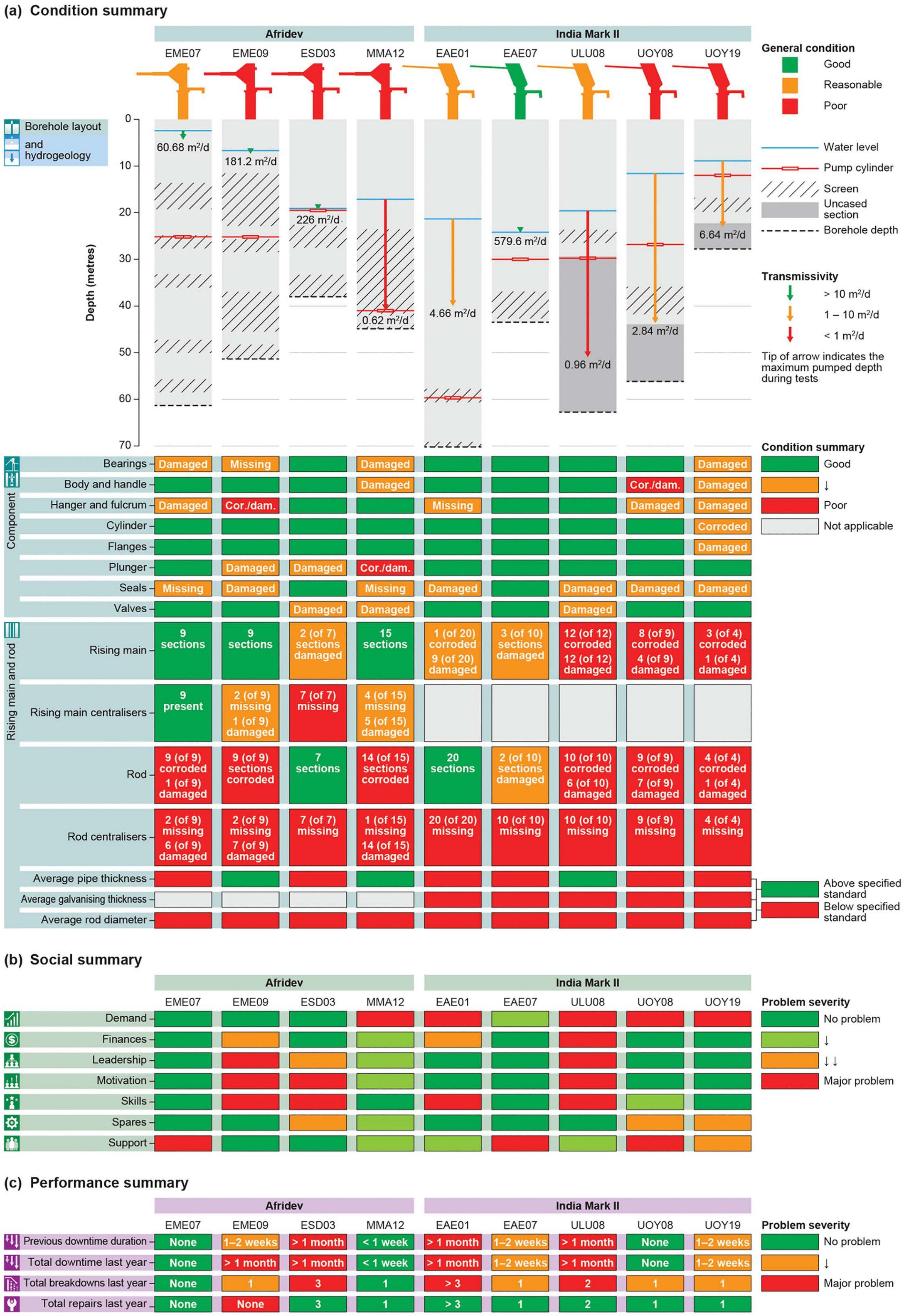

Fig 9. Summary of the social-material status of the nine sites selected for detailed narrative analysis. (a) Physical and technical summary of hydrogeology, borehole construction and handpump condition at each site. **(b)** Social science indicator summary for each site. **(c)** Performance summary for each handpump borehole at each site.

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(EAE07). During the two-hour pumping test, the water level dropped below the level of the HP cylinder due to low transmissivity and poor positioning of the cylinder at the three sites in Uganda (ULU08, UOY08, UOY19) as well as at the Malawi site (MMA12). At one site in Ethiopia (ESD03) the cylinder was placed just below the static water level, risking the water level dropping below the cylinder in dry conditions despite a high transmissivity (226 m^2/d).

The condition of the HPB was ranked relative to every other HPB in the subset of nine that were selected for the site-based analysis. Overall, the India Mark II handpump at site EAE07 in Ethiopia was in the best condition, with all components in a good condition and only three pipe sections (out of 10) showing signs of damage. The India Mark II at site UOY19 was in the poorest condition overall with most components damaged and/or corroded. Pipe diameter was below standards at six of the nine sites, rod diameter was below standards at all nine sites, and galvanising thickness was below standards for all five India Mark II handpumps. Rising main and rod condition was generally poor across the nine sites, which is consistent with previous work that found these components to be in particularly poor condition across most of the 145 sites [26]. Photographs of the handpump and components for the nine sites can be found in S1 Text section 5 (Fig E.1 – E.9).

Overall, high demand on the HPB was a major problem in five communities (MMA12, EAE01, ULU08, UOY08, UOY19, HPs at these sites served on average 279 households ranging between 60 at MMA12 and 500 at EAE01), limited access to relevant skills was a major problem at four sites (EME09, ESD03, EAE01, ULU08), and access to external support was a problem at four sites (EME07, EAE07, UOY08, UOY19). Access to spares was a problem at three sites (ESD03, UOY08, UOY19). Overall, site EME07 had the least problems, six of the seven social factors were reported as not being a problem and only external support was reported as a major problem. Site ULU08 had most problems overall, with demand, finance, leadership, motivation and skills all reported as a major problem. Only at ULU08 was access to spares reported as no problem.

Most sites experienced at least one breakdown and had a total downtime of > 1 month in the last year. Only site EME07 did not experience any breakdowns or downtime in the last year. Three sites experienced cumulative downtime of more than 1 month in the last year, EAE01 experienced more than three breakdowns, ESD03 experienced three breakdowns and ULU08 experienced two breakdowns. At each of these site's repairs were conducted but only after > 1 month of downtime. Site EME09 was the only site where a breakdown had not yet been repaired. At site UOY08, one previous breakdown occurred in the last year, but it was repaired quickly so no significant downtime was experienced by the community.

4. Discussion

We begin our discussion by examining performance and response outcomes and the factors that shape these outcomes (objective 1 and 2). Next, we consider these outcomes in the wider social, historical and political context in our three study countries. Finally, we investigate socio-material interface dynamics, recognising the multidimensional and multidirectional nature of these interactions, and consider the apparently more paradoxical findings of our analysis by drawing on the subset of nine sites across the three countries (objective 3). We find examples where external support providers do not have adequate equipment for repair, making them unwilling and unable to conduct more complex repairs and creating tensions with the communities they serve. We find cases where good hydrogeology (e.g., adequate transmissivity) results in well performing handpumps which allow management and financial arrangements to evolve in dynamic ways which can risk inequitable access to water supply, and we find instances where capture of management arrangements by certain sections of the community results in poorly sited boreholes and inequitable skill development which can lead to poor performance outcomes

4.1. Socio-material factors determining performance and response outcomes

Several common factors emerge across our quantitative and qualitative analysis that appear to be particularly important to help explain the performance outcomes observed. Firstly, and in agreement with MacAllister et al. [26], we find that hydrogeology (particularly transmissivity) and the borehole construction and configuration (particularly position of the HP cylinder) (section 3.3 and 3.4), are important determinants of HPB performance. Poorly positioned cylinders increase the likelihood of the handpump running dry. Hydrogeology has a complex non-linear relationship with the annual cumulative rate of failure, possibly indicating that in areas with difficult hydrogeology communities adapt to manage handpumps in a way that reduces the probability of failure (Fig 8a), but where failure does occur downtimes can be longer (Fig 8b). Consistent with our previous study [26], poor condition of pipes and rods is widespread. However, our regression analysis does not indicate that rising main and rod condition is an important determinant of performance outcomes. However, the condition of the handpump more generally does influence the probability of any failure occurring and the rate of failure over the past year (Fig 8a).

Demand is the most frequently highlighted variable across our regression models, influencing the likelihood of any failure occurring in the previous years and influencing downtime duration (Fig 8a and 8b). When demand is very low or very high the probability of failure and longer downtimes is increased. This contrasts with previously published studies which found sources with low users' numbers had substantially higher functionality than those with very high user numbers [12]. However, this finding makes conceptual sense because when handpumps are used infrequently, there is unlikely to be significant pressures for rapid repair and when repairs are conducted, they may be makeshift and result in higher probability of failure, particularly during periods when demand might be higher (e.g., during the dry season or drought). Handpumps that experience very high demand are more likely to breakdown through intensive use and may experience longer breakdowns because they require more complex repairs.

Finance is a statistically significant factor influencing the annual cumulative rate of failure and downtime (Fig 8a and b). Access to funds and the arrangements to ensure access, whether that be fee structure, access to bank accounts or subsidies is a critical element in the sustainability of any rural water supply scheme [3,5,6,11,69–72]. Here we consider finance to include the ability of communities to source funds to cover spare parts and/or the costs incurred when using service providers. Our analysis indicates that while having an effective finance system in place reduces the probability of higher rates of failure, having an ineffective financial system can produce worse outcomes than having no system at all (Fig 8a). Where communities can access funds from an existing bank account with savings set aside [24] or can responsively raise funds, our analysis indicates that number of breakdowns is reduced, and annual cumulative downtime is less. The ability of communities to source finance for repairs and the availability of spare parts are the crucial to reducing the duration of annual cumulative downtime (Fig 8a, b). However, communities often struggle to raise funds and there is a well-documented gap between revenues from users and the cost of sustained service [69]. Thus, there is a need for national governments and donors to recognise and address systemic underfunding of rural water services [69] and to find innovative sources of funding including, for example, carbon credits, impact investment [69], performance-based funding for service providers [73], pay-as-you-fetch [61] and other innovations.

Our results indicate that, in communities that are highly motivated to resolve problems, effective leadership can emerge because of high rates of waterpoint failure. Once in place, effective leadership, in combination with the availability of adequate skills for timely repair, can reduce downtimes. Murray et al. [24] find that better water point performance is associated with functional water management arrangements, which includes the ability to name someone with the appropriate skills for maintenance.

While skills within the community are important for reducing downtimes, effective external support systems can reduce rates of failure (Fig 8a). Several studies consider new models of professionalised maintenance provision as a means of external support and find that they have the potential to substantially improve performance [3,15,16]. However, other studies find that current tariff structure [74] and finance arrangements are not sufficient to fund these at a large scale [16]. Furthermore, service reliability is crucial for fee collection and willingness to pay [70], but limited capacity of service providers [5] and misaligned policy incentives [75] can undermine service outcomes, all findings that are consistent with our regression results which indicate that the highest rates of failure are associated with ineffective external support. Where external support complements and build on existing community arrangements it is likely to be more effective [17,27,62].

Our regression results indicate that different combinations of independent variables are important for different performance outcomes. Thus, when designing surveys of rural water supply it is important that the aims and objectives are tightly defined, to ensure the surveys yield insightful, and actionable, information.

4.2. Wider social, historical and political contexts

In Malawi, where the Village Level Operation and Maintenance (VLOM) Afridev HP is used at all sites surveyed, handpumps have good functionality and are repaired quickly when they break down. The Afridev is designed for ease of repair and uses materials less susceptible to corrosion [26]. Good outcomes in Malawi, despite the poor state of the community level social indicators (Fig 7), may be due to the development of extension worker networks, formalisation and training of area mechanics and increasing collaboration between donors and NGOs [76]. Our results support this conclusion as external support appears to be the strongest of the social indicators in Malawi (Fig 7a) despite some evidence that in its current form it might undermine longer term sustainability of rural water supplies. In Malawi, some studies suggest that there is an over reliance on donor and non-governmental organisation funding and support [74], as well as an under-recovery of costs from community tariffs [77].

Cumulative annual downtime in Ethiopia was the longest of all three countries (Fig 5a) and it generally took longer to repair HPs after the most recent breakdown in Ethiopia than in the other two countries (Fig 5b and 6). Long duration of downtime in Ethiopia agrees with previous studies [78]. Ethiopia uses a mix of Afridev and India Mark II HPs [26]. The India Mark II is not a VLOM pump which means that communities likely rely more on external support for repairs. In a large country with difficult terrain, this can be logistically challenging for external support providers, possibly explaining the relatively long downtimes [78,79]. In Ethiopia our results indicate that access to skills within the community is a problem at almost 50% of sites (Fig 7a), likely contributing to longer downtimes.

Rates of failure are high in Uganda (Fig 4), which is likely to be a result of its distinct hydrogeological conditions. In Uganda, transmissivity is universally low [26,80]. Furthermore, corrosive groundwater [37] and the extensive use of India Mark II HPs with galvanised iron components result in high rates of corrosion [26]. The de-prioritisation of point source water supplies, such as HPBs, relative to piped water [81] and low priority in national budgets [82], are likely to further contribute to these performance challenges in Uganda.

In addition to these specific contextual factors, there are also some common challenges that likely impact performance outcomes across all three countries. For example, there are limited financial resources and human capacity constraints for operation and maintenance of rural water supplies across all three countries [76,82,78]. Despite this, and the fact that in Malawi social factors were weakest, HPB performance was generally better than in Uganda and Ethiopia. This apparent paradox may be related to the original development of the Afridev (first known as the Maldev) and the VLOM approach, which took place in Malawi in the 1980s [83]. The Afridev was informally adopted as the standard HP soon after development and formally adopted by the Government of Malawi in 1997 [20]. Decentralisation and devolution of water management has also had significant impacts across all three countries [76,79,82]. Other common factors that likely impact these outcomes include limited monitoring of rural infrastructure [22], inappropriate procurement procedures for rural water infrastructure [64,84,85], and lack of quality control of infrastructure at both import and installation [21,26]. Although these wider contextual issues were beyond the main scope of this study, we note that these factors are important aspects of the enabling environment and likely impact the more context specific factors we consider in the following sections.

4.3. Socio-material interface dynamics

In this and the next sub-section, we contextualise the study's findings by examinging in more detail the ways in which dynamics at the socio-material interface can play out in practice (objective 3). The narratives below were developed from the focus group and interviews conducted as part of the social science surveys.

We start with the challenge of providing effective external support in Ethiopia, which is illustrated at site ***EAE01*** (Fig 9). The HP at this site is an India Mark II with galvanised iron (GI) pipes. Until one year before the fieldwork visit, technical ***support*** for the waterpoint was being provided by a foreign NGO. This NGO had the necessary equipment to remove the GI pipes when undertaking repair work, and the community were happy with the service. However, in what is a common experience, the NGO left abruptly without the community understanding why. At this point technical ***support*** was handed over to the Woreda water office (akin to the district level of government). The Woreda staff do not have the same equipment as the NGO and instead must remove the GI pipes by hand. This undermined the provision of support, as Woreda staff are reluctant or unable to perform some forms of repair. It has also led to tension between the community and the Woreda, with a feeling on the community's part that the support they are receiving is not being carried out in good faith. This suspicion is evidenced by the short timeframe between repair work, the onset of subsequent breakdowns, long duration of downtime, and regular breakdowns (Fig 9c).

In Uganda, challenging hydrogeology leading to high rates of failure play out in unexpected ways at the community level. In the case of ***ULU08*** (Fig 9), there are issues with both water quality and ***hydrogeology*** which impact the performance of the India Mark II HP. The transmissivity at this site (0.96 m2/d) is below the threshold required for a HP to deliver its design yield (1.4 m^2/d, [54]) and there is evidence of iron contamination because of corrosion. Moreover, when the HP breaks down it can take many weeks to be repaired. Yet despite this, most of the village (c.400 households) relies on the waterpoint. The most notable feature of the water management arrangement is the personal control the caretaker has over the affairs of the borehole. She lives near to it, allowing for ongoing oversight. She is also well connected. The waterpoint caretaker is on good terms with local authority figures, including the police and staff at the district subcounty. These relationships have allowed the caretaker and her contacts to use the waterpoint as a source of income. The caretaker only permits payments for water use annually at 12,000 UGX or as two six-monthly instalments of 6,000 UGX. Anyone who has not paid is forbidden to use the waterpoint. This tariff structure helps to explain the slow repair time for this case. When the waterpoint breaks down, the caretaker has typically already banked user fees for many months to come and is therefore less inclined to act. Moreover, breakdowns serve as an opportunity to wrestle more money from water users, on the grounds that the repair won't take place without them.

Further evidence of the socially embedded nature of the tension between technical demands and socio-cultural dynamics is evidenced at site ***MMA12*** (Fig 9) in Malawi. The village chief was the one to decide where the borehole was sited: *"the chief made the decision as to where exactly to drill the borehole and later he handed over the responsibilities to the water point committee."* At this site the transmissivity (c.0.6m^2/d) is below the threshold required for a HP to deliver the design yield (1.4 m^2/d). Furthermore, the water level is deep at 40.85 m, but the borehole is relatively shallow in comparison at 45 m, and the cylinder is placed only 0.15 m below the watertable. This combination of challenging ***hydrogeology*** and poor ***borehole*** configuration will inevitably result in regular breakdowns. Given, these factors it is not clear what the logic of the chief's decision was. However, should it have been something other than hydrogeological conditions and handpump yield then it may have contributed substantially to the poor functioning of the waterpoint. This could be one explanation for the surprising result in the regression analysis which indicate that strong leadership is associated with negative performance outcomes (Fig 8a).

Our qualitative analysis provides interesting insights into how questions of finance comingle with local social arrangements and the performance of the HP. At ***EAE07*** in Ethiopia (Fig 9), we see how good performance of the waterpoint facilitates the emergence of a form of governance whose scope extends beyond the waterpoint itself. In particular, the strong governance structure, well-functioning waterpoint, and the reliance of the community on the waterpoint resulted in a situation where user fees could be increased from 10 cents to 25 cents per jerry can. This price hike was part of an initiative to use waterpoint savings to pay for other projects in the village, including the construction of a school and the installation of taps with water supply lines.

In Uganda, at site ***UOY08*** (Fig 9), there is a waterpoint that performs reasonably well, partly because it is installed in an area of adequate ***hydrogeology.*** Importantly, however, it has experienced some breakdowns, including one in the last year which was repaired within 3 days. The community also heavily relies on the waterpoint. The management arrangement at ***UOY08*** includes a user fee system that has evolved into a loan scheme whereby members of the community can borrow money and pay it back with interest. The need to ***finance*** this scheme, and the potential to accrue interest, has increased the impetus to collect user fees in full and in a timely fashion. It has also been accompanied by a harsher system of fines. The physical performance of this waterpoint is therefore implicated in the evolution of an institutional innovation that, on the face of it, has resulted in a more effective management arrangement with strong ***leadership***. Yet this arrangement is less inclusive and has the potential to promote perverse incentives, so is a system that is liable to abuse. Observations at sites ***EAE07*** and ***UOY08*** highlight the potential benefits of 'working with the grain' (Whaley et al., 2020), where community innovation has occurred and is improving performance of rural water supplies, external actors should work with that to help ensure those outcomes are sustained. At the same time these actors must recognise and plan for the more negative, or perverse, outcomes that may be associated with local innovation such as those observed at site ***ULU08*** or ***ESD03***, the latter of which we describe below.

The material dimension of the waterpoint – its performance, siting, and relationship to other water sources – can also have an influence on ***motivation*** to repair and maintain it. This in turn affects waterpoint performance. The regression results indicate that when there is good motivation within a community, HP failure rates are reduced (Fig 8a). One example of how these dynamics play out is at the Afridev handpump installed at site ***ESD03*** (Fig 9) in Ethiopia. Here the waterpoint was drilled near to a school. The school director is also a member of the kebele (the village council) and after waterpoint construction he used his influence to request from the kebele chairperson that schoolteachers don't have to pay or queue for water. This created a tension between the teachers and the rest of the community. However, the waterpoint does not perform well despite being located at a site with good ***hydrogeology***. The ***borehole*** configuration is suboptimal with the HP cylinder placed only about 0.45 m below the water table, likely resulting in the risk of the water dropping below the cylinder during dry periods or times of excessive use. Components are also in a poor overall condition with reports of valves and the plunger requiring regular replacement (Fig 9a). The physical surveys found that the HP has stopped working three times in the last year (Fig 9c) and has only worked for four months in total in the last three years. Roughly twenty years ago, the handpump type was changed from an India Mark II HP, but the community still have recollections of the India Mark II requiring less frequent repairs. Over time, the combination of these social and physical factors has undermined the community's ***motivation*** to continue investing time and money to repair the waterpoint. It is especially the case given that many community members have their own private hand-dug well or can use the well of a neighbour. This, however, is not the case for the schoolteachers, none of whom have their own alternative source. Instead, when the waterpoint is not functioning they must draw on social relations with households and individuals in the community to use their water sources. For some teachers, this situation requires them to use their authority to make school children bring them water from their homes. Here, then, is a situation where borehole siting, waterpoint performance, alternative water sources, history of repair, and social dynamics including strong ***leadership***, co-constitute one another. The result is a situation where ***motivation*** to repair the waterpoint is low, resulting in longer downtimes.

4.4. Social-material interface paradoxes

Our regression results indicate that ***leadership*** has a counter-intuitive relationship with rates of failure over course of the year, with strong leadership apparently resulting in more breakdowns (Fig 8a). While the regression results might indicate that better leadership is in fact a result of higher rates of failure we can't rule out other dynamics which might offer alternative explanations. Leadership is important in normal day-to-day operation and use of the waterpoint. How the waterpoint is used and who uses it should be managed to ensure it continues to function over time. When the waterpoint breaks down, the capability for certain individuals to take a lead, mobilise community members, and engage with external service providers is crucial. Leadership may be seen as fair and legitimate by most people, or as unfair and self-serving. It is this balance between the ability to get things done and the perception that leaders may not manage the waterpoint in an equitable manner that might offer further insight into this counter intuitive result.

Our qualitative analysis also reveals examples of the tension between strong leadership and negative outcomes. This is observed at site ***EAE07*** (Fig 9) in Ethiopia, where the water point has a strong governance structure that includes ***support*** from institutions and actors inside the community (the waterpoint committee, village council, and 'idir' – a traditional burial society) and outside the community (the Woreda water office and an NGO). Yet this dependency on the waterpoint has also allowed elements of the governance structure to use the waterpoint as an instrument of control. For example, the kebele (the village level of government) will force the WPC to lock the waterpoint to ensure that community members attend meetings or contribute their time and labour to various public projects within the village. It is possible that the complex leadership dynamics like this, also observed at sites **UOY19** and **MMA12** (Fig 9), lead to non-trivial casual relationships between physical and social factors and surprising performance outcomes, which may be reflected in the regression results.

4.5. The socio-material interface as a framework for analysis and it's limitations

In this study we have incorporated quantitative and qualitative datasets into a socio-material analysis of the technological, physical, and social dimensions of hand-pumped boreholes in Ethiopia, Malawi, and Uganda. Both the type of study and its scope is unusual given the substantive nature of the various datasets and the resulting need to work across physical and social science disciplines, rather than from primarily within one or the other (as many STS studies ultimately do). Yet doing so has not been without its challenges, not least in relation to questions of epistemology. For example, the challenge of developing an understanding of how different forms of data and different types of approach remain valid despite their differences, the relationships that emerge between these differences and how they are navigated, and the findings, insights, and conclusions that can be drawn from such an analysis. We found that close collaboration between social and physical scientists during design, fieldwork and analysis helped overcome these challenges. Our study demonstrates that as much value can be gained from focussed interdisciplinary observational studies as from large quantitative analysis, the latter of which have been more common in recent years. We would argue that a framing akin to that of the socio-material interface is crucial for attempting to tackle the multi-dimensional challenges that characterise the performance and sustainability of rural water supply infrastructure.

Our study has some inherent limitations. Firstly, the selection of sites to specifically represent a range of different functionality categories means that our statistical analysis findings are not generalisable beyond the cases we analysed. Our use of structured questionnaires to determine break down, downtime and repairs also relies on community recall which is a well-known issue with data gathered in this way. However, our study was designed to minimise recall bias by focussing on shorter recall periods (i.e., asking respondents for their recollection of one year of failure and downtime) and encouraging field teams to probe for clarity and consistency in community responses. The qualitative interface analysis of the nine sites represents the interaction of factors only at these sites, we can't draw general conclusions about how these factors might interact at other locations. However, this would apply equally if we examined these interactions at all 67 sites with adequate data. Thus, for purpose of clarity and concision we chose to focus on a smaller number of sites. However, while each site is unique our findings do illustrate how factors can interact in surprising ways and highlight the need to consider the local context, in other words working with the grain [17], when planning rural water supply interventions.

5. Conclusions

Using a socio-material interface analysis we examined the dynamic multidimensional relationship between rural water supply performance and the interrelated physical, technical and social factors that shape these outcomes in Ethiopia, Malawi and Uganda. Situating our analysis in the field of Science and Technology Studies (STS) helped us to bring together the broad insights provided by statistical methods and the detail and nuance provided by qualitative social science research (i.e. connecting narratives and numbers). Our study highlights the benefits of taking an interdisciplinary approach, particularly its ability to draw out nuanced and counterintuitive relationships and dynamics, thereby allowing a fuller characterisation of the complex nature of the dynamic socio-material interface that shape rural water supply outcomes.

We found several common socio-material factors that determine breakdowns, downtime and timely repair. These included the social factors of access to finance, skills, external support, and the motivation of the community. Common physical factors, in agreement with our previous work, included the configuration and construction of the borehole, in particular the position of the handpump cylinder, and the hydrogeology, particularly transmissivity. Different combinations of these factors are important for each performance outcome: risk of any failure occurring in the previous year, annual cumulative failure, annual cumulative downtime, the duration of the most recent breakdown, and timeliness of repair. Thus, when designing surveys of rural water supply it is important that the aims and objectives are tightly defined, to ensure the surveys yield insightful, and actionable, information.

Site-scale qualitative analysis allowed us to construct narratives to examine in detail how these, and other, factors and performance outcomes mutually shape each other. We find that management arrangements are often shaped by the physical location of boreholes in communities, leadership in a community may make decisions about borehole siting based primarily on concerns other than hydrogeological conditions, but where hydrogeological conditions (transmissivity in particular) subsequently determine performance outcomes. Furthermore, within a community the acquisition of skills to conduct repairs can be intrinsically linked to leadership. This is not always to the community's advantage and can undermine performance outcomes by leading to over dependency on a limited skill set and capture of management arrangements. The availability of finance and external support in and of themselves are not sufficient for good performance outcomes. Rather, finance and external support systems must be effective to deliver improved performance outcomes. Effective external support consists of continuity of service and ensuring providers have the necessary tools and skills to undertake repairs. Effective finance systems consist of the ability to access funds responsively, transparency in the use of funds and perceptions of fairness.

Moreover, our results highlight cases where well performing HPBs have led to unexpected outcomes, including undermining long-term ability of communities and/or external providers to conduct repairs in a timely manner, HPBs being used as an instrument of control within communities, and the emergence of perverse management arrangements. Over time dynamics such as these can slowly undermine the community's relationship to their water point. Likewise, where performance is good it is easier to collect fees but when fees are collected a lack of equality and transparency in how they are used, can lead to communities that are less motivated to repair.

The implications of our study include: bottom-up community arrangements are recognised and supported for rural water management (i.e., 'working with the grain'); anticipating and working with the emergence of contextual innovation stemming from diverse community management arrangements; recognising the need for continuity of external support for communities, while developing skills equitably within communities; ensuring that hydrogeological conditions are properly characterised before water points are installed; and building the technical capacity of drillers, technicians and hydrogeologists to support development of groundwater for rural water supply. As the rural water supply sector increasingly looks to more complex technologies, such as solar and piped water supplies, to deliver water to communities across Africa, it is important to reflect on and learn from the experience of 50 years of investment in HPBs. At the same time, it is also important to recognise that HPBs will continue to play an important, perhaps crucial, role for many communities in the future.

Supporting information

S1 Text. Supplementary material .
(DOCX)

S1 Checklist. Inclusivity in global research.
(DOCX)

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