Science of the Total Environment 626 (2018) 156–164

Contents lists available at ScienceDirect

Science of the Total Environment

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

Risk factors associated with rural water supply failure: A 30-year retrospective study of handpumps on the south coast of Kenya

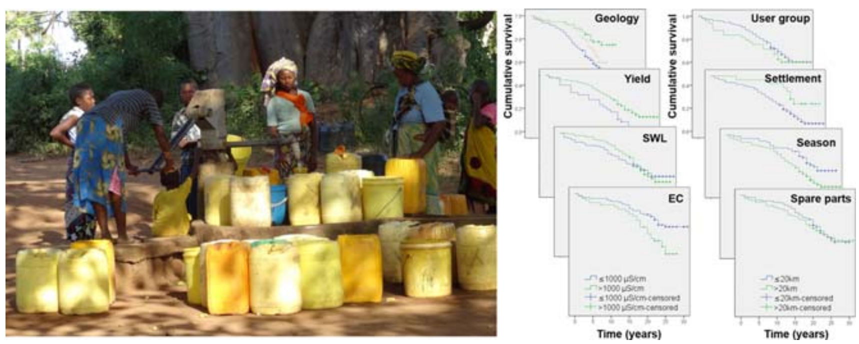
Tim Foster [a,b,*], Juliet Willetts [a], Mike Lane [c], Patrick Thomson [b], Jacob Katuva [b], Rob Hope [b]

[a] Institute for Sustainable Futures, University of Technology Sydney, 235 Jones St, Ultimo 2007, NSW, Australia
[b] School of Geography and the Environment and Smith School of Enterprise and the Environment, Oxford University, South Parks Road, Oxford OX1 3QY, United Kingdom
[c] Rural Focus Ltd, Box 1011-10400, Nanyuki, Kenya

HIGHLIGHTS

- Sustainability of water supplies a major challenge in rural Africa
- This study assesses rural water supply outcomes in Kenya over a 30-year period.
- Survival analysis applied to identify risk factors for water supply failure.
- Failure risks associated with groundwater salinity, depth, geology, and remoteness.
- Service delivery models need to mitigate environmental and geographical risks.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 31 October 2017
Received in revised form 24 December 2017
Accepted 25 December 2017
Available online xxxx

Editor: D. Barcelo

Keywords:
Survival analysis
Rural water supply
Handpumps
Groundwater
Kenya

ABSTRACT

An improved understanding of failure risks for water supplies in rural sub-Saharan Africa will be critical to achieving the global goal of safe water for all by 2030. In the absence of longitudinal biophysical and operational data, investigations into water point failure risk factors have to date been limited to cross-sectional research designs. This retrospective cohort study applies survival analysis to identify factors that predict failure risks for handpumps installed on boreholes along the south coast of Kenya from the 1980s. The analysis is based on a unique dataset linking attributes of >300 water points at the time of installation with their operational lifespan over the following decades. Cox proportional hazards and accelerated failure time models suggest infrastructure failure risks are higher and lifespans are shorter when water supplied is more saline, static water level is deeper, and groundwater is pumped from an unconsolidated sand aquifer. Water point failure risks also appear to grow as distance to spare part suppliers increases. To bolster the sustainability of rural water services and ensure no community is left behind, post-construction support mechanisms will need to mitigate heterogeneous environmental and geographical challenges. Further studies are needed to better understand the causal pathways that underlie these risk factors in order to inform policies and practices that ensure water services are sustained even where unfavourable conditions prevail.

1. Introduction

Water point sustainability has long been an elusive goal in rural sub-Saharan Africa. Studies and monitoring data have repeatedly revealed a considerable proportion of water points – especially wells and

* Corresponding author at: Institute for Sustainable Futures, University of Technology Sydney, 235 Jones St, Ultimo 2007, NSW, Australia.
E-mail address: tim.foster@uts.edu.au (T. Foster).

https://doi.org/10.1016/j.scitotenv.2017.12.302

boreholes equipped with handpumps – in a state of disrepair (RWSN, 2009; Jiménez and Pérez-Foguet, 2011; Foster, 2013; Cronk and Bartram, 2017). The human development implications of this situation remain unquantified, but the health and welfare consequences are likely to be substantial. With almost one million handpumps installed across the continent (MacArthur, 2015), it is plausible that tens of millions of rural Africans bear the burden of non-functional systems at any point in time.

A burgeoning body of literature has sought to unravel the predictors and causes of water point operation and maintenance failures. Methodologies and diagnostic frameworks have included multivariable statistical analysis – usually of relatively large water point mapping datasets – to understand determinants of functionality (Whittington et al., 2009; Foster, 2013; Fisher et al., 2015; Cronk and Bartram, 2017), detailed technical assessments of failure modes (Harvey, 2001; Bonsor et al., 2015), in-depth socio-technical root cause analysis (Bonsor et al., 2015), and systems dynamic modelling (Walters and Javernick-Will, 2015). Each approach has its attendant strengths and weaknesses, bearing in mind that they each seek to answer different questions with varying levels of precision.

Multivariable logistic regression has been a commonly employed statistical technique to empirically assess water point functionality risk factors (Whittington et al., 2009; Foster, 2013; Fisher et al., 2015; Cronk and Bartram, 2017). More recently, Bayesian network modelling has been proposed as an approach better able to accommodate the interdependent nature of explanatory variables (Fisher et al., 2015; Cronk and Bartram, 2017). A key shortcoming of these cross-sectional analyses is the imperfect (albeit routinely available) dichotomous functionality status indicator that has been applied as the outcome variable of interest. The limitations of a point-in-time snapshot of 'functionality' are well documented (Thomson et al., 2012; Carter and Ross, 2016), and there is a need for more nuanced examination that distinguishes between those non-functional water points that have long been abandoned and those which are temporarily broken down but likely to be repaired in the near future.

A related potential drawback of cross-sectional studies utilising a functionality outcome variable is their susceptibility to reverse causation. Take, for example, the collection of revenue from water users, which is a commonly employed explanatory variable and has emerged as a significant determinant of water point functionality in several cross-sectional studies. A lack of user fees is clearly a plausible reason why faulty water points might go unrepaired; however, this association might also arise when water points initially fall into disrepair for non-financial reasons, and this failure subsequently leads water committees to abandon user fee collection. In other words, the outcome of interest could in some cases precede and influence an explanatory variable rather than the other way around. Cross-sectional water point datasets do not necessarily distinguish between situations when such factors are a pre-cursor to water point failure and when they are a consequence.[1]

A further weakness of functionality studies drawing on large cross-sectional datasets has been their tendency to omit important groundwater characteristics specific to each water point, such as depth and water quality parameters. This is partly due to practical constraints: assessing water quality for a non-functional handpump often requires the pump to be disassembled, as does the measurement of static water level regardless of operational status (with some exceptions).[2] Collecting such data for handpump water supplies post-installation can therefore be a laborious and expensive process. Although there are alternative measures that have been used as proxies, they tend to be imprecise. For example, Fisher et al. (2015) and Cronk and Bartram (2017) incorporated groundwater storage, depth and yield into their analysis by overlaying spatial datasets bearing a 5 km resolution, while Foster (2013) relied on user perceptions of water quality.

In contrast, Bonsor et al. (2015) have proposed a toolbox of approaches and a diagnostic framework that enables a more comprehensive assessment of underlying causes of failure, and more precisely considers the role of hydrogeological characteristics. Qualitative narratives are an important component of this process of enquiry in order to untangle the longitudinal and interlinking sequence of events that lead to a water point failure (Carter and Ross, 2016). However, the flipside to these more rigorous investigative processes is that they are likely to be more time consuming and costlier than analysis of water point datasets collected through routine monitoring efforts. The financial implications may also result in smaller sample sizes, making it more difficult to draw definitive conclusions of broad application.

This study utilises a research design and analytical approach that avoids some of the abovementioned limitations of statistical analysis of large cross-sectional datasets, but can still be applied where resource or time constraints might prevent a thorough water point-by-water point root cause analysis. We apply a set of statistical techniques collectively known as survival analysis to the context of water supply systems in rural Kenya. Specifically, we employ Kaplan-Meier estimates (Kaplan and Meier, 1958), Cox proportional hazards models (Cox, 1972), and accelerated failure time models in order to identify risk factors associated with the failure of handpump water supplies on the south coast of Kenya over the course of several decades. The analysis exploits data drawn from water point installation records documented during the 1980 and 1990s, and a follow-up assessment of their location, operational status, and lifespan in 2013.

Survival analysis adopts 'time until an event occurs' as its outcome variable of interest. The techniques that fall within the survival analysis umbrella have been used extensively in medical literature due to their ability to accommodate right-censored data – that is, subjects that have not yet undergone the event of interest (such as disease onset, remission or death) by the end of an observation period (see e.g. Clark et al., 2003; Bradburn et al., 2003). In that respect, the techniques can be used to examine water point lifespans, even if a subset of those water points is still operational and their ultimate survival time is not yet known. As well as applying analytical techniques that have not yet been brought to bear on rural water sustainability issues, by matching installation records with subsequent survival times the investigation is able to avoid concerns relating to reverse causation, and consider the influence of hydrogeological conditions irrespective of a water point's ultimate functionality status.

2. Study site

The study took place in Kwale County, a predominantly rural region situated on the south coast of Kenya. Kwale has a unique place in the history of rural water supply programming, as it was the site for the first large scale deployment of the Afridev handpump. The Afridev is a lever-action reciprocating handpump originally designed to be maintained at the village-level, and capable of a pumping lift of up to 45 m (Baumann and Furey, 2013). It is now a mainstay water supply technology across rural sub-Saharan Africa, being the favoured handpump model in seven countries, and common in at least 12 others (MacArthur, 2015).

A small field trial of the Afridev commenced in the then Kwale District in 1983. The positive results arising from the pilot spurred a district-wide roll-out of the technology from 1985 under the banner of the Kwale Water and Sanitation Project (KWSP) (Narayan-Parker, 1988; McCommon et al., 1990). The Swedish International Development Cooperation Agency (Sida) played a critical role in financing the programme's expansion. The vast majority of handpumps were fitted

[1] The interpretation ultimately depends on the specific point in time to which respondents refer when they provide information forming the basis of explanatory variables, and this in turn may hinge on the way a question is worded by an enumerator. Other explanatory variables that could potentially serve as both drivers and consequences of functionality status include a water committee's composition and status, user group size, and number of water sources in a community.

[2] Some handpump models include an inspection panel that allows for water level measurements to be taken without the need to remove down-the-hole pump components

on boreholes, and County Government records suggest >550 had been installed by the mid-1990s (Fig. S1 in Supplementary material). The handpump-equipped boreholes installed under the KWSP (hereafter termed 'KWSP water points') were distributed across a number of geological formations (Fig. S2 in Supplementary material). These include Pleistocene coral limestones, Pleistocene and Pliocene sands (Kilindini and Margarini formations), Triassic sandstones and shales (Mazeras, Mariakani, and Maji-ya-Chumvi formations), and to a smaller extent, igneous intrusives (Caswell, 1953). In addition to installing hardware, the KWSP made concerted efforts to establish community-based water committees, and provide training on administrative, financial and technical aspects of operation and maintenance.

For several reasons, Kwale provides an instructive setting in which to assess water point lifespans, and the predictors thereof. First, as one of the earliest programmes of its kind in sub-Saharan Africa, it allows for an analytical frame spanning three decades. Second, as a large number of water points were installed under the same programme, some implementation fundamentals are held relatively constant – such as technology and approach to community participation – as compared with many other rural water landscapes that are more fragmented and less harmonized. The communities in Kwale therefore shared the same technical and institutional starting point for operation and maintenance (e.g. Afridev handpumps, local mechanics, trained water committees), allowing for a clearer distillation of the effect of environmental and geographical factors. Crucially, this coordinated approach also resulted in a centralized repository of installation records containing key characteristics of the water points installed.

3. Methods

3.1. Data collection

A water point mapping exercise was carried out in Kwale in 2013 with the aim of locating Afridev handpump installations in Msambweni, Matuga and Lunga Lunga sub-counties. This data collection took place as part of a wider research programme into rural water sustainability (see Foster and Hope, 2016, 2017). During this process, a range of geographical information on water points was captured, including community name, GPS coordinates, and – where extant – unique identification codes and installation dates inscribed on auxiliary concrete works such as aprons and washstands. In total, 571 Afridev installation sites were located (Fig. 1), of which 314 (55.0%) were functional, 238 (41.7%) were non-functional (i.e. not producing water at the time of inspection), and 19 (3.3%) had been replaced by a motorized pump. For those water points that were deemed non-functional, the respondent was also asked to estimate the duration of the current breakdown. To mitigate recall bias, the same question was also asked of other surrounding households (mean 4.8 households per water point), and the median value of the breakdown duration was determined.

Subsequent to the water point mapping, original installation records kept by the Kwale County Government were consulted. These written records contained details for 580 handpump-equipped boreholes installed between 1983 and 1995. This included information on community name, water point identification code, drilling commencement and completion dates, borehole depth, static water level, yield, and electrical conductivity. Twenty-one water points included in the records were located outside of the study area, and were excluded from the study. Characteristics of the remaining 559 water points at the time of installation are presented in Table 1.

A process was then carried out to match water points identified in the 2013 inventory with those contained in the installation records. Water points were matched based on either the identification code or a unique location name. In total, 337 water points appearing in the installation records were able to be linked with specific water points located during the 2013 mapping process (Table S1 in Supplementary Information). These matched water points constituted 60% of the 559 water points recorded in the installation records, and 59% of the 571 Afridev installation sites located during the water point mapping in 2013. Based on the distinguishing physical features of KWSP handpump installations (i.e. conical concrete pedestal, concrete wash basins), we estimated that a further 113 water points located in the 2013 inventory were KWSP water points; however, these water points could not be traced to specific water points in the installation records. This left 109 water points from the installation records that were not located at all

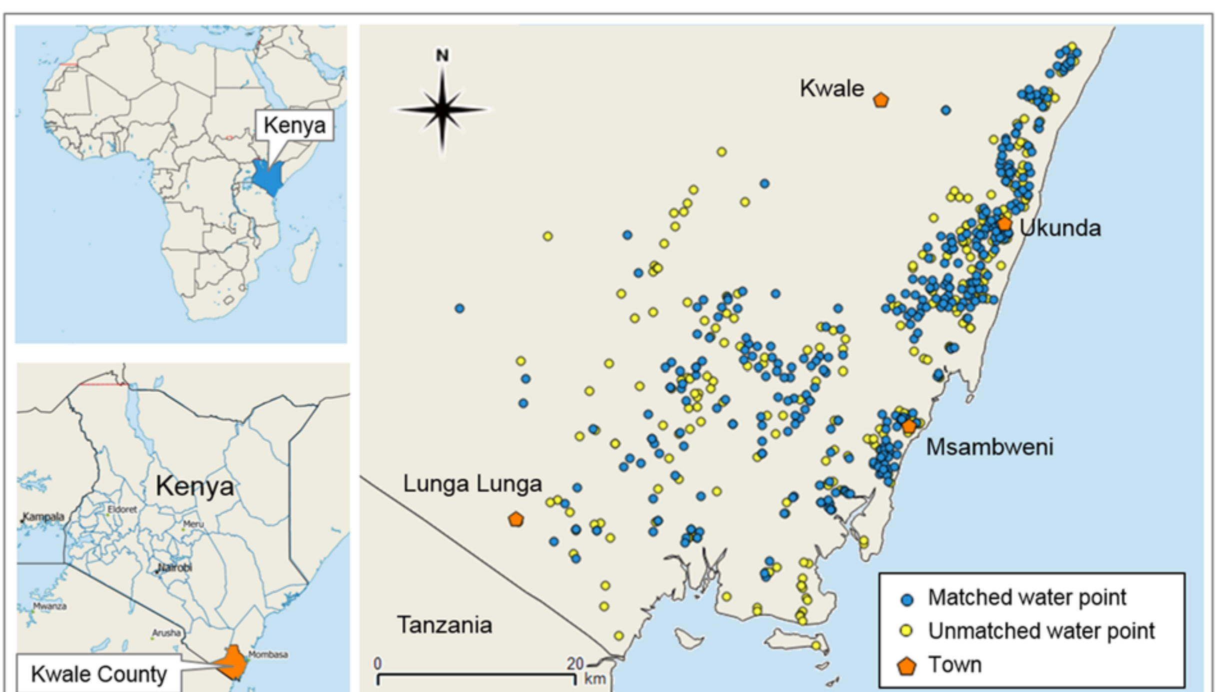


Fig. 1. Study site and distribution of Afridev handpumps in Kwale County, 2013.

Table 1
Characteristics of water points equipped with Afridev handpumps included in Kwale County Government records (1983–1995) (n = 559).

	Mean	SD	Median	Min	Max
Borehole depth (m)	36.2	18.7	32.0	7.0	102
Static water level (mbgl)	17.0	9.3	16.8	0.9	60.4
Electrical conductivity (μS/cm)	1097	1113	690	60	6100
Yield (l/s)	0.73	0.52	0.67	0.08	5.5
Year of installation	1989	3.1	1989	1983	1995

Note: All characteristics relate to the time of installation.

in 2013. It is plausible that some of these residual water points had little or no extant above-ground infrastructure, and hence have been non-functional for years or decades. Some may have also been upgraded or replaced with more advanced water supply systems in a way that left no evidence of the original handpump installation.

3.2. Variables

The outcome variable of interest was operational lifespan. This was defined as the number of years between installation and the point at which a water point had been non-functional for a year (hereafter called "failure"). Those water points that were functional or non-functional for less than one year at the time of the water point mapping were therefore right-censored – in other words, because they were operational or recently operational, their lifespan up until the point of failure was not yet known. Breakdown duration of at least one year was chosen as the threshold for failure so it would not inadvertently capture water points left unused and in a state of disrepair on a seasonal basis.

Nine explanatory variables were included in the analysis (Table S2 in Supplementary Information). The variables were selected based on hypotheses that they would influence a water point's risk of failure, and they were either documented for a large number of water points in the installation records, or could be deduced from the location of the water point. The variables related to a water point's hydrogeological characteristics (static water level; yield; geological formation; electrical conductivity), time of installation (rainfall season); and its location (relative to year-round fresh surface water; relative to spare parts suppliers; settlement type; and whether the water point was institutional or communal).

With the exception of geological formation, hydrogeological variables were obtained from the installation records. In order to control for seasonal variation in hydrogeological variables, drilling completion date was converted into a dichotomous seasonal variable with the 'dry' period defined as January to April – the time of year when groundwater levels tend to be at their deepest in Kwale (Thambu, 1987) – with the remainder of the year constituting 'wet' season. The type of user group (community vs institution) was determined from the name of the water point entered into the installation records. If the water point name specifically referred to a school, health facility or police station then it was deemed institutional; if not, it was assumed to be a community facility. It is acknowledged that in reality such a distinction might not always be clear cut – community members might use an institution's water point and vice versa. A variable indicating distance to spare parts was formulated by calculating the straight-line distance between each water point and Ukunda town, the major commercial centre from which spare parts have been supplied. Geological formations were consolidated into three categories, namely 'corals' (Pleistocene corals), 'sands' (Pleistocene and Pliocene sands), and 'other' (Mazeras sandstones, Mariakani sandstones, Maji-ya-Chumvi sandstones and shales, igneous intrusives). A variable indicating proximity to year-round surface water bodies (streams, rivers, dams) was determined based on each water point location, taking into account that portions of some surface water bodies in Kwale are saline (Chalala et al., 2017). Those water bodies considered to be year-round and fresh were Mukurumudzi River, Mkanda Dam, tributaries of the Ramisi River (upstream of Mkanda Dam), Lower Koromojo Dam, Umba River and Mwena River.

3.3. Analysis

The analysis consisted of four steps. Initially we evaluated whether the eligibility criteria (i.e. ability to match water points located in 2013 with original installation records) introduced any potential bias. We then conducted three forms of survival analysis, all of which assessed time to failure. First, we ran Kaplan-Meier estimations to compare survival distributions for each of the explanatory variables. Second, we ran Cox proportional hazards models to identify explanatory variables that exhibited a significant association with the instantaneous risk of failure. Third, we ran accelerated failure time (AFT) models to identify explanatory variables that exhibited a significant association with a water point's operational lifespan. All statistical analysis was performed using statistical software package SPSS (version 24), with the exception of AFT models, which required STATA (version 14.2).

To assess the possible effect of attrition bias, differences in key parameters between matched and unmatched water points were examined by way of independent samples *t*-tests for continuous variables and Pearson chi-square test for dichotomous variables. Because the precise location of unmatched water points was unknown, the variables assessed were limited to those documented in the installation records and were therefore known for both matched and unmatched water points (i.e. static water level, year of installation, electrical conductivity, yield, user group, season of installation).

Kaplan-Meier estimate analysis was carried out to plot survival distributions for dichotomised explanatory variables, and a series of log rank (Mantel-Cox) tests were run to determine whether any variable led to significantly different survival distributions. Kaplan-Meier estimation is non-parametric, and hence makes no assumption about the shape of the survival function. The cut-off values for static water level, distance to spare parts and electrical conductivity were guided by measures of centrality (mean and median), while the dichotomised threshold for yield was decided with reference to a level expected to support a handpump supply (0.3 l/s) (MacDonald et al., 2012).

Cox proportional hazards (PH) regression was conducted to ascertain unadjusted and adjusted hazard ratios for the explanatory variables. In the context of this study, hazard ratios represented the change in hazard rate (the instantaneous probability of a water point failing at any point of time) associated with a unit change in the explanatory variable. The Cox PH model is semi-parametric as no assumptions are made about the shape of the baseline hazard. The effect of an explanatory variable on the hazard rate in a Cox PH model is multiplicative. Nine explanatory variables were included in the analysis: six as categorical variables (locality, user group, surface water, yield, geology, season of installation) and three as continuous variables (spare parts, electrical conductivity, static water level). As a substantial proportion of water points lacked electrical conductivity measurements, two models were run: one with and one without electrical conductivity. A test of non-zero slope based on Schoenfeld residuals was run on both models to ensure compliance with the proportional hazards assumption that underpins Cox models (Grambsch and Therneau, 1994).

Accelerated failure time (AFT) models were then run (again, one with and one without electrical conductivity), with the choice of survival distribution based on the lowest Akaike information criterion (AIC) value. In contrast to Cox PH models, AFT models are parametric, and thus the shape of the data must be specified. The explanatory variables accelerate or decelerate the subject's time to event. Unadjusted and adjusted time ratios were calculated, representing the proportional difference in survival time associated with a unit change in the explanatory variable. The AFT models included the same explanatory variables as the Cox PH regression.

4. Results

Of the 337 matched water points, 36% were deemed to have failed. The same failure rate was also observed for the 113 KWSP water points that were located in 2013 but could not be matched with a specific entry in the installation records. The failure rate for the other 109 unmatched water points could not be ascertained. Comparisons between matched and unmatched water points revealed significant differences in year of installation, electrical conductivity, and user group (Table 2). On average, matched water points were younger, produced water with lower electrical conductivity, and were more likely to be located within an institution. There were no significance differences between matched and unmatched water point based on static water level, yield or season of installation. Nor were there any significant associations when including all variables into a multivariable logistic regression model with matched/unmatched status as the outcome variable.

Kaplan-Meier estimates are presented in Fig. 2, as well as Fig. S3 and Table S3 in Supplementary material. Four of the explanatory variables resulted in significantly different survival distributions, namely season of installation, yield, geology, and electrical conductivity.

Results of the Cox proportional hazards models are summarised in Table 3 (see also Fig. S4 in Supplementary material). The multivariable models complied with the proportional hazards assumption both globally and for each individual covariate. In model 1, adjusted hazard rates were significantly higher when electrical conductivity levels were elevated, groundwater was pumped from an unconsolidated sand aquifer, water points were located within an institution, and boreholes were drilled in the wet season. In model 2, adjusted hazard rates were significantly higher when static water level was deeper, groundwater was pumped from an unconsolidated sand aquifer, water points were located further away from spare part suppliers, and boreholes were drilled in the wet season.

Results from the AFT models are presented in Table 4. Weibull models were selected by virtue of their low AIC values, signifying the best fitting model. Variables associated with survival times were largely consistent with findings from the Cox proportional hazards models. In AFT model 3, shorter survival times were significantly associated with higher electrical conductivity, institutional water points, and installation during wet season (all else held constant). In AFT model 4, water points failed earlier when they had deeper static water levels, were underlain by unconsolidated sands, and were installed during wet season (all else held constant).

5. Discussion

The results suggest hydrogeological and geographical factors have impinged upon the sustainability of rural water supplies in Kwale over the course of three decades. Water points appear less likely to survive when they supply water with higher electrical conductivity, draw on deeper groundwater, are underlain by unconsolidated sands, and are installed in the wet season. Water points located within an institution and situated further away from spare parts suppliers also have higher failure risks, though these associations exhibit less consistency across the models.

The relationship between electrical conductivity and water point failure probably results from user rejection or abandonment of the handpump because of the unsatisfactory taste of the water supplied. For every increase of 100 μS/cm at the time of installation, the risk of failure rises by 3%, and a water point's operational lifespan is reduced by 2%. A significant relationship between electrical conductivity and palatability has been previously demonstrated in Kwale (Foster and Hope, 2016; see also Fig. S5 in Supplementary data), and has been observed elsewhere in sub-Saharan Africa (Langenegger, 1989). This result points to the importance of monitoring groundwater quality in Kwale, particularly in light of reports that groundwater salinity levels have risen over previous decades, and the ongoing threat of seawater intrusion (Tole, 1997).

Water points with deeper static water levels appeared more prone to failure. With each metre of depth, the models suggested an increase in the hazard rate of 3% (Cox model 2) and the end of a water point's operational life is reached 2% earlier (AFT model 4). The relationship between static water level and water point failure may arise due to a higher frequency of breakdowns that would be expected to accompany greater pumping lifts by virtue of increased stresses, greater wear and tear per unit of water produced as a result of lower pump efficiency, or simply a consequence of a greater number of components (e.g. pipes and rods) increasing the probability of a 'weak link'. These factors could in turn accelerate the occurrence of major mechanical failure or frequency of routine failures, thereby amplifying the recurrent costs that need to be borne by water users. Early operational data describing the lifespans of Afridev bearings in Kwale provides tentative support for the proposition that mean time between breakdowns is influenced by groundwater depth (Reynolds, 1992). An alternative explanation is that deeper boreholes are more complex to drill and construction quality risks are greater. It should be noted that the association observed here is specific to boreholes, and may not apply to hand-dug wells. Despite their shallower water level, there is evidence that hand-dug wells have a higher failure rate than boreholes (Foster, 2013).[3]

The higher failure risk exhibited by water points underlain by Pliocene and Pleistocene sand formations concurs with anecdotal evidence that these aquifers have caused boreholes to backfill with fine sands. Logically, fine sands may also accelerate wear and tear of the handpump by impairing pump efficiency and abrading rubber components. Further investigation is needed to assess whether other hydrochemical or hydraulic mechanisms underlie the link between geology and water point lifespans, noting that differences in yield, static water level and electrical conductivity were controlled for in the Cox PH and AFT models. For example, in some areas of Kwale low pH has been known to cause rapid corrosion of mild steel pump rods (Reynolds, 1992), while hardness also poses problems for some boreholes (Thambu, 1989).

The link between the risk of failure and season at time of drilling completion is consistent the findings of Harvey (2001), who assessed predictors of rapid-onset borehole failure in Ghana. The author in that study concluded that the relationship between borehole failure and rainfall was due to drillers failing to adequately take into account seasonal water level fluctuations, as evidenced by the constancy of cylinder depth relative to dynamic water level across the seasons. Unfortunately,

Table 2
Characteristics of water points equipped with Afridev handpumps included in Kwale County Government records by whether or not they could be matched with an extant water point in 2013.

	Matched			Unmatched			p-value[a]
	n	Mean	SD	n	Mean	SD	
Static water level (mbgl)	332	16.6	8.8	211	17.7	10.0	0.194
Installation year	337	1989.3	3.2	222	1988.7	2.9	**0.017**
Electrical conductivity (μS/cm)	174	987	998	116	1263	1252	**0.048**
Yield (l/s)	323	0.74	0.51	197	0.71	0.53	0.581
User group (community = 0, institution = 1)	337	0.15	0.36	222	0.08	0.27	**0.010**
Season (dry = 0, wet = 1)	335	0.70	0.46	218	0.62	0.49	0.068

Note: Bold text indicates statistical significance ($p < 0.05$).
[a] Independent samples *t*-test (with Welch's correction for unequal variances where required) for continuous variables; Pearson Chi-square test for categorical variables.

[3] This is perhaps due to a greater propensity to dry up, a large diameter that can allow communities to continue fetching water with a rope and bucket in the event of a handpump breakdown, and proximate alternative groundwater sources that can be developed at low cost

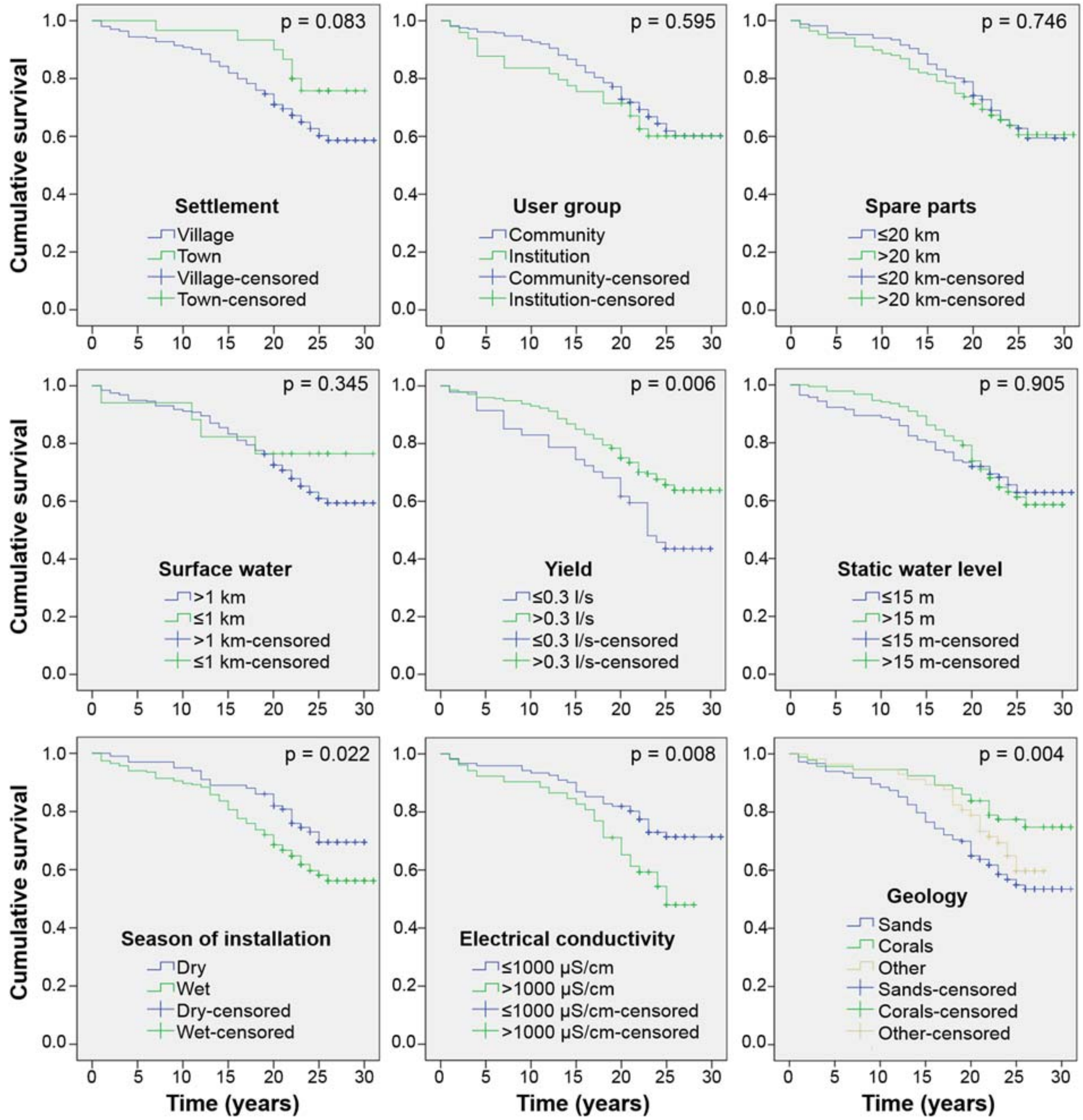


Fig. 2. Kaplan-Meier estimates of the survival functions for Afridev handpumps in Kwale. Note: p-values based on a log rank (Mantel-Cox) test.

cylinder depths were not systematically documented in the Kwale installation records, hence it is not possible to confirm or rule out whether similar issues underlie the emergent seasonal pattern. However, we believe this is unlikely to be the primary explanation for the association in the Kwale context, as seasonal groundwater fluctuations tend to be relatively modest. Though there has been no long-term monitoring of groundwater levels, observations from the time of early installations in 1983 suggest a 1.0 to 2.5 m difference in static water level between wet and dry season in the Pleistocene corals (Thambu, 1987). In comparison, data presented by Reynolds (1992) suggest 19 handpumps installed under the KWSP had cylinder settings that were on average nine metres deeper than the static water level.

A more plausible explanation for the multivariable association in Kwale is that season of installation acts as a control variable for hydrogeological covariates. This proposition is supported by previous investigations in Kwale that have shown seasonal variations in both static water level and electrical conductivity (Thambu, 1989; Mzuga et al., 1998). In other words, the results point to the importance of analysis adjusting for the season in which hydrogeological variables are measured.

The association between water point survival and distance to spare parts conforms to commonly held views about supply chain viability (Harvey and Reed, 2006), and agrees with previous findings about the relationship between functionality and proximity to spare parts in Sierra Leone (Foster, 2013). The Cox model 2 results indicate a 2% increase in the hazard rate for every additional kilometre between the water point and spare parts retailer. In Kwale, the location of spare part suppliers is widely known and we expect the relationship observed is not due to a lack of awareness per se, but rather that those communities farthest away incur the highest transaction costs and greatest logistical challenges to procure spare parts (noting that some communities may procure parts themselves, while others rely on a pump mechanic to source the parts). The relationship may also be compounded or confounded by the possibility that the more remote communities have

Table 3
Results of Cox proportional hazards models for Afridev handpumps in Kwale.

Explanatory variable	Dummy coding/units	Univariable (unadjusted)		Multivariable (adjusted) – model 1[a]		Multivariable (adjusted) – model 2[b]	
		Hazard ratio (95% CI)	p-value	Hazard ratio (95% CI)	p-value	Hazard ratio (95% CI)	p-value
Settlement	0 = village, 1 = town	0.52 (0.24, 1.11)	0.092	0.63 (0.14, 2.91)	0.558	0.76 (0.33, 1.78)	0.533
User group	0 = community, 1 = institution	1.14 (0.70, 1.86)	0.599	**2.38 (1.22, 4.65)**	**0.011**	1.33 (0.80, 2.19)	0.267
Spare parts	Kilometres	1.00 (0.99, 1.02)	0.440	1.01 (0.98, 1.04)	0.437	**1.02 (1.00, 1.04)**	**0.040**
Surface water	0 = ≤1 km away, 1 = >1 km away	1.60 (0.59, 4.34)	0.355	0.80 (0.27, 2.40)	0.694	1.37 (0.49, 3.83)	0.544
Yield	0 = ≤0.3 l/s, 1 = >0.3 l/s	**0.55 (0.35, 0.85)**	**0.007**	0.73 (0.39, 1.36)	0.322	0.66 (0.42, 1.04)	0.075
Static water level	Metres below ground level	1.02 (1.00, 1.04)	0.109	1.03 (1.00, 1.08)	0.079	**1.03 (1.00, 1.05)**	**0.028**
Season	0 = dry, 1 = wet	**1.63 (1.06, 2.51)**	**0.025**	**2.77 (1.32, 5.81)**	**0.007**	**2.01 (1.27, 3.17)**	**0.003**
Electrical conductivity	100 μS/cm	1.02 (1.00, 1.04)	0.060	**1.03 (1.00, 1.05)**	**0.034**		
Geology			**0.006**		**0.033**		**0.012**
Sands vs corals	0 = corals, 1 = sands	**2.18 (1.34, 3.53)**	**0.002**	2.18 (0.92, 5.17)	0.077	**1.70 (1.01, 2.88)**	**0.047**
Sands vs other[c]	0 = other, 1 = sands	1.33 (0.82, 2.16)	0.245	**2.57 (1.07, 6.18)**	**0.036**	**2.08 (1.15, 3.75)**	**0.015**
Corals vs other[c]	0 = other, 1 = corals	0.61 (0.33, 1.12)	0.111	1.18 (0.37, 3.77)	0.782	1.22 (0.58, 2.57)	0.599

Note: Bold text indicates statistical significance ($p < 0.05$). A hazard ratio > 1 indicates a higher risk of failure, and a hazard ratio < 1 indicates a lower risk of failure.
[a] Model 1 (including EC as explanatory variable) comprises 169 water points.
[b] Model 2 (excluding EC as explanatory variable) comprises 319 water points.
[c] 'Other' largely comprises sandstones and shales.

had higher levels of poverty and a lower capacity to pay for ongoing maintenance costs.

There is little contextual information to pinpoint why institutional water points exhibited higher hazard rates relative to community water points. There may be inherent differences related to usage levels, management and financing that could all play a role. The situation is somewhat complicated by the fact that delineation between community and institutional roles and responsibilities is not always well defined. The association must also be interpreted with caution due to the possible effect of attrition bias. Institutional water points were easier to match than community water points because a name referring to a school, police station or health centre tends to be unique. As a result, a disproportionate number of failed institutional water points appear to have been included in the matched sample (as evidenced in Table 2).

Overall, the shape of the survival functions (see Fig. S3) suggests a relatively high proportion of water points survived the first ten years (~90%), followed by a downward steeping of the curve such that the survival rate drops to around 60% by year 25. This is further illustrated by the AFT models, which have a Weibull shape parameter value of $p = 1.7$, indicating a monotonically increasing hazard rate over time. This may reflect a plausible pattern whereby failure risks grow as water points age. Over time, boreholes and handpumps may be more likely to experience failure modes that are technically and financially harder to repair, or alternatively the breakdowns become more frequent and give rise to higher (and at times prohibitive) running costs. Managerial structures may also weaken: committees may become inactive or dissolve entirely or changes in committee membership may diminish management capabilities as new members lack the training and know-how previously imparted at the time of installation.

The shape of the survival functions seemingly contradict national water point datasets from other sub-Saharan African countries, which instead tend to show a relatively high year-on-year failure rate in the early years after installation, followed by a flat-lining beyond the tenth year (Carter and Ross, 2016). This apparent incongruity may be linked to a bias that Carter and Ross (2016) dub the "denominator problem". In the case of cross-sectional water point datasets, failure rates may appear to plateau after a certain age because some older abandoned water points have disappeared and are excluded from the analytical frame, leading to an overestimation of the functionality rate for this older cohort (Carter and Ross, 2016; Jiménez and Pérez-Foguet, 2011). The water point survival rate in the early years of this retrospective assessment in Kwale could be overestimated for the same reasons, potentially causing the survival functions to be upwardly biased. The observation that unmatched water points were slightly older than matched water points (and thus more likely to have failed) provides tentative support for this hypothesis.

Putting in place operation and maintenance arrangements that counter the risk factors observed in this study will be vital to achieving

Table 4
Results of accelerated failure time models for Afridev handpumps in Kwale.

Explanatory variable	Dummy coding/units	Univariable (unadjusted)		Multivariable (adjusted) – model 3[a]		Multivariable (adjusted) – model 4[b]	
		Time ratio (95% CI)	p-value	Time ratio (95% CI)	p-value	Time ratio (95% CI)	p-value
Settlement	0 = village, 1 = town	1.51 (0.91, 2.49)	0.108	1.31 (0.53, 3.29)	0.558	1.16 (0.69, 1.94)	0.580
User group	0 = community, 1 = institution	0.92 (0.67, 1.27)	0.624	**0.61 (0.40, 0.92)**	**0.017**	0.85 (0.62, 1.16)	0.297
Spare parts	Kilometres	1.00 (0.99, 1.01)	0.455	1.00 (0.98, 1.01)	0.615	0.99 (0.98,1.00)	0.051
Surface water	0 = ≤1 km away, 1 = >1 km away	0.73 (0.38, 1.41)	0.355	1.09 (0.56, 2.11)	0.798	0.82 (0.44, 1.54)	0.544
Yield	0 = ≤0.3 l/s, 1 = >0.3 l/s	**1.45 (1.09, 1.93)**	**0.010**	1.20 (0.82, 1.75)	0.359	1.27 (0.96, 1.69)	0.091
Static water level	Metres below ground level	0.99 (0.97, 1.00)	0.088	0.98 (0.96, 1.00)	0.104	**0.98 (0.97, 1.00)**	**0.028**
Season	0 = dry, 1 = wet	0.73 (0.55, 0.97)	0.028	**0.56 (0.36, 0.89)**	**0.013**	**0.66 (0.49, 0.88)**	**0.004**
Electrical conductivity	100 μS/cm	0.99 (0.97, 1.00)	0.058	**0.98 (0.97, 1.00)**	**0.035**		
Geology			**0.003**		0.060		**0.018**
Sands vs corals	0 = corals, 1 = sands	**0.60 (0.44, 0.83)**	**0.002**	0.62 (0.37, 1.05)	0.074	**0.71 (0.52, 0.99)**	**0.042**
Sands vs other[c]	0 = other, 1 = sands	0.85 (0.62, 1.16)	0.306	0.62 (0.36, 1.04)	0.072	**0.66 (0.46, 0.95)**	**0.026**
Corals vs other[c]	0 = other, 1 = corals	1.41 (0.95, 2.09)	0.089	1.00 (0.50, 1.99)	0.989	0.93 (0.59, 1.46)	0.743

Note: Bold text indicates statistical significance ($p < 0.05$). A time ratio > 1 indicates the time to failure is prolonged, and a time ratio < 1 indicates the time to failure is shortened.
[a] Model 3 (including EC as explanatory variable) comprises 169 water points. Weibull shape parameter value of $p = 1.67$ (95% CI, 1.30–2.13).
[b] Model 4 (excluding EC as explanatory variable) comprises 319 water points. Weibull shape parameter value of $p = 1.63$ (95% CI, 1.38–1.93).
[c] 'Other' largely comprises sandstones and shales.

universal access to safe drinking water in Kwale, and in rural sub-Saharan Africa more generally. With a majority of matched water points functioning 25 years after installation, the results demonstrate that with adequate maintenance handpumps can achieve impressive longevity. However, this still falls short of what will be needed to achieve a safe water Sustainable Development Goal (SDG) that is premised upon universality. Provision of external support to communities is now widely advocated as a way to improve the sustainability of rural water services in sub-Saharan Africa. The results from this investigation suggest these external support mechanisms will need to mitigate the heterogeneous environmental and geographical obstacles that water users encounter. This may require providing extra or tailored financial and technical support for those communities that face conditions less conducive to sustainable operation and maintenance, or perhaps consideration of alternative techno-institutional approaches to rural water service delivery. Heuristics based upon the predictors observed in this and other similar investigations may provide a guiding framework as to where and how support could be differentiated. More simply, a centralized maintenance service could facilitate cross subsidies between water points, eliminating inherent financial and technical disadvantages experienced by some communities (Hope et al., 2012). Examples of this approach have been documented elsewhere in Kenya (Thomson and Koehler, 2016; Goodall and Katilu, 2016; Foster and McSorley, 2016).

In addition to usual caveats regarding omitted variable bias, this study has several limitations. First, it is possible that some water points may have previously been non-functional for more than a year but subsequently rehabilitated (in which case, the time to event is biased upwards). Second, the duration of downtime for non-functional handpumps was reliant on self-reported estimates by water users, and therefore susceptible to recall bias. Third, limited information was available on the processes and quality control methods undertaken by borehole drillers and program implementers when measuring and documenting water point characteristics. In recognition of these weaknesses, we would stress the continued importance of high quality and rigorous research designs that are capable of unravelling causal pathways in a more nuanced way.

Notwithstanding these limitations, the study demonstrates the amenability and advantages of applying survival analysis to water point sustainability evaluations, particularly in tandem with installation data. First, the explanatory variables pertained to the time of installation. In addition to avoiding concerns relating to reverse causation, this means insights are highly relevant to practitioners involved in programme implementation. Second, the outcome variable provides information about the longer-term survival time of the handpump rather than a simple binary functionality status indicator. This is arguably more useful to policymakers and practitioners as it better reflects the return on the initial infrastructure investment. Third, as groundwater characteristics used in the study were captured at the time boreholes were drilled, the potential effects of these attributes were able to be assessed specifically for each water point in a low-cost fashion, irrespective of subsequent functionality status. As such, the approach is well suited to assessing water point failure risks in resource-constrained contexts.

6. Conclusion

Survival analysis provides an instructive approach to estimating failure risks for rural water points, and its application to handpump-equipped boreholes in Kwale suggests that groundwater depth, water quality, geology and spare part supply chains are important determinants of sustainability. The season in which groundwater characteristics are measured is also an important factor that should be controlled for in multivariable analysis of water point failure. The findings are of broad relevance given the preponderance of community-managed handpumps across rural sub-Saharan Africa. The insights are strengthened by the application of a novel analytical technique that avoids some of the shortcomings of logistic regression modelling, as well as the multi-decadal nature of the data underpinning the study. Future investigations should look to incorporate a broader range of hydrogeological and socio-economic variables where possible, including time-series data for time varying characteristics, and triangulate results with a more detailed understanding of failure modes and social processes to explain causal routes. This information will be critical for policymakers and practitioners to facilitate more sustainable water services and achieve a greater return on infrastructure investments.

Acknowledgements

This paper is an output from the "New Mobile Citizens and Waterpoint Sustainability in Rural Africa" (ES/J018120/1) and "Groundwater Risk Management for Growth and Development" (NE/M008894/1) research projects supported by the UK Department for International Development (DFID), the UK Economic and Social Research Council and the UK Natural Environment Research Council. The views expressed in this paper are those of the authors and do not necessarily represent those of DFID. The authors would like to thank Rural Focus Ltd. and the Kwale County Government for their assistance with data collection, and Dr Peter Harvey (UNICEF) and Eng. Robert Gakubia (WASREB) for supporting the wider research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.12.302.

References

Baumann, E., Furey, S., 2013. How Three Handpumps Revolutionised Rural Water Supplies: A Brief History of the India Mark II/III, Afridev and the Zimbabwe Bush Pump. Rural Water Supply Network, St. Gallen.

Bonsor, H., Oates, N., Chilton, P., Carter, R., Casey, V., MacDonald, A., Calow, R., Wilson, P., Tumutungire, M., Bennie, M., 2015. A Hidden Crisis: Strengthening the Evidence Base on the Sustainability of Rural Groundwater Supplies: Results From a Pilot Study in Uganda. British Geological Survey, Keyworth.

Bradburn, M., Clark, T., Love, S., Altman, D., 2003. Survival analysis part II: multivariate data analysis – an introduction to concepts and methods. Brit. J. Cancer 89 (3), 431–436.

Carter, R., Ross, I., 2016. Beyond 'functionality' of handpump-supplied rural water services in developing countries. Waterlines 35 (1), 94–110.

Caswell, P., 1953. Geology of the Mombasa-Kwale Area. Report No. 24. Geological Survey Kenya, Nairobi.

Chalala, A., Chimbevo, L., Kahindo, J., Awadh, M., Malala, J., 2017. Sea water intrusion and surface water salinity and its influence on irrigation water quality in Ramisi Area. Kenya 12 (1), 1–13.

Clark, T., Bradburn, M., Love, S., Altman, D., 2003. Survival analysis part I: basic concepts and first analyses. Brit. J. Cancer 89 (2), 232–238.

Cox, D., 1972. Regression models and life-tables. J. Roy. Stat. Soc. B. Met. 34 (2), 187–220.

Cronk, R., Bartram, J., 2017. Factors influencing water system functionality in Nigeria and Tanzania: a regression and Bayesian network analysis. Environ. Sci. Technol. 51 (19), 11336–11345.

Fisher, M., Shields, K., Chan, T., Christenson, E., Cronk, R., Leker, H., Samani, D., Apoya, P., Lutz, A., Bartram, J., 2015. Understanding handpump sustainability: determinants of rural water source functionality in the greater Afram plains region of Ghana. Water Resour. Res. 51 (10), 8431–8449.

Foster, T., 2013. Predictors of sustainability for community-managed handpumps in Sub-Saharan Africa: evidence from Liberia, Sierra Leone, and Uganda. Environ. Sci. Technol. 47 (21), 12037–12046.

Foster, T., Hope, R., 2016. A multi-decadal and social-ecological systems analysis of community water point payment behaviours in rural Kenya. J. Rural. Stud. 47, 85–96.

Foster, T., Hope, R., 2017. Evaluating waterpoint sustainability and access implications of revenue collection approaches in rural Kenya. Water Resour. Res. 53 (2), 1473–1490.

Foster, T., McSorley, B., 2016. An Evaluation of the BluePump in Kenya and the Gambia. ISF-UTS & Oxfam.

Goodall, S., Katilu, A., 2016. FundiFix: exploring a new model for maintenance of rural water supplies. 39th WEDC International Conference: Ensuring Availability and Sustainable Management of Water and Sanitation for All, Kumasi, Ghana.

Grambsch, P., Therneau, T., 1994. Proportional hazards tests and diagnostics based on weighted residuals. Biometrika 81 (3), 515–526.

Harvey, P., 2001. Borehole sustainability in rural Africa: an analysis of routine field data. 30th WEDC International Conference: People-centred Approaches to Water and Environmental Sanitation, Vientiane, Laos PDR.

Harvey, P., Reed, R., 2006. Sustainable supply chains for rural water supplies in Africa. P. I. Civil Eng. Eng. Su. 159 (1), 31–39.

Hope, R., Foster, T., Thomson, P., 2012. Reducing risks to rural water security in Africa. Ambio 41 (7), 773–776.

Jiménez, A., Pérez-Foguet, A., 2011. Water point mapping for the analysis of rural water supply plans: case study from Tanzania. J. Water Resour. Plan. Manag. 137 (5), 439–447.

Kaplan, E., Meier, P., 1958. Nonparametric estimation from incomplete observations. J. Am. Stat. Assoc. 53 (282), 457–481.

Langenegger, O., 1989. Groundwater quality-an important factor for selecting handpumps. Dev. Water Sci. 39, 531–541.

MacArthur, J., 2015. Handpump Standardisation in Sub-Saharan Africa: Seeking a Champion. Rural Water Supply Network, St Gallen.

MacDonald, A., Bonsor, H., Dochartaigh, B., Taylor, R., 2012. Quantitative maps of groundwater resources in Africa. Environ. Res. Lett. 7 (2), 024009.

McCommon, C., Warner, D., Yohalem, D., 1990. Community Management of Rural Water Supply and Sanitation Services. UNDP-World Bank Water and Sanitation Program, Washington, DC.

Mzuga, J.M., Tole, M.P., Ucakuwun, E.K., 1998. The impact of geology and pit latrines on groundwater quality in Kwale District. Coast. Ecol. Ser. 4, 85–96.

Narayan-Parker, D., 1988. People, Pumps and Agencies: The South Coast Handpump Project. PROWWESS/UNDP, Nairobi.

Reynolds, J., 1992. Handpumps: Toward a Sustainable Technology. UNDP-World Bank Water and Sanitation Program, Washington DC.

RWSN, 2009. Handpump Data. Selected Countries in Sub-Saharan Africa. http://www.rural-water-supply.net/_ressources/documents/default/203.pdf, Accessed date: 19 September 2016.

Thambu, G., 1987. Variations in Quantity and Quality of Groundwater in the South Coast Region of Kenya. Masters Dissertation. University of Manitoba.

Thambu, G., 1989. Conditions in shallow wells in the South Coast Region of Kenya. Water Int. 14 (3), 112–121.

Thomson, P., Koehler, J., 2016. Performance-oriented monitoring for the water SDG–challenges, tensions and opportunities. Aquat. Procedia 6, 87–95.

Thomson, P., Hope, R., Foster, T., 2012. Is silence golden? Of mobiles, monitoring, and rural water supplies. Waterlines 31 (4), 280–292.

Tole, M., 1997. Pollution of groundwater in the coastal Kwale District, Kenya. Sustainability of Water Resources under Increasing Uncertainty: Proceedings of the Rabat Symposium Rabat.

Walters, J., Javernick-Will, A., 2015. Long-term functionality of rural water services in developing countries: a system dynamics approach to understanding the dynamic interaction of factors. Environ. Sci. Technol. 49 (8), 5035–5043.

Whittington, D., Davis, J., Prokopy, L., Komives, K., Thorsten, R., Lukacs, H., Bakalian, A., Wakeman, W., 2009. How well is the demand-driven, community management model for rural water supply systems doing? Evidence from Bolivia, Peru and Ghana. Water Policy 11 (6), 696–718.