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

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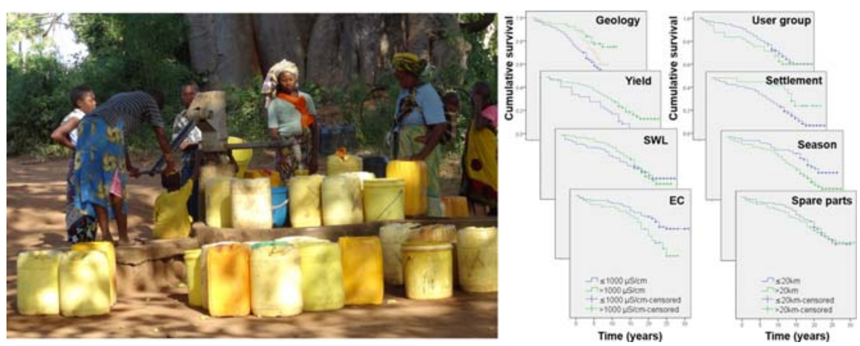
HIGHLIGHTS

- 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



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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

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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