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THE HAGUE, THE NETHERLANDS | 12 – 14 MARCH 2019

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A methodology for assessment of the physical sub-system of hand pumped boreholes: initial insights from Ethiopia

Paper for the WASH systems symposium

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This paper was drafted by DJ. MacAllister, Kebede, S., Dessie, N., Yehualaeshet, T., Zemenu, G., H. Fallas, and A.M. MacDonald for the All systems go! WASH systems symposium, The Hague, The Netherlands, 12-14 March 2019.

Cite this publication as follows. MacAllister, DJ., Kebede, S., Dessie, N., Yehualaeshet, T., Zemenu, Fallas, G., H. and MacDonald, A.M. [United Kingdom] 2019. A methodology for assessment of the physical sub-system of hand pumped boreholes: initial insights from Ethiopia.

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Perceived poor performance of hand pumped boreholes has been a persistent problem in Africa. The UPGro Hidden Crisis project has brought together an interdisciplinary team of researchers to examine boreholes equipped with hand pumps in Ethiopia, Malawi and Uganda. The project has 1) devised and applied a survey method to provide nuanced data on the functionality of the hand pumped borehole system and 2) conducted a full physical sub-system investigation, consisting of the assessment of 150 hand pumped boreholes. The physical sub-system consists of the hydrogeology and hydrochemistry, the borehole and the hand pump. Results from the functionality survey show that although up to 80% of hand pumped boreholes may be producing water, much fewer (often <50%) are able to deliver the hand pump design yield reliably for more than 11 months of the year.

Our physical sub-system investigation of hand pumped boreholes involved testing the aquifer, hand pump materials, water quality and borehole examination with a CCTV camera. The initial data analysis, carried out using three sites in the Ejere district of Ethiopia, highlights potential issues with aquifer yield and borehole construction that could contribute to failure. In parallel, communities were asked detailed questions about their experience of the source, using focus group discussions and transect walks, and sanitary and geological surveys were also conducted. Data from the study will be examined using different approaches, including predictive and casual statistical approaches and systems thinking. These methods will be applied to facilitate investigation of the relationship between, and influence of, the physical and social factors underlying poor borehole functionality.

Introduction

Anecdotal evidence, and studies by national governments, donor organisations and implementing bodies indicate that around 35% of improved water sources are non functional at any one time. Furthermore, many water points fail within a few years of installation and then enter repeated cycles of failure and repair [Bonsor et al., 2015; Wilson et al., 2016]. Evidence also suggests that failure rates have remained at between 30 and 50% over the last 40 years [Bonsor et al., 2015; Wilson et al., 2016], despite innovations such as community management and demand responsive approaches which aimed to improve sustainability of water supplies.

Water point functionality is a multi faceted issue and the factors that contribute to functionality outcomes include [HC Bonsor et al., 2015]: primary causes (e.g. mechanical failure, reduced yield, poor water quality); secondary causes (e.g. geology, poor siting, lack of spare parts, basic maintenance, local governance arrangements); the underlying conditions (including the institutional, financial and social factors that shape an environment in which failure is more or less likely); and long term trends (e.g. changes in demand for water, evolution of governance arrangements, reduction in regional groundwater availability, climate change, deterioration of water quality). In the Hidden Crisis project the issue of functionality is considered within a systems framework, and applied to study functionality of rural hand pumped boreholes in three countries in sub-Saharan Africa: Ethiopia, Malawi and Uganda. The project has five main objectives:

1. To provide a nuanced definition of hand pumped borehole functionality which facilitates tracking of future progress towards the Sustainable Development Goals (SDG).
2. Survey 1: To apply this new definition to 600 hand pumped boreholes, 200 each in Ethiopia, Uganda and Malawi, and to carry out field surveys for a statistically significant sample of water points.
3. Survey 2: Conduct a full hand pumped borehole system assessment to unravel the multi-faceted factors governing hand pumped borehole failure and success. Interdisciplinary studies were conducted to investigate casual pathways leading to hand pumped borehole system failure and success. These detailed surveys were conducted on just under 150 hand pumped boreholes, at approximately 50 sites in each of the three countries.
4. To examine and forecast future rural water supply coverage by modelling the impact on water points of different future pathways, including groundwater recharge scenarios, different development approaches and future rural water demand scenarios.
5. To develop a dynamic approach for building resilience into future rural water supply programmes, through detailed interdisciplinary analysis of the datasets developed in 1 – 3 and develop several pathways for uptake within the WASH community.

Here we summarise the main findings from Survey 1 and consider the factors, based on the hand pumped borehole system assessment (Survey 2), that led to functionality outcome and categorisation of a subset of 150 (Survey 1) hand pumped boreholes. Rather than examining the whole system, this paper focuses on understanding a key component of the hand pumped borehole system,

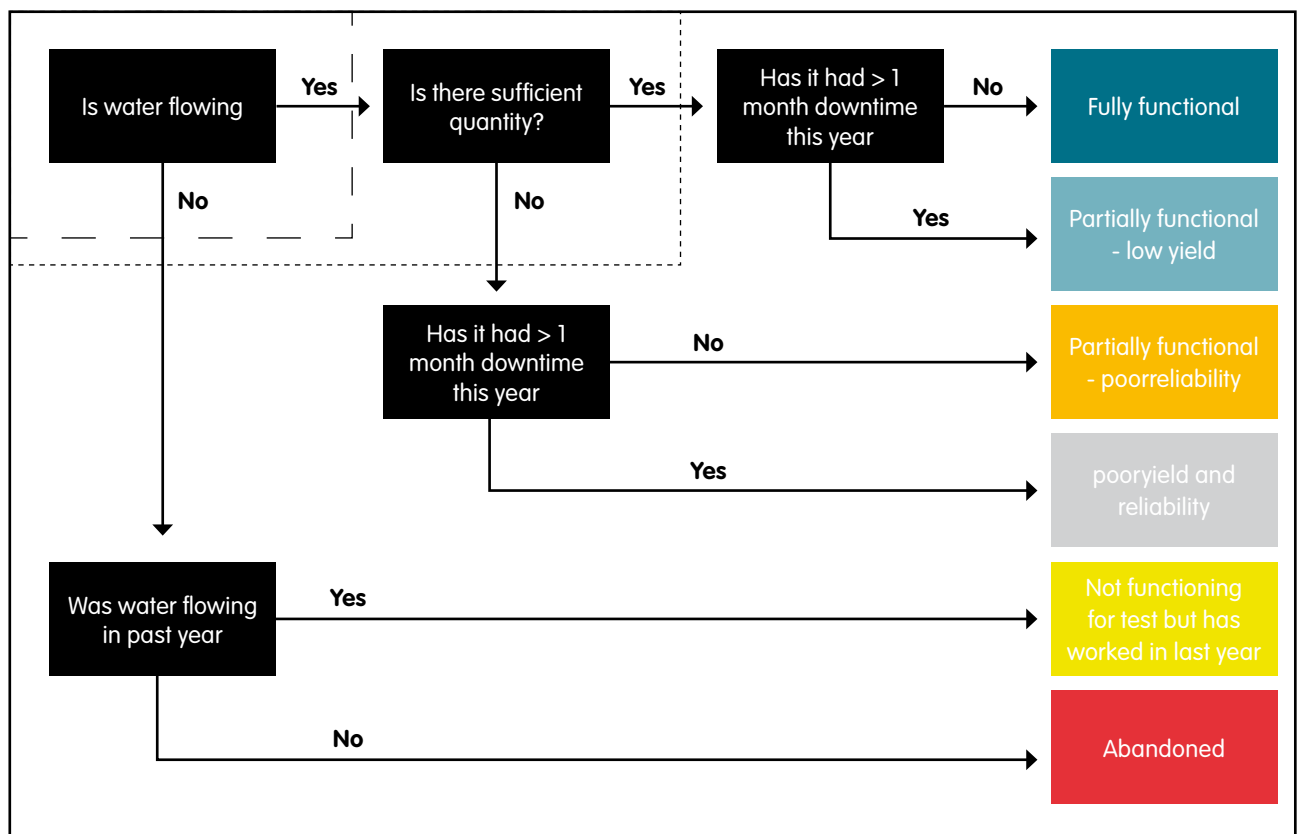
the physical sub-system. In addition to the work reported here, and to ensure the project addressed the whole hand pumped borehole system, longitudinal studies and social surveys were also conducted. The longitudinal surveys examined water resource dynamics and community experience of their resource. Social surveys included detailed focus group discussions and transect walks to better understand social, economic and governance factors affecting functionality. The physical sub-system constitutes the borehole, hand pump and the broader hydrogeological regime. By adopting this system perspective, we anticipate identifying the key physical factors that influence functionality, as defined in Survey 1, of the hand pumped borehole system. The paper begins by summarising the approach adopted in Survey 1 and the definition of functionality adopted. The methods used in Survey 2 are then outlined and some initial results are reported. We focus on three sites in Ejere district of Ethiopia, hand pumped boreholes in this area draw from a porous igneous aquifer system and it has a relatively wet climate. Finally, we discuss the next steps required to form a deeper understanding of the relationships between

the physical components of the hand pumped borehole system and the wider system including the social and governance factors. Finally, we identify mechanisms by which our data might help explain the key properties of functional and non-functional hand pumped borehole systems, and which might provide explanations for poor levels of hand pumped borehole functionality in sub-Saharan Africa.

Background: Definition of system functionality and overview of Survey 1

The Hidden Crisis project adopted the following principals as the foundations for detailed functionality assessments of hand pumped borehole systems. Firstly, functionality should be measured against an explicitly stated standard and population of water points. It should be measured separately from the users' experience of the service it provides. The assessment should be tiered, allowing for a more detailed understanding of the status of the hand pumped borehole system, but always allowing assessments of functionality to be reduced to a simple measure (i.e. delivering water or not delivering water).

Figure 1. Definition of hand pumped borehole functionality. The area surrounded by the dashed box provides a binary assessment of system functionality. The area surrounded by the dotted box provides a snapshot of system functionality against a defined yield. The remaining questions provide an assessment of system performance including temporal behaviour of the system.



Source: Bonsor et al. [2018]

Finally a distinction should be made between surveying functionality as a snapshot (e.g. for national metrics) and monitoring individual water point performance (including an assessment of temporal behaviour of the system). The approach to functionality assessments adopted by the Hidden Crisis project is outlined in detail by Bonsor et al., [2018]. The key components of the assessment approach are reproduced in Figure 1. The definition adopted provides four levels of functionality information about hand pumped borehole system performance, these are:

1. **Binary:** Is the water point physically working and producing some water at the time of the survey visit?
2. **Yield snapshot:** Does the water point provide the minimum design yield (e.g. 10 litres/min)?
3. **Reliable yield:** Does the water point provide a reliable yield (meeting criteria 1 and 2 above) year round (less than 30 days downtime in the previous 12 months)?
4. **Reliable yield including water quality:** Does the water supply pass WHO inorganic and pathogen guidelines, as well as provide a reliable yield year round?

This definition of functionality was applied to assess 600 hand pumped boreholes, primarily equipped with Afridev and India Mark 2 hand pumps, across the three study countries. Two hundred hand pumped boreholes were selected in each country using a stratified three-stage random sampling approach. At each hand pumped borehole a stroke test was conducted, well-head water chemistry and microbiology were sampled and users were asked questions about their perception of functionality. Each hand pumped borehole was classified according to the functionality categories in Figure 1. The results are shown in Figure 2. More details on Survey

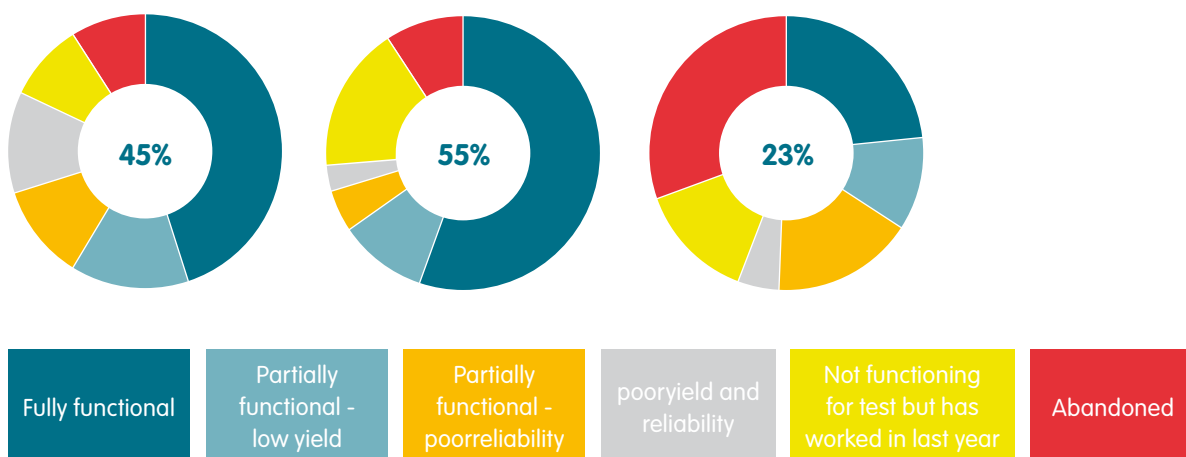
1 analysis and results can be found in Kebede et al., [2017]; Mwathunga et al., [2017]; Owor et al., [2017].

The new definition of hand pumped borehole system functionality provides a clear indication of system performance, which includes system reliability and ability of the hand pumped borehole to deliver against design yield. By including these system properties, the new definition of functionality also provides an indication of the level of service provided by the hand pumped borehole system. There are striking differences in overall functionality levels between the three countries, but also clear differences between reliability and yield components of the system in the three countries. Survey 2 was designed to deconstruct the entire system in order to understand what underlying factors might affect functionality outcomes as shown in Figure 2.

Survey 2: Methodology

Survey 2 involved a full system assessment of 150 hand pumped boreholes across the three countries. Fifty sites were selected in each country based on the results shown in Figure 2. The sites were selected to ensure that each of the six functionality categories (Figure 1) were represented in the Survey 2 dataset, approximately eight to nine sites were selected in each category. The inclusion of sites from each functionality category was designed to allow identification of key physical factors, which influence a particular functionality outcome. In order to achieve this the methods had to cover all physical components of the system, the aquifer and hydrogeology, engineering of the hand pump, borehole construction, water chemistry and geographical and hydrological context of the area surrounding the hand pumped borehole. Figure 3 shows

Figure 2. Results of Survey 1 using the definition (and colour scheme) shown in Figure 1. (A) Ethiopia, (B) Malawi, (C) Uganda. The percentages of sampled water points that are fully functional in each country are shown.



Source: (A) Kebede et al., [2017]; (B) Mwathunga et al., [2017]; (C) Owor et al., [2017].

the key methodological steps and the sequence in which the methodology was conducted at each of the 150 study sites. The full methodology adopted during the survey is outlined below, and some examples of the results from three sites in Ejere district in Ethiopia are presented.

Pump component observations

Survey 2 began by making systematic observations of the pump and surrounding area, a detailed sanitary survey was conducted and observations of the pump condition

were recorded using both photographs and visual observations based on a predefined list of hand pump problems. Next the hand pump was dismantled and pump cylinder, rising mains, rods and all other components were removed from the borehole. As components were removed they were clearly labelled and laid out systematically for further inspection. The condition of each of the downhole components was systematically recorded, again using photographs and recording visual observations against a list of predefined problems.

Figure 3. Field methods as conducted during Survey 2. Clockwise from top left; pump component inspections; pumping test - used to assess aquifer yield; field chemistry - used to assess corrosivity of water and overall water quality; borehole inspections - used to assess borehole construction.



Source: Photo taken by first author.

Further measurements were made for rising mains and rods. Standard measurements included length and diameter measurements, but additional measurements were made to understand rising main and rod condition in more detail. These additional measurements were dependant on the type of hand pump assessed and the material used. If metal pipes were used these were

weighed and the wall and galvanising thickness were measured using an acoustic and magnetic device respectively. If PVC pipes were used the wall thickness was measured using an acoustic measuring device. The purpose of these measurements was to make quantitative estimates of corrosion and assess the quality of materials used in the hand pump.

Figure 4. Observations of pump components from site EEJ10, which was classified as fully functional under the Survey 1 classification scheme.

Figure 5. Observations of pump components from site EEJ06, which was classified as partially functional (poor reliability and low yield) under the Survey 1 classification scheme.



An example of above and below ground observations for a fully functional, partially functional (poor reliability and low yield) and non-functional hand pumped borehole are shown, respectively, in Figure 4 for site EEJ10, Figure 5 for site EEJ06 and Figure 6 for site EEJ20. The fully functional and partially functional boreholes appear very similar from a quick interrogation of the images, the main difference is that the rods from the partially functional borehole appear to be more corroded. The non-functional borehole is in a very poor condition and has many missing components. Further work is required to utilise these images and the manually recorded observations and quantitative measurements to draw conclusions about influence of the component condition on functionality outcomes and whether these represent causes or symptoms of poor functionality.

Figure 6. Observations of pump components from site EEJ20, which was classified as non-functional under the Survey 1 classification scheme.



Users perceptions – water quality, quantity and breakdown history

While component measurements and observations were being made, users were asked about their experience of the hand pumped borehole with respect to quality and quantity. Users were also asked if they could help construct a breakdown history of the hand pumped borehole.

Pumping test

Once the pump was dismantled, the pumping test began. Prior to installing the submersible pump the water level and total depth of the borehole were measured. Then the submersible pump and a pressure transducer were installed. The submersible pump, a Grundfos SQ3-65 cable of pumping at a flow rate of 3 metres cubed per hour to a total height of 60 metres, was installed at or near the hand pump cylinder level or one metre from the bottom of the borehole if there was evidence that the borehole was low yielding. The borehole was then pumped at one litre per second for 2.5 hours, during which time the change in water level was measured manually and recorded. In some cases, for example if there was evidence that the borehole was low yielding, a lower pumping rate was used. Once the pump was switched off water level recovery was monitored manually for one hour. The pressure transducers were left in the borehole overnight, meaning a full record of the pumping test and water level recovery is available. The pumping tests were interpreted using BGSPT which solves Darcy's equation analytically and is designed to minimise the error between observed and calculated drawdown.

Examples of pumping test results for fully functional, partially functional (poor reliability and low yield) and non-functional hand pumped boreholes are shown, respectively, in Figure 7 for site EEJ10, Figure 8 for site EEJ06 and Figure 9 for site EEJ20. The results show that the estimated transmissivity is highest for the fully functional hand pumped borehole and lowest for the non-functional borehole. Although these results are from a very small subset of the larger dataset, they indicate the importance of aquifer yield on the functionality of hand pumped boreholes, particularly in the Ejere district of Ethiopia. The transmissivity in the partially functional borehole (Figure 8) is also very low and suggests that a low yielding aquifer will have implications not only for hand pump yield but also for the reliability of the hand pumped borehole.

Figure 7. Observed and modelled pumping test drawdown, and interpreted transmissivity, for the borehole at site EEJ10, which was classified as fully functional under the Survey 1 classification scheme.

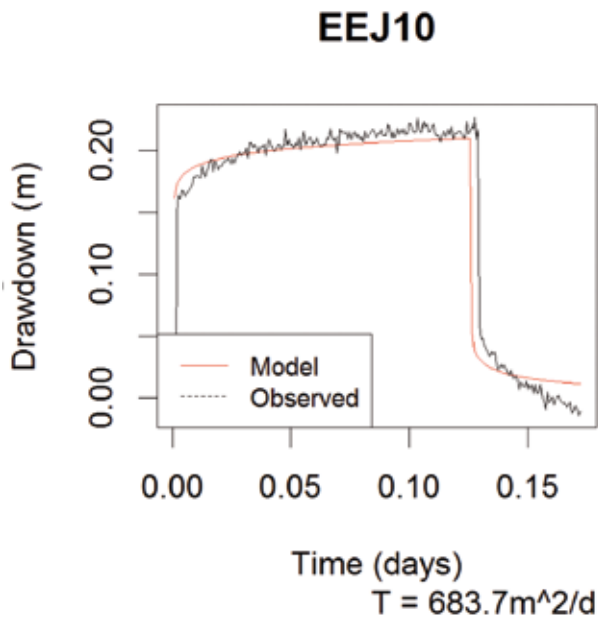


Figure 9. Observed and modelled pumping test drawdown, and interpreted transmissivity, for the borehole at site EEJ20, which was classified as non-functional under the Survey 1 classification scheme.

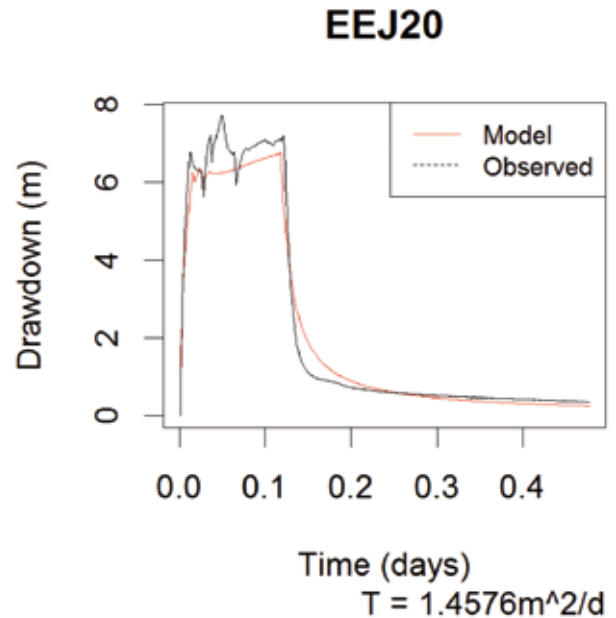
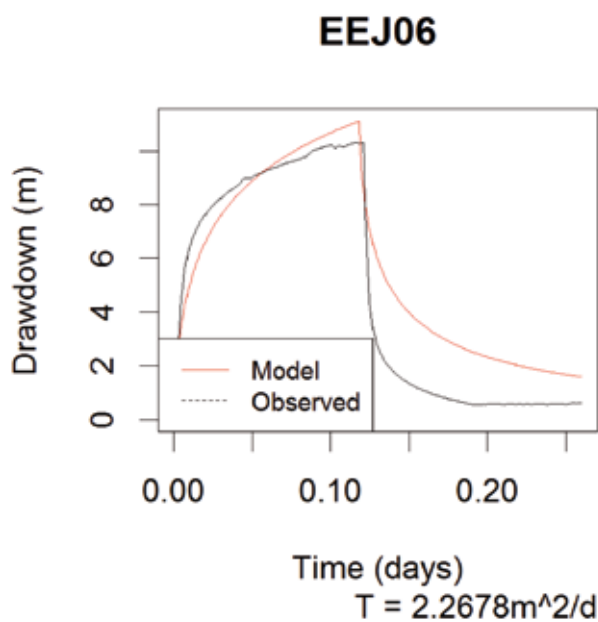


Figure 8. Observed and modelled pumping test drawdown, and interpreted transmissivity, for the borehole at site EEJ06, which was classified as partially functional (poor reliability and low yield) under the Survey 1 classification scheme.



Water chemistry and residence times

In the final one hour of the pumping test, water chemistry was sampled. Before taking water samples pH, electrical conductivity (EC), dissolved oxygen (DO), redox potential (Eh) and temperature were recorded. Iron was monitored using a field colorimeter for the duration of the pumping test. Once each of these parameters stabilised, water samples were taken to allow water quality analysis for a full suite of organic and inorganic parameters, microbiology (using Aquagenx compartmental bags for MPN), residence time indicators (CFC and SF6) and stable isotopes. The main function of the water sampling was to determine the risk of corrosion and/or scaling to the hand pump components. CFC, SF6 and stable isotopes were used to assess aquifer recharge mechanisms which are a critical component of total water available to the hand pumped borehole system.

An example of field chemistry results from a fully functional, partially functional (poor reliability and low yield) and non-functional hand pumped borehole are shown in Table 1. The non-functional borehole has a very high electrical conductivity (EC) and a low pH, suggesting that these parameters might have an important impact on hand pumped borehole functionality. However, the pH is also quite low for the fully functional site so further investigations are required to fully understand the impact of these and other water quality parameters on hand pumped borehole functionality.

Table 1. Field chemistry from a fully functional (EEJ10), partially functional (poor reliability and low yield, EEJ06) and non-functional (EEJ20) hand pumped borehole.

	Temp (°C)	pH	EC (µs/cm)	Eh (mV)	DO (mg/l)	Alkalinity (mg/l)
EEJ10	21.8	6.72	676	97	0.22	236
EEJ06	23.4	7.39	253	318	0.14	120
EEJ20	21.9	6.44	1028	308	0.36	140

Borehole construction assessment

On the second day, borehole CCTV surveys were conducted. The CCTV surveys were designed to assess borehole construction and focused on examining the positions and lengths of individual screen, blank casing or uncased sections within the borehole. The condition of each section was also assessed.

An example of a borehole construction log for a fully functional, partially functional (poor reliability and low yield) and non-functional hand pumped borehole are shown, respectively, in Figure 10 for site EEJ10, Figure 11 for site EEJ06 and Figure 12 for site EEJ20. The fully functional borehole has a pump in the screened section but there is approximately 15 metres between the water level and the pump cylinder. In contrast the partially functioning borehole has only about 5 metres between pump and water level, although it also has the cylinder in the screened section. The smaller water column may have an important impact on the reliability of the pump, with increased risk of the pump cylinder leaving the water column with intensive use, particularly because of the lower aquifer yield of this well (Figure 8). The pump cylinder is above the water level which is a clear explanation of why this particular borehole is classified as non-functional. However, for the non-functional site there are important questions as to why the pump cylinder was installed so high within the borehole given the poor aquifer yield, the positions of the screened sections in the bottom half of the borehole and the relatively deep total borehole depth. These will be investigated further as the analysis progresses.

Figure 10. Borehole construction at site EEJ10, which was classified as fully functional under the Survey 1 classification scheme.

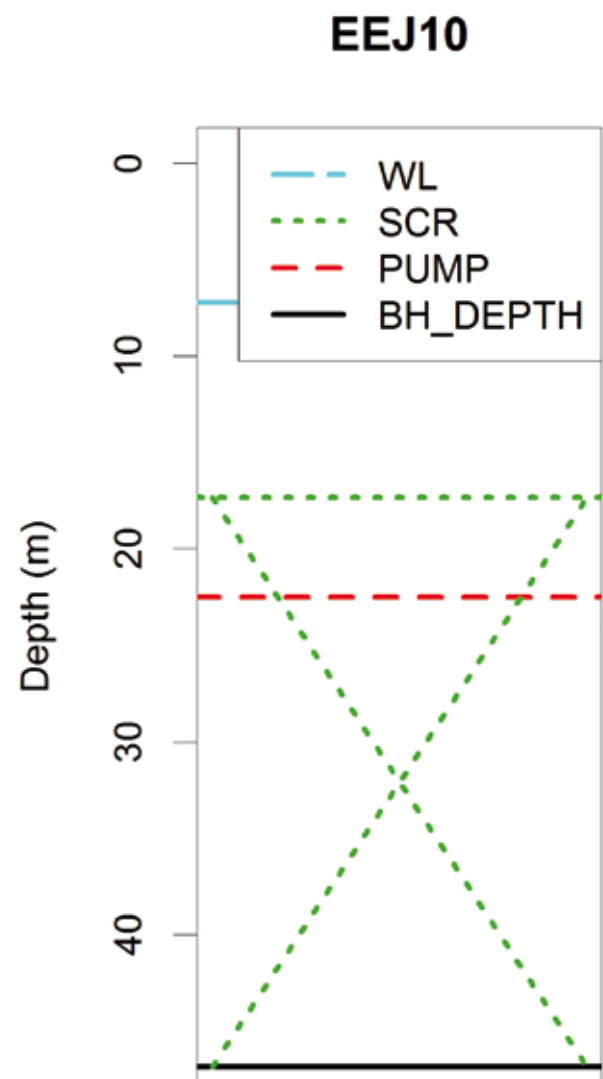


Figure 11. Borehole construction at site EEJ06, which was classified as partially functional (poor reliability and low yield) under the Survey 1 classification scheme.

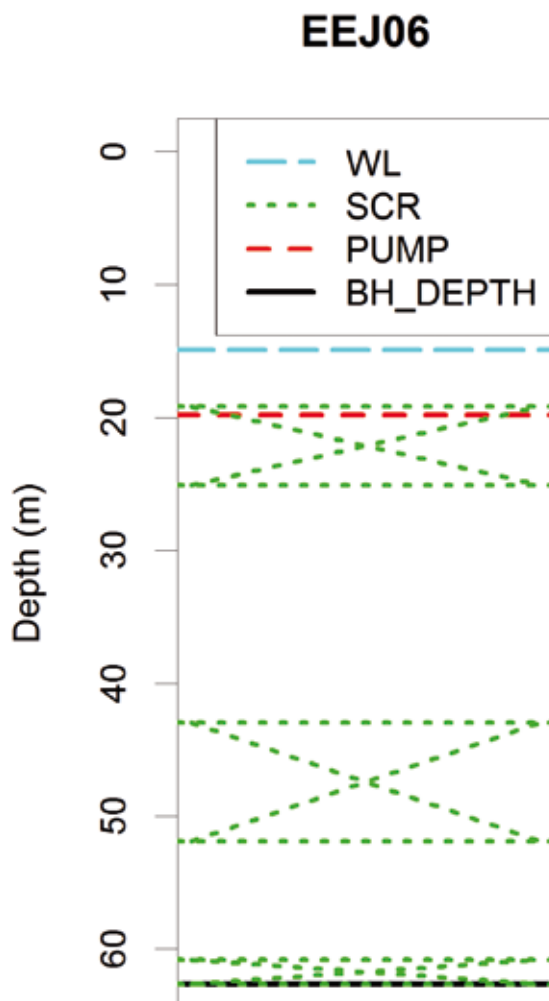
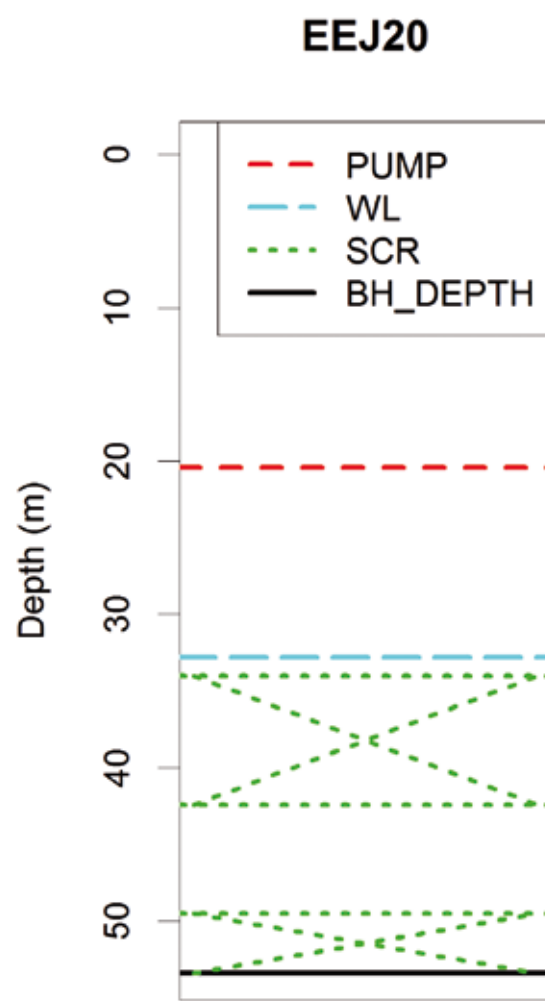


Figure 12. Borehole construction at site EEJ20, which was classified as non-functional under the Survey 1 classification scheme.



Geological survey and geographical context

Finally, a geological and geographic survey of the area was conducted. The aim of the survey was to assess the local hydrogeology and hydrology, surrounding land use and general features of the area that might have an influence on the hand pumped borehole system.

Next Steps

The methodology described above has produced a comprehensive and detailed dataset of the physical causes of hand pumped borehole system functionality. The results presented are only representative of a very small subset of the overall dataset. However, they provide interesting insights into the importance of aquifer yield and borehole construction for three sites in Ejere district of Ethiopia, and hint at the importance of these factors more broadly. Further work is required to extract the full

value from this dataset. The immediate next step is to produce summary outputs from each component of the methodology and begin to extract meaningful indicators of functionality from the data. These indicators will be used in conjunction with social science data to understand causal factors and pathways to each of the functionality outcomes shown in Figure 1. The methods used to understand these relationships will include systems thinking approaches [Little and Fenner, 2017] and multivariate linear regression [Andres et al., 2018; Cronk and Bartram, 2017; Foster, 2013; Foster et al., 2018; Kativhu et al., 2017]. Other techniques could also be explored such as fuzzy-set qualitative comparative analysis (QCA) [K Gasparro, 2017; K E Gasparro and Walters, 2017; Marks et al., 2018] a method which combines qualitative and quantitative methods by applying principles of logical comparison. These methods could also be applied to examine, in more detail,

relationships between properties of physical sub-system, as described above. Much of the value in the dataset is related to the cross-country comparisons but individual country assessments will also be conducted. Failure and success pathways will be mapped for individual sites in order to build a more comprehensive understanding of the mechanisms and properties of functional, partially functional and non-functional hand pumped boreholes.

Summary and Conclusions

The Hidden Crisis project has defined a new functionality categorisation that allows a tiered assessment of the functionality of hand pumped borehole systems. The definition has been tested in three countries in sub-Saharan Africa. In Survey 2 these definitions were interrogated by fully deconstructing 150 hand pumped borehole systems. The methodology adopted considers the hand pumped borehole as an interconnected physical sub-system, and provides quantitative and qualitative data on each individual component of the sub-system. An initial analysis of parts of the sub-system, namely hand pump components, aquifer yield, water chemistry and borehole construction, provide useful insights as to possible factors that led to survey 1 functionality classifications of three sites in Ethiopia. In particular aquifer yield and borehole construction seem to have an important influence on functionality outcome. No causal pathways can be determined from the initial analysis described. However, the dataset will be interrogated further using a number of different techniques to understand the likely causal pathways that lead to particular functionality categorisations of hand pumped borehole systems.

Acknowledgements

The authors would like to thank Michael Owor and Joseph Okullo of Makerere University, Evance Mwachunga and Chikondi Shaba of Chancellors College at the University of Malawi and Patrick Makuluni and Theresa Mkandawire of The Polytechnic at the University of Malawi, all of these individuals were key to the data collection conducted in Uganda and Malawi. WaterAid country staff are also thanked for their assistance in the field in all three countries. NERC and DFID are thanked for funding this project.

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Keywords

Functionality, hand pumps, boreholes, rural water supply, groundwater.

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