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Contribution of physical factors to handpump borehole functionality in Africa

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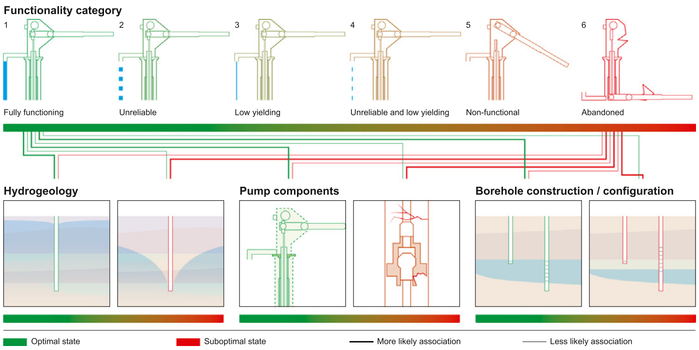
HIGHLIGHTS

- Functionality classifications were used to assess the role of physical factors on handpump borehole (HPB) performance.
- Hydrogeology, borehole configuration and handpump (HP) components were examined by dismantling 145 HPBs.
- HP components are in very poor condition overall, negatively affecting HPB performance.
- Transmissivity and borehole configuration are important factors for classification of HPBs as low yield and/or unreliable.

GRAPHICAL ABSTRACT



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ABSTRACT

Handpumps are the main water supply for rural communities across sub-Saharan Africa. However, studies show that >25 % of handpumps are non-functional at any time. We present results from a systematic field study of handpump borehole functionality. The study was designed to investigate the contribution of physical factors to functionality outcomes, including; hydrogeology, borehole configuration, and handpump components. To achieve this, we deconstructed and examined 145 handpump boreholes in Ethiopia, Uganda and Malawi. Pumping tests showed that 19 % of boreholes were located in aquifers with transmissivity below the minimum required to sustain a handpump. Water levels, measured during the dry season, had a complex relationship with borehole configuration and transmissivity. The handpump cylinder was <10 m below the water table at 38 % of sites, which increases the risk of the handpump running dry during intensive use and/or in areas of low transmissivity. The water column was <20 m at 23 % of sites and screens were <10 m long at 29 % of sites and often sub-optimally positioned in the borehole. Borehole depth had no clear relationship with functionality. Using multinomial regression and four functionality categories (functional; unreliable; low yield; unreliable and low yield) as dependant variables, we found that transmissivity is a significant risk factor for the classification of handpump boreholes as low yield. The configuration of the borehole

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(e.g. cylinder position, screen/casing configuration and water column) is a statistically significant risk factor for the classification of handpump boreholes as unreliable. Handpump components were in poor overall condition but rising main pipes were a particular problem with 53 % of galvanised pipes corroded and 82 % of uPVC pipes damaged, with implications for handpump performance. Our study highlights the importance of; understanding aquifer properties, investing in borehole siting, construction (including supervision) and commissioning, and improving the quality of components and maintenance of handpumps.

1. Introduction

Handpumps (HP), which can be fitted on boreholes or hand-dug wells allowing access to groundwater, are an important means of water access for many rural communities in sub-Saharan Africa (SSA). Up to 200 million people (MacArthur, 2015, Danert, 2022a) rely on between 500,000 and 1.5 million HPs (Foster et al., 2019; Danert, 2022a) to access water for their daily needs across the continent. HPs have been key to increased access to safe water supply across SSA since the water decade of the 1980s. It is estimated that since 2015, which marked the inaugural year of the sustainable development goals (SDGs), the proportion of the total population in SSA accessing at least basic water supplies, defined as water from an improved source with a roundtrip collection time of <30 min, has increased from 60 % to 65 % (WHO and UNICEF, 2021). Much of the improvement in water supply coverage in recent decades has been achieved by the installation of HPs (Truslove et al., 2019). However, after accounting for rapid population increase in SSA, the total number of people without access to basic water supplies has increased from 350 million to 387 million (WHO and UNICEF, 2021). The rate at which access is improved needs to increase by at least four times to meet SDG target 6.1 (WHO and UNICEF, 2021).

While other water source types and technologies do, and will increasingly, play an important role in increasing access to safe water, it is clear that HPs, whether installed on boreholes or hand-dug wells, will continue to serve many millions of people in SSA for many years to come particularly in rural areas (Carter, 2021). Recent studies have shown that HPs installed on boreholes are essential for many rural communities during drought (MacAllister et al., 2020, MacDonald et al., 2019) and that groundwater, is a resilient and safe source of water supply (Lapworth et al., 2020; Banks et al., 2021). However, poor performance of HPs, installed on boreholes or hand-dug wells, is a persistent problem in SSA (Arlosoroff et al., 1987, Parry-Jones et al., 2001, Harvey and Reed, 2004, Carter et al., 1996). Recent evidence suggests that as many as one in four HPs may be non-functional at any one time (Foster et al., 2019). Thus, there is a clear need to better understand the key factors underlying HP functionality. Here we focus on functionality of HPs installed on boreholes, which we term handpump boreholes (HPBs).

Recently there has been a concerted effort to better understand the factors that affect functionality and performance of rural water supplies (Cronk and Bartram, 2017; Andres et al., 2018a; Andres et al., 2018b), including rural HPBs (Foster, 2013; Foster et al., 2019; Foster et al., 2018b; Fisher et al., 2015; Klug et al., 2017; Anthonj et al., 2018; Klug et al., 2018; Truslove et al., 2019; Truslove et al., 2020; Mkandawire et al., 2020). Most studies are based on large-scale water point monitoring datasets that enable a broad geographic assessment but are not designed to enable a detailed analysis of the underlying physical factors affecting HPB functionality. Other studies have examined the management of rural HPBs (Whaley and Cleaver, 2017; Whaley et al., 2021; Chowns, 2015; Whaley et al., 2019) and reveal complex relationships between the capacity of communities to manage water supplies and HPB functionality (Whaley et al., 2019).

Here we focus solely on understanding the underlying physical factors that may influence HPB functionality. The research constitutes the second major survey phase of the NERC/FCDO/ESRC funded project; Hidden Crisis: Unravelling Current Failures for Future Success in Rural Groundwater Supply. A key part of the Hidden Crisis project was the development of an inter-disciplinary field-based methodology which was designed to systematically examine the range of factors (e.g. physical, social, economic) that influence HPB functionality in Ethiopia, Malawi and Uganda. Here, our objective was to understand how physical factors influence HPB functionality across the three countries. We postulate that three broad categories of physical factors influence functionality outcomes: 1) hydrogeology, i.e. aquifer transmissivity and depth to water level, 2) pump components, i.e. material quality and condition, and 3) borehole construction and configuration. Analysis of underlying socio-economic factors and their relation to the physical factors reported here represents the next step of our analysis and is beyond the scope of this paper.

Our aim was to understand the condition, properties and interaction of the physical factors that influence HPB functionality at sites across Ethiopia, Malawi and Uganda (Fig. 1). The analysis represents an open-ended quantitative investigation into the absolute and relative contributions of physical factors to HP functionality outcomes. Our three main objectives were: 1) assess the condition and properties of the primary physical factors that underlie HPB performance including hydrogeology, pump components, and borehole construction and configuration; 2) compare and contrast hydrogeology, pump components, and borehole configuration in different contexts; and 3) assess the relationship between hydrogeology, pump components, and borehole configuration, and functionality of HPBs.

2. Methods

2.1. Study areas: hydrogeology and climate

Our study was conducted in Ethiopia, Uganda and Malawi representing three distinct geological and climatic settings. The highland areas of Ethiopia, where our investigations of HPBs were conducted, are underlain by volcanic aquifers (i.e. igneous aquifers, Fig. 1c). Ethiopia's igneous aquifers have moderate to high transmissivity and low groundwater storage capacity (Kebede, 2012, MacDonald et al., 2012). The main seasonal rainfall in Ethiopia occurs between June and September, five nearby climate stations have mean annual rainfall of c.1280 mm/year. In Uganda, most rural groundwater supplies abstract from fractured crystalline basement aquifers (Fig. 1d). The basement rocks are highly weathered, often clay rich and typically have low storage and transmissivity (Cuthbert et al., 2019; Tindimugaya, 2007). Rainfall in Uganda occurs throughout the year, but the heaviest rainfall occurs between March and May, and September and November. Mean rainfall from four nearby climate stations is c.1290 mm/year. Malawi is primarily underlain by crystalline basement (Fig. 1b) which forms a weathered and fractured aquifer with low transmissivity and storage (Smith-Carington and Chilton, 1983; Mkandawire, 2004). Cretaceous sedimentary rocks occur in the Shire Basin in southern Malawi and alluvium is associated with Lake Malawi. Our study sites in Malawi were located in areas underlain by basement and unconsolidated sedimentary aquifers (Fig. 1b). Malawi has a sub-tropical climate characterised by a wet season from November to March and dry season from April to October. The mean annual rainfall at three nearby climate stations is c.880 mm/year. Further details of the hydrogeology of each country can be found in Banks et al. (2021). All HPB sites were visited during the dry season in each country.

2.2. Site selection and functionality classification

The physical assessments were conducted on a sub-sample of HPBs chosen from a larger survey conducted in an earlier phase of the Hidden Crisis

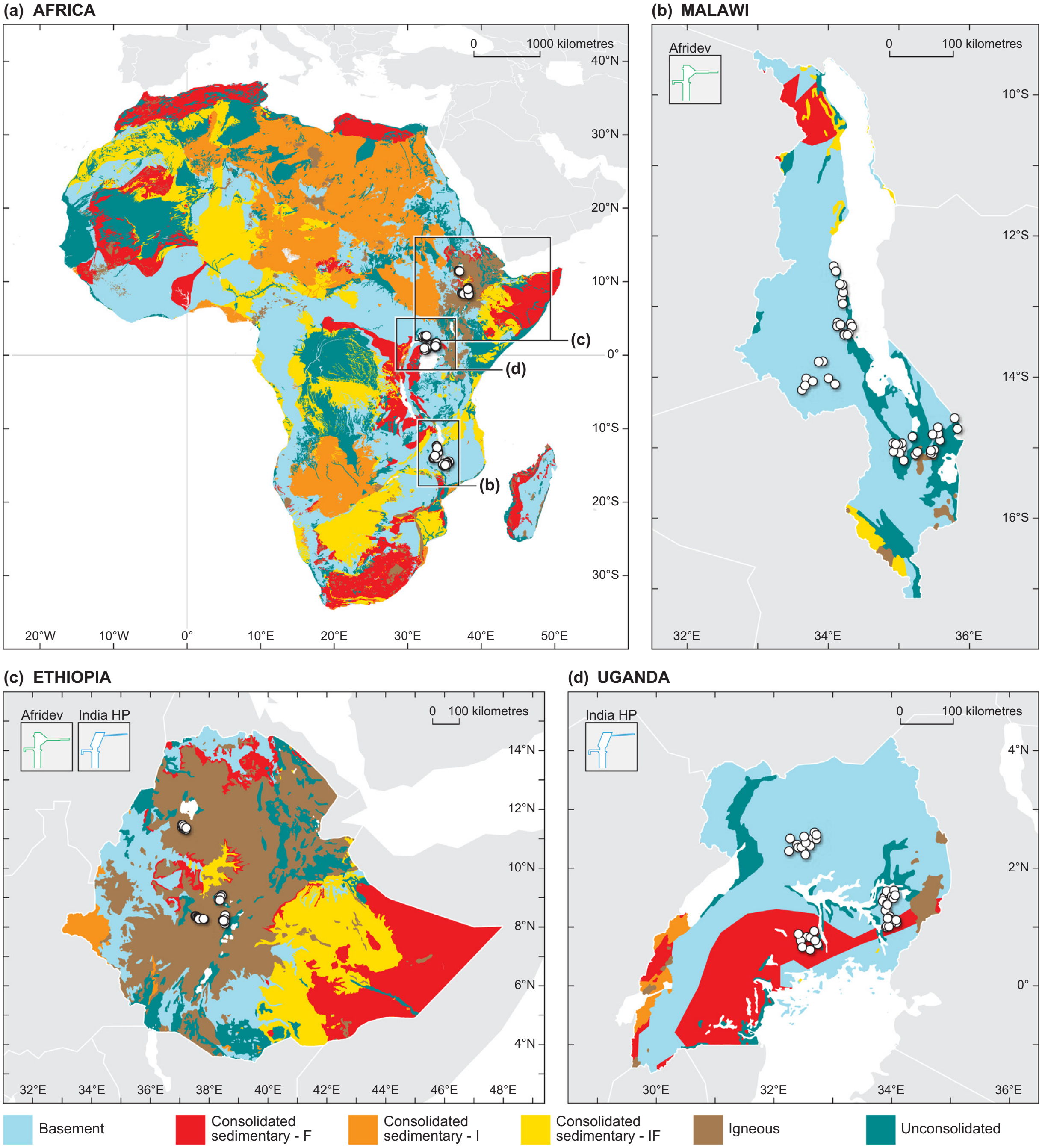

Fig. 1. Hydrogeology and locations of HPBs examined in this study. The box in the top right corner of each map panel shows the type(s) of HP used in each country. Individual HPB locations are indicated by the white circles on each map. (a) Hydrogeological map of Africa and HPB locations. Hydrogeological map and HPB locations for (b) Malawi, (c) Ethiopia, and (d) Uganda. The three categories of consolidated sedimentary aquifers are; F – fractured, I – intergranular, IF – intergranular and fractured. Hydrogeological information is taken from O'Dochartaigh and Upton (2016).

project. In this earlier survey phase, 200 HPBs were visited in each country (Kebede et al., 2017; Mwathunga et al., 2017; Owor et al., 2017), and were selected using a stratified, randomised sampling design ensuring a representative HPB sample (Lapworth et al., 2020). Using a standardised functionality classification (Bonsor et al., 2018) each HP was then classed into one of the six functionality categories: fully functional (FF); unreliable (UR); low yield (LY); unreliable and low yield (UR-LY); non-functional (NF); and abandoned (AB) (Bonsor et al., 2018). HPBs were classed as follows: LY if the fitted HP did not meet the minimum design yield (10 l/min), UR if HPB downtime was >30 days in the past year; UR-LY if the criteria for categorisation as LY and UR were both met; NF if the HPB was not functioning at the time of the test but had delivered water at any point in the past year; and AB if not functioning for more than one year. More information on each functionality category can be found in Supplementary materials Section 1. These six categories were then used to select sites for detailed physical investigations. HPBs were purposefully selected to ensure that the physical assessments covered the full range of possible functionality outcomes. Approximately 10 sites in each functionality category in each country were selected, which was the maximum achievable given time and resource constraints. Country survey teams received common training in the standardised survey methodology and spent approximately one and a half days at each HPB site.

2.3. Pump material and condition assessment

Four different types of handpump were found at our study sites across Ethiopia, Uganda and Malawi. In Ethiopia, a mix of Afridev, India Mark II, India Mark II Extra Deep and India Mark III HPs (Erpf, 2007) are used and all four were found at our study sites. In Uganda, India Mark II and India Mark III HPs are used. Malawi uses Afridev HPs (Baumann, 2007). The India Mark II is a conventional public domain lever action handpump defined by Indian standards and Rural Water Supply Network specifications, designed for heavy duty use, serving communities of up to 300 people and pumping from depths of up to 50 m. The India Mark III is a variation of the India Mark II with modified below ground components allowing it to be classified as a village level operation and maintenance handpump (VLOM) (Arlosoroff et al., 1987). VLOM HPs are designed to be easily maintained by communities and manufactured in-country, robust and reliable in the field, and cost-effective (Arlosoroff et al., 1987). The India Mark II Extra Deep pump is capable of pumping from depths of up to 80 m and, like the standard India Mark II, it is not a VLOM HP. For the purposes of this study, we refer to the India Mark II, India Mark II Extra Deep and India Mark III as the India HPs. In general India HPs use rising main pipes and other components made from low carbon steel, commonly referred to as galvanised iron (GI) (Erpf, 2007) because of its iron content. The main distinguishing feature between the India HPs and the Afridev is the use of un-plasticised polyvinyl chloride (PVC) and other corrosion-resistant materials as a standard feature in the latter (Baumann, 2007); this is the key difference we used to distinguish between HPs in our analysis. The Afridev HP is a conventional public domain lever action HP defined by Rural Water Supply Network specifications and designed to serve communities of up to 300 people and pump from depths up to 45 m. The Afridev is classified as a VLOM HP. In Ethiopia, where Afridev and a range of India HP types were used, our priority was to ensure that we examined a sufficient number of HPBs in each category within the districts agreed with project and district government officials. Thus, we did not distinguish between HP types in our HPB borehole selection criteria in Ethiopia.

The physical assessments involved methodically dismantling the HPs. HP cylinders (which contain the pistons and valves used to create suction), rising mains, rods and all other components were removed from the borehole. Systematic observations were made on all above and below ground components. Observations of HP condition were recorded using photographs (Supplementary materials Section 4) and visual observations based on three predefined tick lists of possible HP problems (corroded, damaged, missing). Components were classified as damaged, using the standardised tick list, if they were; bent, cracked dented and/or worn. Components were classified as corroded, again using the standardised list, if any of the following were observed on visible surfaces; precipitate/scaling, red/orange staining, pitting, and/or a flaky and/or powdery surface texture (Langenegger, 1994; Langenegger, 1989; Clarke, 1980). Measurements were made of rising main galvanising thickness (for India HPs) using an Elcometer® 456 coating thickness gauge and magnetic probe with an accuracy of ±2.5 μm and resolution of 0.1 μm. Pipe wall thickness was measured using an Elcometer® MTG4 ultrasonic material thickness gauge and a 1 MHz transducer for GI pipes (India HPs) and a 5 MHz transducer for PVC pipes (Afridev HPs) both with an accuracy and resolution of ±0.1 mm. The diameter of HP rods and the length of rising main pipes and rods were also measured using a standard measuring tape. These quantitative measurements of pipe and rod dimensions allowed an assessment of component quality with respect to the design standards detailed in the Afridev (Baumann, 2007) and India HP manuals (Erpf, 2007).

2.4. Hydrogeological assessment

Once the HP was dismantled the water level and total borehole depth were measured, and then a pumping test was conducted to determine aquifer transmissivity. Water levels were likely to be at, or close, to the deepest annual rest water level as our investigations were conducted during the dry season and early in the morning at all HPB sites. The submersible pump, a Grundfos SQ3-65 capable of pumping at a flow rate of 3 m^3/hour against a total dynamic head of 60 m, was installed at or near the HP cylinder position or 1 m from the bottom of the borehole if there was a risk of water levels dropping below the submersible pump during the pumping test. A pressure transducer was installed to record the water levels during the pumping and recovery tests and checked with manual monitoring using a groundwater level dipper. The borehole was then pumped at 1 l/s (3.6 m^3/hour), or a lower rate if the borehole was low yielding, for 2.5 hour. Once the pump was switched off, water level recovery was monitored manually for 1 hour and pressure transducers were left in the borehole for 12 hours. The drawdown and recovery data from the pumping tests were interpreted to estimate aquifer transmissivity using BGSPT software (Barker and MacDonald, 2000). BGSPT is a freely available program which numerically solves the generalised well function (Barker, 1985; Barker, 1988) for fractured aquifers and incorporates many other well functions as special cases. The solution is evaluated using numerical Laplace transform inversion and achieves a fit to data by least squares through a series of iterations. In the final hour of the pumping test, water chemistry and environmental tracers were sampled to estimate the residence times of groundwater. Water chemistry results are reported separately (Banks et al., 2021).

2.5. Borehole assessment

Borehole CCTV surveys were conducted on the second day to assess borehole construction. The CCTV survey focused on examining the positions and lengths of individual screen sections, blank casing or uncased sections within the borehole. We did not conduct a condition assessment as the quality of the video recordings was not sufficient for this purpose.

2.6. Exploratory data analysis

An exploratory analysis was conducted on the data to assess the relationship between each functionality category and the underlying physical factors investigated at each HPB. The exploratory analysis focused on: hydrogeology; borehole construction and configuration; and HP materials and condition. Basic descriptive statistics, boxplots, stacked bar charts, bubble charts and histograms were used to examine the properties and condition of the underlying physical factors and their relationship with functionality outcomes. The exploratory analysis formed the basis for the independent variables used in a regression analysis.

2.7. Multinomial regression

Multinomial regression (Venables and Ripley, 2002) was used to assess the role of each of the main physical factors on functionality outcomes. The AB and NF categories were dropped from the multinomial analysis. We dropped the NF category from our multinomial analysis because it is likely to be transient. Classification of a HPB as NF on the day of our first survey may not have been repeated on the day of our second survey a year later. Although we did not repeat the original methodology used for HPB functionality classification (Kebede et al., 2017; Mwathunga et al., 2017; Owor et al., 2017) during the second survey, we asked communities about breakdown and downtime, and ensured that water was flowing before commencing investigations.

The use of multinomial analysis meant that the four remaining functionality categories could be used as discrete categorical dependant variables in the multinomial analysis. Of the four remaining dependant categories, the FF category was selected as the baseline category. Multinomial regression was then used to calculate the probability of one outcome (i.e. UR, LY, or UR-LY) occurring over the baseline category; this is known as the relative risk. A relative risk (RR) > 1 indicates the probability of an HPB being classed as either LY, UR or UR-LY, rather than fully functional, increases as the value of the independent variable increases. A RR < 1 indicates that the risk of an HPB being classed as LY, UR or UR-LY, increases as the value of the independent variable decreases.

Regression models were conducted using a step-wise approach (Venables and Ripley, 2002). The step-wise method iterated through all possible combinations of independent variables and sought to minimise the Akaike Information Criteria (AIC) and optimise the set of independent variables used in the model. Essentially the step-wise approach aims to simplify each of the regression's models without undue negative impact on model performance. Independent variables were determined based on the exploratory analysis of the full dataset described above. The parameters used in the final model were: transmissivity and water level (Hydrogeology); screen/uncased position, pump position and water column (Borehole); above ground components, below ground components, rising main condition, and rod condition (Pump); and HPB age (years since the borehole was installed). HPB age was included as it has been shown to be an important determinant of functionality in multiple other studies (Foster, 2013; Truslove et al., 2019; Fisher et al., 2015; Foster et al., 2018a; Jiménez and Pérez-Foguet, 2011; Truslove et al., 2020). The indicators used in the final model were made up of 22 individual physical factors, details of which are provided in the Supplementary materials Section 2.

3. Results

The survey results are presented in three sections below. Each section focuses on the results of the assessment of each of the primary physical factors that we postulate influence HPB functionality. Table 1 provides summary statistics for all measured parameters for each of the primary physical factors that underlie HPB performance, country level statistics can be found in the Supplementary materials Section 3.

3.1. Hydrogeology

Water levels (Fig. 2a) and aquifer transmissivity (Fig. 2b) are highly variable across the three countries. Across the sampled sites, water levels ranged from 2.0 m to 62.2 m with a median depth of 12.2 m. Water levels were measured in the dry season in each country meaning these values are likely to reflect the deeper end of the range of water levels in a year. Overall, average water levels were deepest in Ethiopia (median depth 20.37 m). In both Ethiopia and Malawi, there is an increase in depth to water through the five functionality categories. In Ethiopia median depth to water in the fully FF category was 10.3 m while in the LY category median water level was 27.8 m. The range of water levels in the LY category is larger than in the other five categories. In Ethiopia, water levels were deeper than 45 m at 13 % of sites which is the maximum advised pumping depth of Afridev HPs. However, India Mark II HPs and India Mark II Extra Deep HPs were used at sites with depths to water >50 m and 80 m respectively. In Malawi, there is a similar change in water level through the functionality categories as that observed in Ethiopia, but the range of water level values is much lower (median depths range from 11.4 m in the UR category to 19.4 m in the UR-LY category), water levels exceed 45 m at only 1 site. In Uganda, water levels do not display any clear trend through the functionality categories and all sites had water levels <45 m deep (median depths range from 8.7 m in the LY category to 13.8 m in the UR-LY category).

Transmissivity values range from 0.02 m^2/day to 986 m^2/day with a median of 7.2 m^2/day (Fig. 2b). Given the significant differences in the geology of the three countries, a large range of transmissivity values is to be expected. Highest transmissivities are found in the volcanic aquifers in Ethiopia (median 26.8 m^2/day) and the lowest in the basement aquifers of Uganda (median 3.4 m^2/day). In Ethiopia, the median transmissivity of wells in the FF category (684 m^2/day) is an order of magnitude larger than wells in the other five categories. The NF category has the lowest mean transmissivity (2.9 m^2/day). Transmissivity in Malawi varies in a similar way through the functionality categories as observed in Ethiopia, but with lower median transmissivity (8.3 m^2/day) than that in Ethiopia. In Malawi, the median transmissivity (1.8 m^2/day) is significantly lower in the NF category than in the other categories. In Uganda, transmissivities are uniformly low, although median transmissivity is highest in the FF (7.2 m^2/day) and UR (16 m^2/day) categories. In Uganda, approximately 30 % of HPBs are installed in areas where transmissivity values are below the threshold value, of about 1.4 m^2/day (Bianchi et al., 2020), required for a HP to deliver against design yields (1.4 m^3/h for Afridev and 1.8 m^3/h for India Mark II and III HPs). Lowest median transmissivity values in Uganda were found at HPBs which were classed as LY (0.96 m^2/day) or UR-LY (2.7 m^2/day). In Ethiopia, only 8 % of HPBs are below the threshold transmissivity, while in Malawi 16 % of pumps are installed at sites with transmissivities below 1.4 m^2/day.

3.2. Borehole construction and assembly

Borehole depths vary across the three countries (Fig. 3a, top panel). Median borehole depth is greatest in Uganda (53.50 m) and the borehole depth range is similar across each of the six functionality categories. Given the predominance of basement geology and low transmissivities in Uganda (Fig. 2b) deeper boreholes are expected, as drillers are likely to drill deeper to achieve sufficient yield. The shallowest median borehole depth (37.30 m) is in Malawi and there is little variation through the functionality categories. An observed increase in borehole depth through the functionality categories in Ethiopia (median 50.32 m) reflects the pattern observed between water levels, transmissivity and functionality (Fig. 3).

Median HP cylinder depth (middle panel Fig. 3a) is similar for Uganda and Malawi (24.09 m and 24.57 m respectively) and there is little evidence of any relationship with functionality category, borehole depth (top panel Fig. 3a) or water level (Fig. 2b). In Ethiopia (where median cylinder depth is 30.60 m) an association is observed between functionality categories and HP cylinder depth, the shallowest HP cylinders are found on HPBs classed as FF and deepest HP cylinders on HPBs classed as UR-LY, similar to the pattern of variations in borehole depth (top panel Fig. 3a), depth to water level (Fig. 2a) and transmissivity (Fig. 2b).

Table 1
Summary statistics for all measured parameters and HPB age.

	Variable	Mean	Min	5th	25th	Med	75th	95th	Max	Standard deviation
Hydro-geology	Transmissivity (m^2/day)	71.12	0.02	0.46	1.65	7.19	28.42	579.6	986.7	188.3
	Depth to water (m) during dry season measured early morning	15.72	2.00	4.13	8.62	12.20	19.38	40.98	62.16	11.97
Borehole	Borehole depth (m)	47.82	14.73	20.65	36.30	46.10	59.52	80.02	101.4	17.58
	Pump depth (m)	28.80	2.99	14.86	20.88	26.79	33.11	52.03	68.74	11.91
	Top of screen or uncased section (m)	23.97	0.70	7.60	14.61	22.29	30.18	52.94	65.60	13.35
	Screen or uncased section length (m)	16.63	0.00	2.63	6.92	13.44	21.23	41.29	75.29	13.21
	Number of screen sections	1.18	0.00	0.00	1.00	1.00	2.00	3.00	5.00	0.96
Pump	PVC rising main thickness (mm)	4.89	2.80	3.56	4.50	5.10	5.31	5.73	6.80	0.68
	PVC rising main length (m)	2.22	0.14	0.47	1.44	2.76	2.82	2.99	8.08	0.91
	GI galvanising thickness (μm)	43.77	0.00	4.13	29.88	42.20	56.67	83.87	310.0	27.50
	GI rising main thickness (mm)	3.13	0.77	1.47	2.60	2.90	3.20	5.53	7.03	1.19
	GI rising main length (m)	2.92	0.25	2.75	2.98	3.00	3.02	3.04	5.83	0.40
	Rod diameter (mm)	9.94	0.83	6.44	9.10	10.10	11.70	12.00	15.00	2.37
	Rod length (m)	2.82	0.12	1.29	2.92	2.94	3.01	3.04	3.23	0.51
HPB age	Date since borehole installation (years)	15.42	1.00	2.00	6.00	11.00	19.00	55.00	77.00	14.07

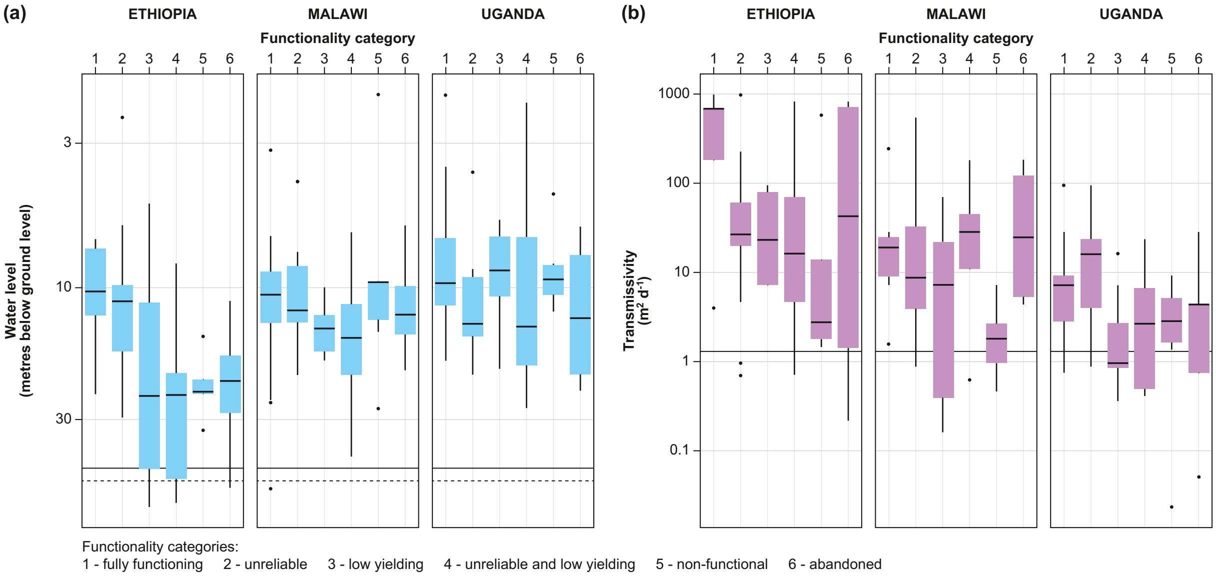

Fig. 2. (a) Water level (shallowest depths at the top of the y-axis). The solid line shows the maximum advised pumping depth for Afridev HPs and the dashed line for India MK II HPs. (b) Transmissivity plotted by country and functionality category, the solid black line indicates the minimum transmissivity required to deliver the typical HP design yield. The interquartile range is shown by the upper and lower bounds of the box, the median is represented by the black line, the whiskers represent the interquartile range times 1.5 and the points represent outliers.

No clear trend is observed between the functionality categories and the relative position of the HP cylinder (with respect to the borehole depth) (bottom panel Fig. 3a). The exception is Uganda where the position of the HP cylinder in the borehole gets shallower through the functionality categories. The HP cylinder is generally found in the shallowest half of the borehole in Uganda and the deepest half in Ethiopia and Malawi (bottom panel Fig. 3a). In Uganda, the shallowest cylinders are found in the LY, NF and AB categories.

Fig. 3b illustrates how water column length and HP cylinder position change through the functionality categories with respect to both static and dynamic water levels (the latter determined by the maximum water level depth reached during the two-hour pumping test). Water column length (top panel Fig. 3b) is greatest in Uganda (median is 44.13 m) where boreholes are deeper and water levels relatively shallow (medians in Ethiopia and Malawi are 32.65 m and 25.10 m respectively). The range of water column lengths above the HP cylinder when not pump testing the borehole (middle panel Fig. 3b) are similar across all countries and functionality categories (medians in Ethiopia, Uganda and Malawi are 9.58 m, 15.14 m, 13.78 m respectively). However, there are observable declines in the water column length above the HP cylinder position through the functionality categories during the pump test (bottom panel Fig. 3b) (medians in Ethiopia, Uganda and Malawi are 0.55 m, −5.58 m, 0.68 m, negative values mean the water level dropped below the HP cylinder). Fig. 3d (top panel) summarises sites where the HP cylinder position was above the dynamic water level during the pumping test. The water level dropped below the level of the HP cylinder in >50 % of wells in Uganda in all functionality categories, which reflects the low transmissivities observed (Fig. 2b). The proportion dropping below the HP cylinder level increased through the UR, LY, NF and AB categories in Uganda. In Ethiopia and Malawi, the percentage of sites where water levels dropped below the HP cylinder is highest in the LY category, this happened at approximately 25 % of sites in the LY category in Ethiopia and 50 % of sites in the same category in Malawi.

The length, position, and depth of the screened and uncased sections (Fig. 3c) were also measured as part of the borehole assessment. In Uganda, basement rocks constitute the main aquifers and have good structural integrity. Thus, boreholes are generally uncased below the weathered zone. Depths to the top of uncased sections (median is 22.63 m) are deepest in the FF category and generally decrease through the functionality categories in Uganda (top panel Fig. 3c). This may be related to the thickness of the weathering layer at the top of the bedrock (e.g. Owor et al., 2022 (in prep)). Uncased section lengths (median is 9.59 m) also vary through the functionality categories (middle panel Fig. 3c) providing evidence that larger open-hole sections are associated with poorer functionality, likely because boreholes are drilled deeper to achieve sufficient yield as described above. Tops of uncased sections were generally found to be in the upper half of boreholes in Uganda (bottom panel Fig. 3c) and there was a clear change in uncased section position, from deeper to shallower, through the functionality categories.

In Ethiopia and Malawi, it is normal for the full length of the borehole to be cased and screened. In Ethiopia screen depths (median is 34.74 m) are deepest in the UR-LY, NF and AB categories, reflecting deep water levels and low transmissivity (top panel Fig. 3a). In Malawi, there is no apparent relationship between screen depth (median is 16.00 m) and functionality categories. Median screen lengths (middle panel Fig. 3c) are 17.25 m in Malawi and 12.08 m in Ethiopia with little variation through the functionality categories. Screens are generally in the lower half of the borehole in Ethiopia (bottom panel Fig. 3c), although screen position is generally deeper in boreholes with poorer functionality. In Malawi, screens are generally positioned in the mid sections of the borehole.

Further analysis was conducted on the configuration of the boreholes with respect to the static and dynamic water levels and the cylinder position (Fig. 3d). In most cases the static water level is above screened or uncased sections, although in Malawi a higher number of sites with water levels in screened sections occur in the UR-LY and NF categories (middle panel Fig. 3d). In Ethiopia and Malawi, HP cylinder is in, or between, screened sections (bottom panel Fig. 3d) at most sites. In most design guidelines it is recommended that HP cylinders are placed above the screened sections (Driscoll, 1986; Misstear et al., 2017) to avoid the risk of turbulent flow, although this is likely to be less of a problem in HPBs with pumping rates significantly less than motorised boreholes.

3.3. Pump materials and condition

Systematic assessments of the HP components in all three countries reveal that rods, rising mains and centralisers have the greatest percentage of problems, regardless of HP type or material (Fig. 4). Rising main and rod condition is poor across all functionality categories. In Uganda, where

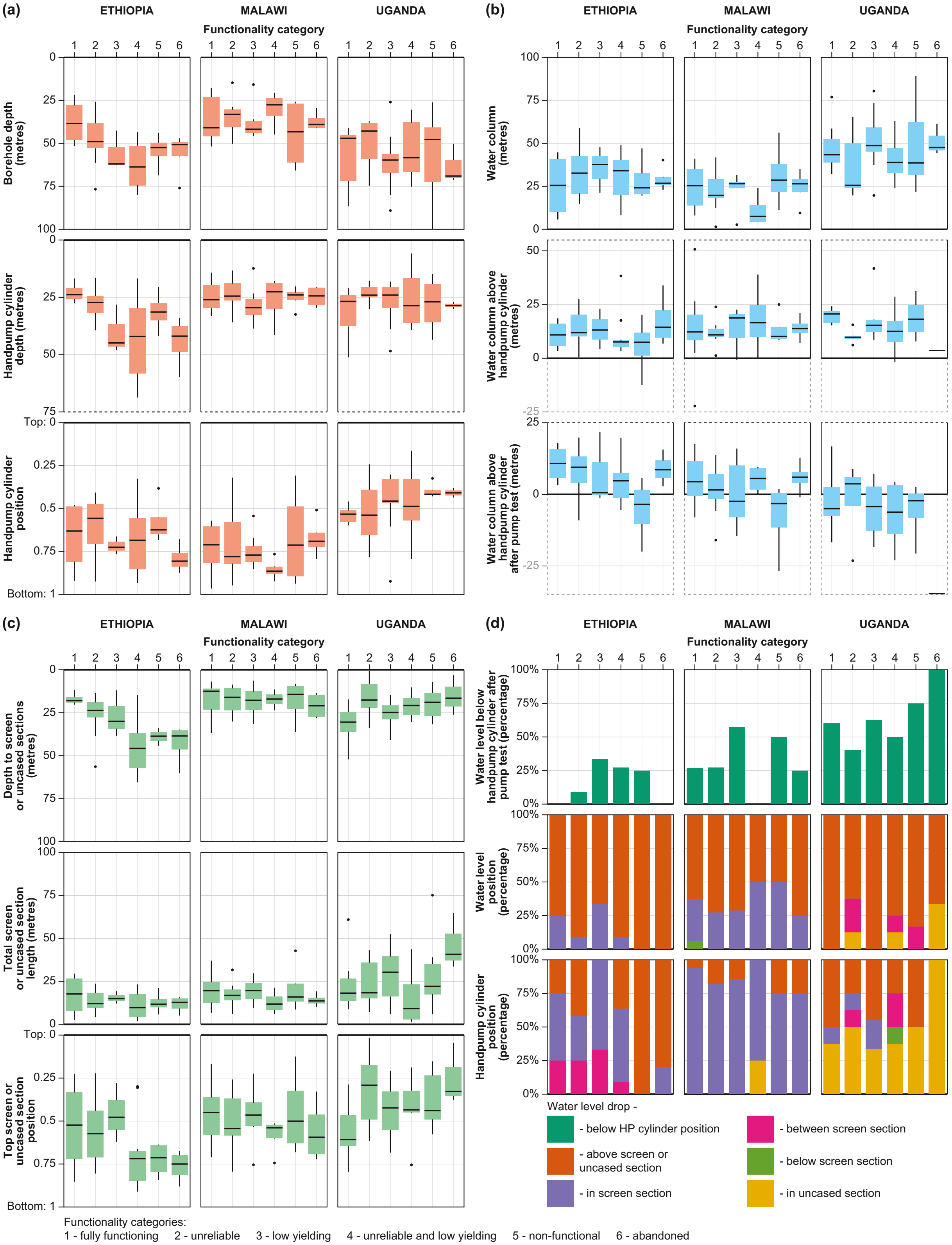

Fig. 3. Summary of borehole construction and configuration by country and functionality category. Plots showing depths have ground level at the top. For plots showing position in the borehole, 0 represents the top and 1 the bottom of the borehole. (a) Top panel shows borehole depth, middle HP cylinder depth and bottom HP cylinder position. (b) Top panel shows borehole water column length. Water column lengths with respect to HP cylinder both before (middle panel) and after pumping test (bottom panel) are also shown (in the latter negative values mean the cylinder was above the water table). (c) Top panel shows depth to top screen or uncased section, middle total screen length and, bottom position of top of screen or uncased section as a fraction of borehole depth. (d) Top panel shows water level position before pumping test with respect to screened and/or uncased sections. The middle panel shows HP cylinder position before pumping test with respect to screened and/or uncased sections. The bottom panel shows water level position after pumping test with respect to screened and/or uncased sections and HP cylinder depth. For boxplots the interquartile range is shown by the upper and lower bounds of the box, the median by the black line, the whiskers represent the interquartile range times 1.5 and the points represent outliers.

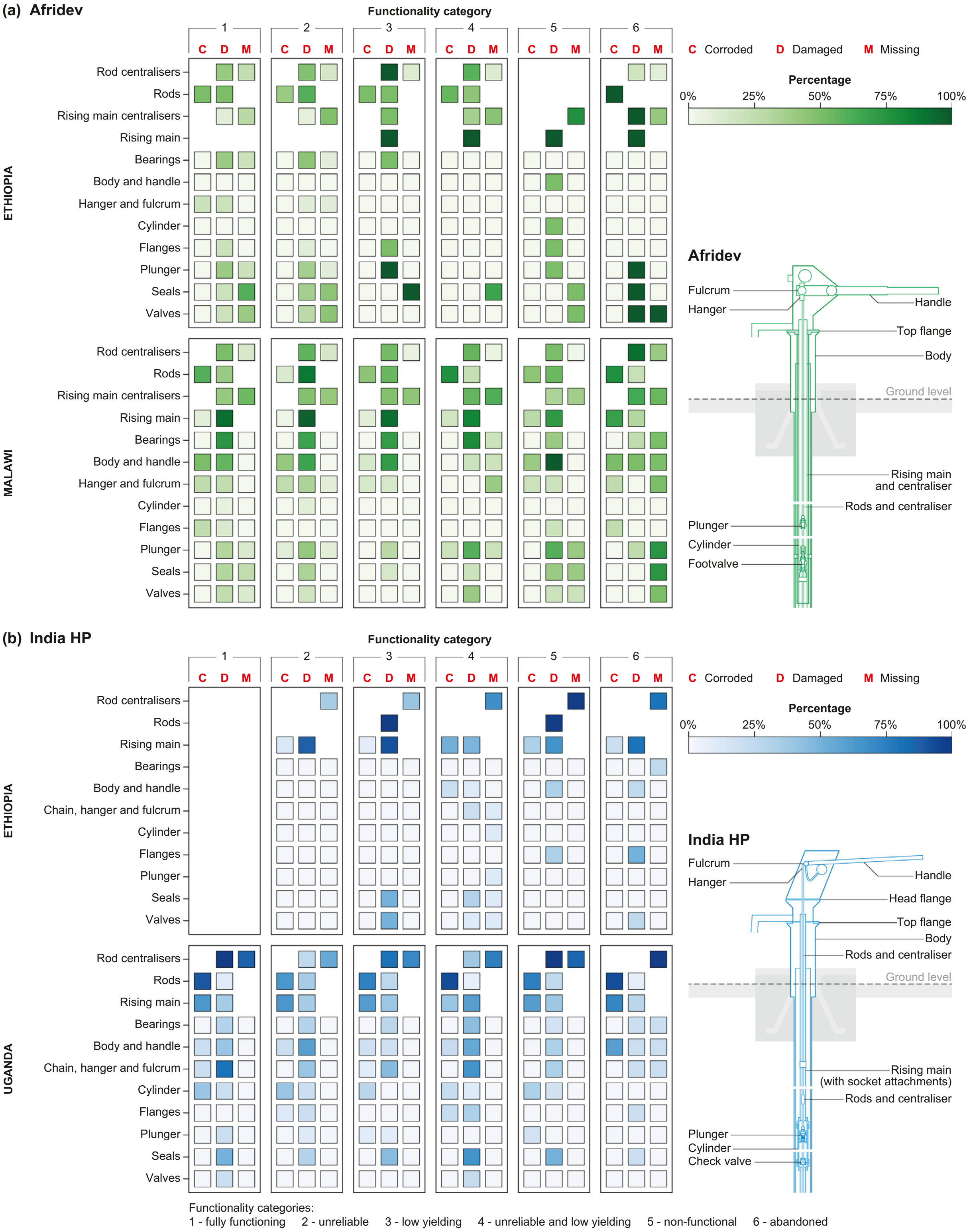

Fig. 4. Summary of HP component condition, for (a) Afridev and (b) India HPs, plotted by country and functionality category.

India HPs are used (Fig. 4b), rising mains are made from GI and approximately 61 % of all pipes examined were corroded and 38 % were damaged. In Malawi, where Afridev HPs are used (Fig. 4a), rising mains are made from PVC, and approximately 81 % of pipes examined were damaged. In Ethiopia both Afridev (Fig. 4a) and India HPs (Fig. 4b) are used with rising mains made from PVC and GI pipes respectively. Approximately 63 % of India HP and 100 % of Afridev rising mains examined were damaged in Ethiopia, while 37 % of India HP rising mains were corroded. The terms damaged and corroded are used here as defined in the methodology section. Similarly, rods, the vast majority of which are made of GI (top panels Fig. 5c and d), are in poor condition in all three countries. In Ethiopia, 52 % of rods are damaged and 55 % are corroded. In Uganda, 17 % and 82 % of rods are damaged and corroded respectively, and in Malawi, it is 56 % and 43 % respectively.

Further quantitative assessments were made of the rising main and rod (Fig. 5) condition in all three countries. In Ethiopia and Uganda, where GI rising main pipes are used in the majority of India HPs (top panel Fig. 5a), pipe galvanising thicknesses are below design standards in approximately 75 % and 98 % of pipes in each country, respectively (middle-bottom panel Fig. 5a). Similarly, pipe wall thickness is below design standards for approximately 93 % and 67 % of rising main pipes in Ethiopia and Uganda, respectively (middle-top panel Fig. 5a). The majority of India HP rising main sections are of the specified length but a significant proportion are below standard lengths in Uganda (bottom panel Fig. 5a), which is likely caused by rethreading of damaged and corroded pipes. While the majority of India HP rising mains are made from GI, about 25 % of rising main pipes are made using PVC in Uganda. In Uganda, only 1 % of PVC pipes are damaged compared to 37 % of GI pipes. The presence of PVC pipes in Uganda may be partly explained by the use of the U3M handpump, which has a similar configuration to the India HPs for above ground components but a similar below ground configuration to the Afridev (Erpf, 2001). For Afridev HPs pipe, wall thicknesses are below design standards at approximately 52 % sites in Ethiopia and approximately 20 % of sites in Malawi (top panel Fig. 5b). In Malawi, 61 % of rising mains are below design standard lengths, while this is only 18 % in Ethiopia (bottom panel Fig. 5b).

Most India HP rods are made from GI but approximately 25 % of rods in Uganda are made from stainless steel (top panel Fig. 5c). In Uganda, 2 % of stainless steels rods are damaged and 3.5 % corroded compared to 14 % of GI rods damaged and 69 % corroded. In Ethiopia and Uganda, 64 % and 70 % of India HP rods are below design diameter respectively (middle panel Fig. 5c). In Ethiopia, 100 % of India HP (top panel Fig. 5c) and Afridev (top panel Fig. 5d) rods are made from GI. In Malawi, the vast majority of Afridev rods are made from stainless steel with some made from GI or fibreglass (top panel Fig. 5d). Most rods are of specified length in all three countries (bottom panels in Fig. 5c and d). In Ethiopia and Malawi, 86 % and 98 % of Afridev rods are below design diameter respectively (middle panel Fig. 5d).

Of the other below ground components, seals, valves and the plunger were commonly reported as damaged (at 32 %, 14 % and 23 % of sites respectively), while seals and valves were commonly reported missing (at 16 % and 10 % of sites respectively). In Uganda, where India HP cylinders are made from cast iron and lined with brass, a significant percentage of cylinders are corroded and damaged (Fig. 4b). Of all the internal above ground components, bearings are most commonly reported as damaged (37 % of sites). In Uganda, the internal above ground components (i.e. chain, hanger, fulcrum and bearings) are damaged at a high percentage of sites (Fig. 4b). Moreover, in Malawi (Fig. 4a) and Uganda (Fig. 4b), the external above ground components (i.e. the HP body, handle and flanges) are corroded and damaged at a large percentage of sites. In Ethiopia, Afridev flanges are commonly damaged in LY and NF HPs (Fig. 4a), while India HP flanges are often damaged in the NF and AB categories (Fig. 4b).

3.4. Interaction of physical factors for functionality outcomes

The results from the exploratory analysis were used to inform the construction of independent variables for use in regression analysis. Ten independent variables were used in the regression models, each variable fell into one of the following summary classifications: 1. Hydrogeology, 2. Borehole and 3. Handpump. The construction of the independent variables is described in the Supplementary materials Section 2. A correlation matrix of the individual independent variables (Fig. 6a) shows little correlation between variables (maximum correlation coefficient was 0.57 between water level and water column, and minimum was -0.64 between water column and pump position). Thus, all independent variables were suitable for use in the regression models. Each of the independent variables were scaled between zero and one and combined to create a summary classification for the three physical categories which were then compared to the six functionality categories for each country (Fig. 6b–d). The summary classes (Fig. 6b–d) illustrate that the value of the combined hydrogeology class declines through the functionality categories in all three countries, i.e. water levels get deeper and/or aquifer transmissivity lower through the functionality categories. The change in the combined hydrogeology class value through the functionality categories is clearest in Ethiopia but occurs in all three countries, although the UR-LY and AB categories in Malawi appear to deviate from the general trend with relatively higher scores. The value of the HP class (i.e. condition of rising main, rods, above and below ground components including seal and bearing conditions) declines through the functionality categories in Malawi (Afridev) and Ethiopia (Afridev and India HPs). In Uganda (India HPs), there is a less obvious pattern in the combined HP class through the functionality categories. It is notable that the combined HP class values are lowest in Uganda overall where only India HPs are used, this is driven in large part by the use of GI rising mains and rods. In Malawi, the value of the combined borehole class declines through the functionality categories. However, values for the combined borehole class are lowest in Uganda, which is likely to indicate the challenge of designing boreholes in low yielding bedrock aquifers, and in Ethiopia, where water levels are deepest.

To further investigate the importance and interaction of the combined physical factors on functionality we constructed a multinomial regression model. We used the indicators shown in the correlation matrix in Fig. 6a as the independent variables' and the functionality categories as the dependant variables (excluding the NF and AB category). The multinomial regression results are shown in Table 2.

The multinomial results (Table 2) indicate the factors that influence the likelihood of an HPB being classed as UR, LY or UR-LY relative to the likelihood of an HPB being classed as fully functional. For UR HPBs (category 2), sub-optimal HP cylinder position, casing and screen layout and short water column are all factors that are more likely to result in an UR HPB. For LY HPBs (category 3), low transmissivity is the main factor that influences the likelihood of an HPB being classed as LY rather than FF in the full model. In the step-wise regression model, HPB age and sub-optimal casing/screen length and position are also likely to result in a classification of HPB as LY. The risk factors for UR-LY HPBs (category 4), are a combination of the statistically significant risk factors for UR and LY functionality categories, i.e. low transmissivity, sub-optimal casing/screen length and position and a short water column. Our full model has a good prediction accuracy for the UR (59.5 % prediction accuracy) and UR-LY category (61.7 % prediction accuracy) but only predicts 40 % of LY correctly. The full model is able to predict 52.5 % of functional sites. The step model shows limited improvements in some measures of model fit (i.e. AIC, prediction accuracy) and deterioration (i.e. deviance and EDF) in others, suggesting that the step model result does not represent a significantly more accurate model overall than the model containing all of the independent variables.

4. Discussion

4.1. Hydrogeology

Our results suggest that hydrogeological conditions are an important factor influencing functionality status in all three countries (Figs. 2 and 6 and Table 2), but that hydrogeological conditions are particularly challenging in Uganda. Several previous studies have indicated the importance of hydrogeology as a determinant of functionality (Foster et al., 2019; Foster et al., 2018b; Fisher et al., 2015; Cronk and Bartram, 2017), but usually only considering groundwater depth and rarely with in-situ measurements of water level or transmissivity. Our results demonstrate that transmissivity is a key determinant of HP borehole functionality, with statistical significance as a risk factor for classification as low yielding and/or unreliable categories relative to the functional category in the multinomial analysis. The relationship between aquifer transmissivity and depth to water table observed in the data for individual countries reflects the non-linear reduction of permeability with depth.

Bianchi et al. (2020) demonstrate that boreholes need to be drilled in areas with transmissivity >1.4 m^2/day to sustain the yield of a HP (1.4 m^3/h for Afridev and 1.8 m^3/h for India Mark II). Approximately 15 % of sites have transmissivity below 1.4 m^2/day in Ethiopia and Malawi which compares to similar data for boreholes sited in basement

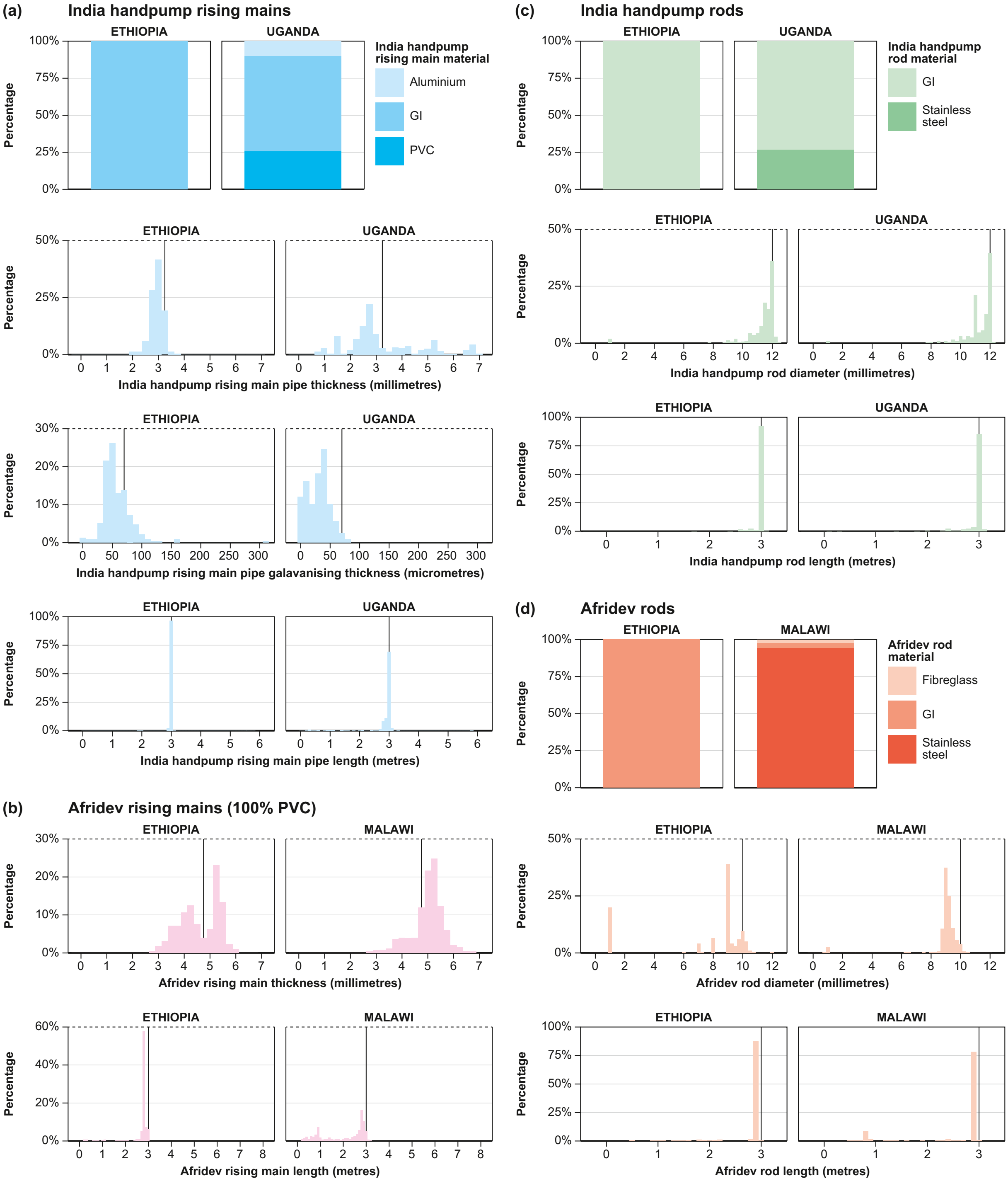

Fig. 5. Summary of rising main and rod material and material quality. (a) India HP rising main components showing; in the top panel materials, the middle top panel rising main thickness, the middle bottom panel galvanising thickness, and the bottom panel rising main length. (b) Afridev rising main components showing; in the top panel rising main thickness, and in the bottom panel rising main length. (c) India HP rod components showing; in the top panel materials, in the middle panel rod diameter, and in the bottom panel rod length. (d) Afridev rod components showing; in the top panel rod material, in the middle panel rod diameter, and in the bottom panel rod length. In all plots the vertical line represents the material or component standard used in the HP specification.

aquifers using standard geophysical methods in West Africa. In Uganda, 30 % of HPs are below the 1.4 m^2/day transmissivity threshold reflecting the challenge of siting boreholes with sufficient yield in some very low transmissivity crystalline basement aquifers (Owor et al., 2022, in press). Increased investment in siting methods using geophysics, remote sensing and possibly even trial drilling may be required to help increase the success rate of boreholes in these challenging hydrogeological settings. The use of alternative pumping technologies may allow sustainable extraction from lower yielding boreholes. However, alternative technologies can often solve one problem but lead to another, for example at sites with deeper water levels in Ethiopia India Mark II Extra Deep HPs are used instead of Afridev HPs but this leads to an increased risk of corrosion related problems because of the use of GI for the downhole components. Depth to groundwater is discussed in more detail, in conjunction with HP borehole construction and configuration, below.

4.2. Borehole construction and assembly

Few previous studies have systematically examined the influence of borehole construction on functionality status of HPBs. A notable exception is the work of Harvey (2004) who found that static water level, dynamic water level and depth to HP cylinder had little bearing on borehole failure (defined as a borehole unable to deliver at least 10 l/min throughout the year) in central Ghana. However, they found that boreholes with an initial yield below 10 l/min and those drilled during the wet season had a much higher rate of failure than those with higher yields and/or drilled in the dry season. Our results indicate that HP cylinder position, screen and casing position, and water column are important factors influencing functionality status (Figs. 3 and 6 and Table 2).

The position of the HP cylinder in the borehole is usually determined by two factors. The first is depth to groundwater. In Ethiopia, deeper groundwater levels (Fig. 2a) were linked to deepening of the HP cylinder position to keep it below the water table. These sites were also often associated with unreliable or abandoned boreholes (Fig. 3a). Banks et al. (2021) demonstrated that deep water levels were not a result of low recharge, instead observations during the fieldwork in Ethiopia suggest competition from nearby industrial and agricultural uses likely contributed to deeper water levels (UPGro, 2022). The second issue is related to corrosion and failure of the rising main. There was evidence of corrosion and damage of rising mains at many sites. Numerous rising main pipes had been shortened, particularly in Malawi (bottom panel Fig. 5b) where maintenance practice routinely involves cutting riser pipes to separate glued PVC sections to access and repair below ground components for repair or replacement. In Uganda and Ethiopia, there was evidence of rising main pipe sections (Fig. 5d) and individual rods (Fig. 5d) being shortened and rethreaded instead of whole pipe or rod sections being replaced, a practice which reflects limited maintenance budgets.

The casing/screen configuration was shown to be a significant risk factor for the classification of HPBs as unreliable. The design of a borehole should be driven by hydrogeological conditions. However, it is common in SSA for hydrogeology not to be a primary consideration in borehole design and construction (Harvey, 2004) due to limited technical capacity of procurement and drilling personnel, the use of standard borehole designs, lack of geological or hydrogeological data, contractual limitations (Liddle and Fenner, 2019), and the logistical difficulty of construction and site supervision in remote areas. Previous studies hint at some of the reasons why casing/screen configuration flags as an important risk factor in our multinomial analysis, for example Liddle and Fenner (2019) reported the use of fewer casing/screen materials in construction than the hydrogeology of a site might demand. In the case of Ethiopia and Malawi, this might mean the use of fewer screen sections than required, meaning water levels are at risk of dropping below screened sections (particularly in Malawi where most screen sections are in the middle of the borehole). Due to the use of standard borehole designs with limited reference to the geology there is also a risk of placing screens in the wrong place in the borehole and blocking the more productive parts of the aquifer. Poor borehole design may also allow fine material into the borehole resulting in accumulation of silt and reduction in open hole or screen length. For example, the minimum open hole length observed was 0.7 m (Table 1), which was clearly not the original design length.

4.3. Pump materials and condition

Our exploratory analysis highlights many issues with component conditions (Fig. 4) and the quality of materials used in HPs (Fig. 5), consistent with previous studies (Klug et al., 2018; Cook and Lahren, 2017). HP components in poor condition have inevitable impacts on the yield and reliability of HPs. For example, we observed many HPs with worn and/or missing seals and valves, and leaking rising main pipes, all of which meant these HPs would not be able to deliver against design yields. Similarly, HPs with broken rods will not be able to deliver any water (Arlosoroff et al., 1987). However, due to the almost universal poor quality of components in our sample, the regression analysis did not highlight component condition as a significant factor for functionality outcomes. Nevertheless, HP materials and conditions are an important factor when considering overall HP performance (see Supplementary materials Section 4 for pictures of components at selected sites). We find that rising main pipes and rods are in particularly poor condition overall.

The rising mains and rods do not meet design criteria as laid out in the India HP (Erpf, 2007) and Afridev handbooks (Baumann, 2007) at the majority of sites (Fig. 5). Sub-standard galvanising thickness is less effective at protecting the pipes from corrosion and is a particular problem at threaded pipe joints. The deterioration of pipe galvanising is more rapid in aggressive groundwaters, such as those found in Uganda (Bonsor et al., 2015; Casey et al., 2016), which explains the overall poor condition of rising mains and rods there. Sub-standard pipe wall thickness could be a result of poor manufacturing practice or, in the case of GI pipes, gradual corrosion for which the risk and rate is increased by inadequate galvanising. The use of low-quality materials in rising mains increases the likelihood of damage (Casey et al., 2016) for example, pipe perforation. The use of low-quality

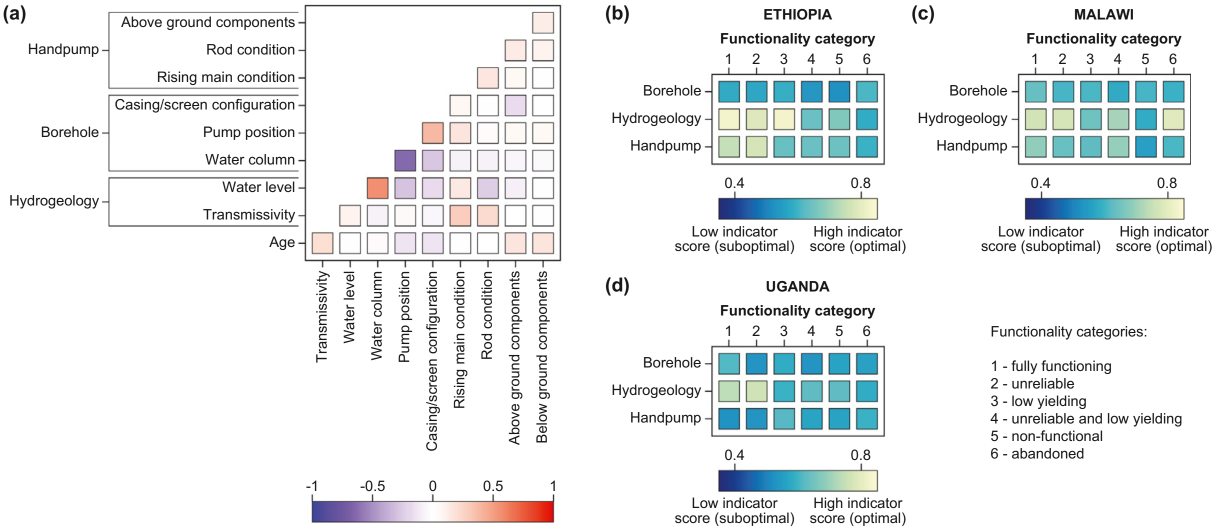

Fig. 6. (a) Correlation matrix of independent variables used in the regression models, black boxes indicate the three categories of independent variables used in the regression models. (b) – (d) Combined classes summarising the general state of hydrogeology (HG), borehole (BH) and HP components (PUMP) by functionality category in (b) Ethiopia, (c) Malawi and (d) Uganda. The combined physical classes are based on the groupings of independent variables in the black boxes shown in the correlation matrix in part (a).

Table 2

Multinomial and backwards and forwards step-wise multinomial regression results. A relative risk (RR) > 1 indicates the probability of an HPB being classed as either LY, UR or UR-LY rather than FF increases as the value of the independent variable increases. A RR < 1 indicates that the likelihood of an HPB being classed as either LY, UR or UR-LY rather than FF increases as the value of the independent variable decreases. Independent variables with a p-value < 0.05 are shown in bold and superscripts are as follows: ***p < 0.001; **p < 0.01; *p < 0.05. Italics indicate that the independant variable occurs in both the full model and step model. Also shown are the Akaike information criterion (AIC), deviance and empirical distribution function (EDF) which are estimates of relative model fit, a lower number suggests a better fit when comparing two models for the former two measures and a higher number suggests a better fit for the latter measure. The overall and category specific prediction accuracies are also shown when splitting the dataset 80 % for training and 20 % for a prediction.

Functionality category	Independent variable	Full model				Step model			
		RR	95 % confidence interval		p	RR	95 % confidence interval		p
2	Transmissivity	6.37e−01	3.35e−02	8.37	6.52e−01	7.89e−01	5.77e−02	9.37e+00	8.13e−01
2	Water level	3.20	1.27e−01	3.23e+03	2.45e−01				
2	***Casing/screen configuration***	**7.75e−02**	**1.45e−18**	**4.37e−03**	**1.05e−02****	**6.16e−02**	**9.28e−20**	**4.80e−04**	**5.31e−03****
2	**Pump position**	**1.16e−01**	**4.48e−05**	**6.26e−01**	**3.14e−02****				
2	**Water column**	**6.77e−02**	**2.61e−06**	**1.32e−01**	**7.09e−03****	1.56e−01	1.13e−03	1.20	6.35e−02
2	Above ground components	3.07	1.95e−01	4.07e+02	2.62e−01				
2	Below ground components	8.93e−01	6.65e−03	8.71e+01	9.10e−01				
2	Rising main condition	1.39	2.05e−01	9.25	7.43e−01	1.57	2.71e−01	8.05	6.51e−01
2	Rod condition	1.39	2.31e−01	7.87	7.39e−01				
2	HPB age	1.45e−01	8.05e−05	1.07	5.36e−02	2.02e−01	5.71e−04	2.13	1.10e−01
3	***Transmissivity***	**9.35e−02**	**1.59e−03**	**5.43e−01**	**1.78e−02****	**7.05e−02**	**1.71e−03**	**3.84e−01**	**8.00e−03****
3	Water level	1.31	7.42e−03	6.32e+02	7.90e−01				
3	**Casing/screen configuration**	1.47e−01	8.28e−17	1.46	5.48e−02	**1.28e−01**	**1.87e−17**	**4.00e−01**	**3.98e−02****
3	Pump position	3.52e−01	3.34e−04	1.15e+01	2.97e−01				
3	Water column	2.69e−01	2.45e−05	8.18	1.89e−01	2.93e−01	1.39e−03	4.52	2.19e−01
3	Above ground components	4.30	2.84e−01	5.32e+03	1.45e−01				
3	Below ground components	3.92	1.54e−01	3.51e+04	1.72e−01				
3	Rising main condition	1.56	2.10e−01	1.19e+01	6.56e−01	2.08	3.02e−01	1.38e+01	4.64e−01
3	Rod condition	4.63e−01	3.99e−02	4.07	4.41e−01				
3	**HPB age**	3.54	5.75e−02	5.66e+05	2.06e−01	**8.37**	**1.92**	**1.03e+07**	**3.36e−02****
4	***Transmissivity***	**1.38e−01**	**2.48e−03**	**9.66e−01**	**4.74e−02****	**1.29e−01**	**3.72e−03**	**8.84e−01**	**4.05e−02****
4	Water level	1.94	2.93e−02	1.27e+03	5.07e−01				
4	***Casing/screen configuration***	**4.34e−02**	**7.46e−22**	**1.32e−05**	**1.71e−03****	**3.31e−02**	**3.63e−23**	**8.85e−07**	**6.55e−04*****
4	Pump position	1.81e−01	2.39e−05	2.07	8.75e−02				
4	***Water column***	**3.60e−02**	**3.39e−08**	**1.18e−02**	**8.84e−04*****	**2.39e−02**	**7.14e−06**	**2.50e−02**	**1.90e−04*****
4	Above ground components	5.54	5.41e−01	9.19e+03	8.68e−02				
4	Below ground components	2.27	2.45e−02	8.56e+03	4.12e−01				
4	Rising main condition	2.53e−01	2.88e−02	1.86	1.69e−01	2.22e−01	3.63e−02	1.55	1.32e−01
4	Rod condition	1.49	1.86e−01	1.28e+01	6.89e−01				
4	HPB age	9.77e−01	1.92e−03	4.50e+02	9.81e−01	1.84	1.95e−02	1.76e+03	5.43e−01
N					93				93
AIC					249				232
Deviance					183				196
EDF					33				18
Prediction accuracy: dataset split 80/20 for training and prediction	Functionality category	1 2	3	4	Average	1 2	3	4	Average
	Prediction accuracy (%)	52.5 59.2	40	61.7	53.3	61.5 55.7	40	62.2	54.9

materials has been highlighted since at least the 1980s (Langenegger, 1989; Langenegger, 1994; Casey et al., 2016; Danert, 2022b). The use of inappropriate materials or poor-quality components also leads to problems with water quality, including high levels of iron which affects the acceptability of water for communities (Langenegger, 1989; Langenegger, 1994; Casey et al., 2016; Lewis and Chilton, 1989). In Malawi, the cutting of PVC rising main as a routine maintenance practice may contribute to reduced HP yield by introducing new frictions in the pipes and reducing pipe diameters around the new joints. The rethreading of GI pipes in Uganda and Ethiopia is likely to damage pipe galvanising increasing the vulnerability of the pipe to corrosion and damage, we observed significant levels of corrosion and damage around threads.

Overall pump quality deteriorates through our functionality categories (Fig. 6), particularly in Ethiopia (Fig. 6b) where both India HPs and Afridevs are used, and in Malawi (Fig. 6c) where Afridevs are used. The summary pump class values are lowest in Uganda overall (Fig. 6d) where only India HPs are used. Previous studies have highlighted rising main pipe condition as a cause of HP failure in Uganda (Klug et al., 2018; Casey et al., 2016) and elsewhere (Langenegger, 1994). The poor overall condition of India HPs is likely to be influenced by the challenge of conducting repairs as it is not classed as a VLOM HP (Arlosoroff et al., 1987). The corrosivity of groundwater in Uganda (Bonsor et al., 2015, Casey et al., 2016) also presents a significant risk for GI components. However, approximately 25 % of rising main pipes (top panel Fig. 5a) and rods (top panel Fig. 5c) in Uganda used PVC and stainless steel respectively reflecting efforts to address the issue of corrosion of HP components. It is likely that a combination of sub-standard rising main pipe materials, manufacture and inappropriate repair practice contributes to poor overall condition of both PVC and GI rising main components in all three countries.

4.4. Implications for rural water supply in sub-Saharan Africa

Our analysis highlights that there is no single underlying physical factor that determines functionality outcomes. However, we find that two factors are statistically important risk factors for poor functionality; transmissivity, and borehole configuration. We also found that rising main and pump rods were in poor condition across all functionality categories. Corrosion of GI components was pervasive and PVC pipes were often damaged.

In all three countries, there are a number of sites which are below the minimum transmissivity to sustain the design yield of a HP. The fact that these boreholes were commissioned may be related to the lack of hydrogeological capacity available to drilling contractors involved in the development of boreholes and the turnkey contracts and methods of procurement used by drillers (Liddle and Fenner, 2019). However, the underlying hydrogeology itself is also an issue. In Uganda, where failures attributed to hydrogeology were highest, low transmissivities make groundwater conditions challenging, which may require much more investment in borehole siting and/or drilling (Parry-Jones et al., 2001, Sloots, 2010, Tindimugaya, 2016). For some areas, even considerable additional investment in siting boreholes may not find locations that can easily support a HP, and water services and technologies which rely on other water sources, or which can accommodate lower yielding boreholes may have to be developed.

The variable transmissivity displayed across the three countries also has implications for the use of larger pumps that might be used for reticulated and/or piped water supplies or irrigation, including the use of solar pumping technology. To sustain a yield of 60 l/min (approximately 5 times the yield of a HP) the aquifer would require transmissivity of >9.5 m^2/day (Bianchi et al., 2020). In Ethiopia and Malawi, 57 % and 40 % of the sites sampled had transmissivity values below this threshold, respectively. In Uganda, the proportion was 80 % reflecting widespread low aquifer transmissivities. Thus, there are clear challenges for technologies such as solar water pumping in rural SSA and considerable investment is required to improve hydrogeological capacity and understanding prior to large-scale development of these technologies. Furthermore, detailed site investigations are required as standard practice before construction and installation of new technologies, such as solar, intended to be used for water supply and/or irrigation schemes.

Our results also highlight issues around borehole construction and configuration. Borehole construction has received little attention in the literature with one or two notable exceptions (Harvey, 2004; Liddle and Fenner, 2019) and is often assumed to be implemented to a satisfactory standard. However, we find that borehole construction and configuration has an important statistical relationship with functionality outcomes (Table 2), so meriting further investigation. The pressure for cost-cutting during construction may lead to the use of sub-standard borehole designs or reductions in the length of screened sections (Liddle and Fenner, 2019) which result in the productive parts of the aquifer being blocked out, leading to a less reliable water source. These issues can be addressed by supervision during construction and commissioning of boreholes, the use of contracts that incentivise good drilling and construction practice, and ensuring drillers have the capacity to apply good design practice and adapt standard borehole designs to the local hydrogeological conditions as and when necessary.

The use of good quality components in HPs is also very important. Problems associated with the use of GI components in particular are an issue that has been known about for many years (Langenegger, 1989, Langenegger, 1994). It is questionable whether GI should be used at all, but it certainly should not be used in areas where there is known to be an increased risk of corrosion (i.e. areas with low pH or high mineralisation). GI components should be regularly replaced according to maintenance schedules which take account of the risk of corrosion. Our results emphasise the importance of ensuring procurement of good quality materials that meet the design specifications and international standards laid out in the India HP and Afridev manuals. As components gradually fail and/or are replaced there is an opportunity to use better quality materials, most notably replacing GI rising main and rods with corrosion resistant alternatives. However, the use of corrosion resistant materials is not a panacea and can create other issues, including for example higher capital costs (e.g. for stainless steel as compared to GI) and galvanic corrosion if stainless and galvanised steel (including GI) are in direct contact (particularly when installed in saline groundwater). It is important that materials comply with international standards and replacement components meet these standards during routine maintenance. This can be a challenge as materials are commonly imported from India (Harvey, 2011; Danert, 2022c) and spare part supply is often separated from HP procurement (Harvey and Reed, 2006; Danert, 2022c).

Rising mains are not designed to be maintenance free but should form part of the maintenance schedule and be replaced periodically (Erpf, 2007, Baumann, 2007). However, such preventative maintenance is rarely if ever planned for, and generally the rising main is only repaired if a section fails. The use of better-quality components, particularly rising main pipes and rods, is a key area where coordinated action could make a tangible difference to the status of rural water supplies in SSA but this would need the buy-in of all stakeholders including national governments, multilateral organisations and, perhaps most importantly, manufacturers and standards agencies in India (Danert, 2022c). The importance of operation and maintenance of rural water supplies is well established in the literature (Klug et al., 2017, Baumann, 2006, MacAllister et al., 2020) but is often challenging in practice, particularly in remote rural contexts in SSA. In recent years a number of innovative approaches (e.g. Fundifix (Koehler et al., 2018), Uduma and Whave solutions (RWSN, 2019)) and initiatives (e.g. the UPTIME consortium (McNicholl et al., 2019)) have been developed to improve O&M and sustainability of rural water services (Koehler et al., 2018; RWSN, 2019) but none have yet been rolled out successfully on a large scale in SSA.

A detailed discussion of the factors that are required for effective operation and maintenance of rural water supplies is discussed elsewhere (Klug et al., 2017; Harvey, 2017; Fisher et al., 2015; Walters and Javernick-Will, 2015; Foster, 2013; Cronk and Bartram, 2017). However, our study identifies some areas of practice that can make a significant difference. When repairing rising mains and rods it is important to maintain the original position of the HP cylinder. If damaged sections are simply removed without being replaced the HP cylinder gradually moves up the borehole increasing the risk of the water level dropping below the HP cylinder position (see Fig. 5c and d), which might explain why HP cylinder position is an important risk factor in our multinomial analysis (Table 2). In Malawi, we also observed damaged sections of rising main pipes being cut and glued and back together. Cutting of PVC pipes and rethreading of GI pipes not only risks damaging the pipe but it also has the effect of gradually making the cylinder position shallower in the borehole. Furthermore, our methodology and functionality framework can be adapted to better diagnose the root causes of functionality issues. Forensic assessment of individual HPBs is necessary to understand the specific combination of factors that determine individual functionality outcomes. Forensic assessments should include at a minimum: measurements of water level, borehole and HP cylinder depth; a pumping test; and inspection of rising main, rods, seals and valves.

4.5. Definition of functionality

Our study demonstrates the utility of the nuanced definition of functionality developed by Bonsor et al. (2018) to help understand the importance of different physical factors, normally hidden, on functionality outcomes. Our definition has the benefit that it can also be used for binary assessments for large scale functionality surveys, including national asset surveys (Carter and Ross, 2016). While the functionality classifications remain a snapshot in time, the low yield and unreliable categories reveal factors that determine the ability of a HP to perform over the long term as specified by design standards. The delay between initial HPB classification and detailed investigations, which was an unavoidable part of our study, perhaps makes it unsurprising that we did not find a strong statistical relationship between functionality status and HP components in our multinomial regression, as it is possible that these components may have changed in the intervening period. At the very least, it is recommended that seals and rubber valves are replaced annually (Erpf, 2007, Baumann, 2007). The next step of our analysis is to examine how the underlying physical factors we have investigated here relate to downtime and failure rates of HPBs (Carter and Ross, 2016), for which we collected qualitative data during our second survey.

5. Conclusions

Using a nuanced classification of functionality, we investigated the physical factors underlying the functionality status of 145 HPBs across Ethiopia, Malawi and Uganda. The functionality classification takes into consideration the HP yield, with respect to the maximum design yield of a HP, and reliability, which was defined as the ability of a HP to deliver a reliable yield with a downtime of <30 days per year. The classification provided a systematic framework with which to inspect HP status and examine the influence of three broad categories of physical factors on functionality outcomes. We find that characteristics of hydrogeology, borehole construction and HP condition are generally more favourable in the fully functional category and less so in the non-functional or abandoned categories. Using multinomial regression analysis, we found that: (1) aquifer transmissivity is a statistically significant risk factor for the classification of HPBs as low yield; (2) the layout and configuration of the borehole, in terms of screen/casing position, HP cylinder position and water column, were important factors for classification as unreliable; and (3) a combination of aquifer transmissivity and borehole layout and configuration were important risk factors for classification of boreholes as low yield and unreliable. Furthermore, we found that HPs were in poor condition overall which has an inevitable influence on the performance of HPs. India HPs in particular were found to have significant levels of corrosion and the GI riser pipes and rods used often did not conform to design standards in terms of galvanising and pipe wall thickness. Both factors increase the risk of damage to components which can have consequences on the yield and reliability of HPBs.

Our study provides important insights into the contribution of different physical factors to HPB functionality and a new, more detailed, multi-country dataset of HP functionality and condition than was previously available to the research community, NGOs, and governments. The results highlight the importance of hydrogeology, borehole construction and configuration, and component condition in determining functionality outcomes. Our study also provides pointers for improving the functionality of HPBs which are a resilient form of rural water supply (MacDonald et al., 2019, MacAllister et al., 2020) and will remain an important source of water for many communities in SSA for years, perhaps decades, to come (Carter, 2021). Our study has implications for use of HPBs in the rural water supply sector now and in the future including: increased investment in hydrogeological skills and expertise; borehole siting, drilling and construction supervision; and a greater emphasis on the quality of HP components and routine preventative maintenance.

Data availability

The data used in this analysis are available from the National Geoscience Data Centre (NGDC) at the following link: doi:https://doi.org/10.5285/cdbca137-0bb3-4281-b872-399a4df8e946.

CRediT authorship contribution statement

DJ. MacAllister – Conceptualization, Investigation, Data curation, Formal analysis, Methodology, Project administration, Writing – original draft

D. Nedaw - Investigation, Data curation, Writing – review & editing

S. Kebede – Conceptualization, Funding acquisition, Writing – review & editing

T. Mkandawire - Writing – review & editing

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H. Fallas – Conceptualization, Methodology, Project administration, Writing – review & editing

A.M. MacDonald – Conceptualization, Methodology, Funding acquisition, Project administration, Writing – review & editing

Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing – original draft; Writing – review & editing.

Data availability

Data is available on a repository.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary materials

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