Maintenance Practices and Water Quality from Rainwater Harvesting in South-West Uganda

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Abstract: Rainwater harvesting (RWH) provides household water supply to rural and peri-urban populations that do not have access to centralized water services. The climate in south-west Uganda is particularly well suited to rainwater harvesting due to bi-annual rainy seasons, which allows for collection of rainwater to occur over two periods throughout the year. Water quality from RWH, however, depends on how well risk of contamination, from catchment to consumption, is managed. Using a mixed-methods approach, we assessed the maintenance practices and water quality of 20 rainwater harvesting installations in Uganda in the dry and rainy seasons. Both domestic and institutional RWH systems were assessed. Sanitary surveys, site inspections, key informant interviews and physiochemical and bacteriological tests were conducted to identify the factors that have an impact on water quality. Water quality test results were compared to guidelines recommended by the World Health Organisation (WHO). We looked at measures that can reduce the risk of contamination across the water chain. We found that water quality at 75% of the sites met WHO standards. At these sites, end-users reported that they cleaned systems at least twice a year. Where training on system maintenance had been carried out, end-users reported more regular cleaning and maintenance of systems. Sanitary surveys highlighted an absence of first-flush or pre-filtration as the most prevalent risk of contamination. Overall, we found that both access to technical specialists and capacity-building activities led to well-maintained RWH systems that provide acceptable water quality at both a household and community level.

Keywords: decentralized water; domestic rainwater harvesting; rural and urban water supply; water quality.

Introduction

Only 14% of Uganda's population has access to potable water managed by the National Water and Sewerage Corporation (NWSC), the majority of which live in urban environments (WHO/UNICEF, 2015). In the absence of NWSC-provided water in rural environments, hand-dug shallow wells, groundwater collection schemes, gravity-flow schemes and rainwater harvesting are all practiced by rural and peri-urban communities in Uganda (Parker *et al.*, 2010). Rainwater harvesting (RWH) supplies water directly to homeowners, reducing the labour time required to collect and transport water. Western Uganda's climatic conditions are well suited to domestic rainwater harvesting as the bi-annual rainy seasons allow for well-distributed collection of rainwater throughout the year. However, RWH is under-utilised with only 1% of the rural population using it. Barriers to the adoption of RWH in Uganda include challenges with asset maintenance and water quality management (Staddon *et al.*, 2018).

The management of water quality from RWH is a global challenge. Kohlitz & Smith (2015) find that users from Fiji would benefit from improved education and awareness on identifying risks and techniques to manage them. In a survey of RWH in rural Nepal, Domènech, Heijnen & Saurí (2012) find that poor performance of rainwater harvesting systems is attributed to lack of curing during tank construction, lack of maintenance and deficiencies in technical design. Few studies on RWH assess users' practices and how they respond to the responsibility of operation and maintenance of RWH. Identifying practices that can improve water quality from RWH may help to improve user confidence in the technology.

RWH, an improved water source, uses the roof of a building to collect rainwater for a variety of domestic or productive purposes including cooking, cleaning, washing and drinking (Sturm *et al.*, 2009). Typically, existing household rooftops are used to capture rainfall, which is then directed into gutters that carry the rainwater into either cement or plastic storage tanks. When implemented correctly, RWH can provide good quality water in terms of microbial and physiochemical quality (Parker *et al.*, 2010; WHO, 2008). There are, however, strong links between the quality of water provided by RWH systems and whether the system has been maintained (Rahman, 2017). To date, numerous studies have found that the quality of rainwater is directly related to the cleanliness of catchments, gutter and storage tanks (Abdulla & Al-Shareef, 2009; Baguma *et al.*, 2010; Campisano *et al.*, 2017; Misati *et al.*, 2017). This cleanliness can be ensured by regular maintenance tasks such as cleaning gutters, emptying filters, and bi-annual cleaning of the inside of water storage tanks (Kohlitz & Smith, 2015). Overall upkeep of the system such as repairing external cracks in tanks and guttering has also been found to be critical for the collection of good quality water (Domènech, Heijnen & Saurí, 2012).

Risks to the contamination of rainwater arise between the point of collection (roof catchment) and consumption. Quality of rainwater can deteriorate at any point in the water chain. Wind-blown dirt, leaves, and animal faeces can contaminate the catchment area (rooftop) and guttering. Unprotected cisterns, and contaminated storage tanks can also impact water quality (Despins, Farahbakhsh & Leidl, 2009). These risks can be identified and mitigated by regularly conducting sanitary surveys. Sanitary surveys are recommended by the JMP as party of a comprehensive Water Safety Plan (WSP), providing a simple, risk-based assessment of water sources and are structured to provide clear guidance for remedial action to improve water systems (Luby *et al.*, 2008). Misati *et al.* (2017) assess whether sanitary surveys can replace water quality testing but find that a more suitable approach is for sanitary surveys to help users identify potential hazards.

The objective of this research was (a) to identify the most common risks associated with the contamination of rainwater (b) to identify the relationship between the results of sanitary surveys and the quality of water provided by RWH systems and (c) to identify the RWH system management practices that have the potential to reduce the risk of contamination in RWH systems. Twenty sites for assessment were selected by local partners. Sites that had RWH tanks for at least two years, and where users were willing to participate in the study, were selected. In the urban Kakoba division of Mbarara, ten RWH systems, installed by a private plumber, were selected. In rural Keeru, Rubanda District, two sites were installed by end-users themselves and eight RWH systems were installed in parallel with end-user training by the Kigezi Diocese Water and Sanitation Project (KDWSP).

Methods

A mixed methods evaluation including site inspections; key informant interviews, sanitary surveys and water quality testing, was used to assess the sites. Sanitary surveys, site inspections and water quality testing were carried out twice, in September 2018 (rainy season) and July 2019 (dry season).

Site Inspections

Inspections were carried out at each site and included a checklist of eight questions on the physical attributes such as roof material & size, number of roofs in the catchment, type of guttering, tank material & volume and whether the site was a community institution or a private household.

Sanitary Surveys

Sanitary surveys for RWH consist of ten questions with 'yes' or 'no' answers. 'Yes' answers indicate that there is a risk of contamination. Each 'yes' is assigned 1 point. Each 'no' answer scores 0 points. The maximum risk of contamination (ROC) score for RWH is 10. A higher score corresponds to more hazards present during the survey and thus a greater risk that drinking water is contaminated by faecal pollution (Mushi *et al.*, 2012).

Sanitary Survey Questions for Rainwater Harvesting Sites according to the WHO (2008).

(1) Is there visible contamination on the roof catchment area?
(2) Are the guttering channels dirty?
(3) Is a method of diverting the first-flush present?
(4) Is a filter or any form of water treatment used prior to storage?
(5) Is there any source of pollution around the tank or water collection area?
(6) Is there an opening to the tank that is not covered?
(7) Is there any defect in the walls or top of the tank which could let in water?
(8) Is the tap leaking or otherwise defective?
(9) Is the cement floor under the tap defective or dirty?
(10) Is the water collection area inadequately drained?

A Shapiro-Wilk's test ($p > 0.05$) showed that the sanitary survey results for the dry season were normally distributed (p=0.085). The results for the wet season, however, were not normally distributed (p=0.03) (Razali & Wah, 2011). As a result, and due to the small sample size (n<20) the non-parametric, Wilcoxon signed-rank test was used to compare the results between the two seasons (McDonald, 2014).

Water Quality Testing

Samples were collected in 300ml sterile plastic sample bottles and were tested for pH, turbidity, colour and thermotolerant coliforms (TTC). Water quality tests were done using the Oxfam-DelAgua testing kit (Wiltshire, UK), which uses the membrane filtration method to determine the number of TTCs. Samples were passed through a sterile filter, which was then placed on a pad soaked in liquid growth medium. Samples were then incubated at 44^{o}C for 16 hours, which ensured only thermotolerant bacteria grew. All samples were tested at both time points, in duplicate, within 4 hours of collection to ensure accuracy of results. pH was measured using phenol red. Turbidity was measured in-situ using a turbidity tube. Positive and negative controls were included in the analysis. Results were included only if negative controls were blank.

Data was manually recorded using Microsoft Excel 2011 Version 16.37 (Redmond, Washington, USA) and analysed using and IBM Statistical Package for Social Sciences Version 26.0.0.0 (SPSS Inc. Chicago, IL, USA). Microbiological water quality results were compared to WHO's risk classification levels. Fisher's exact test, appropriate to compare was used to assess the relationship between TTCs and turbidity (McDonald, 2014). The significance level was set at $p < 0.05$.

Key Informant Interviews

Interviews were carried out with twenty end-users and five stakeholders involved in the management of RWH systems. A semi-structured interview approach was adopted as recommended by Bryman (2008). An interview guide can be found in the appendix. The interview guide included 18 questions on demographics, RWH system cost, functionality and management practices, alternative sources of water and comparative cost, availability of water and perception of water quality. A translator was used where English was not spoken. Interviews were recorded using a Dictaphone, then transcribed and coded using Nvivo (QSR Int. Doncaster, Victoria, Australia). Key quotations were extracted for common themes. The grouped themes were then assessed in order to link them to the findings from the quantitative data. The study was approved by the University of Cambridge Department of Engineering Ethics Review Board and informed consent was obtained before each interview.

Results and Discussion

Site Inspection

Table 1 - Physical properties and demographics of users at domestic and institutional rainwater harvesting sites in south-West Uganda (n=20)

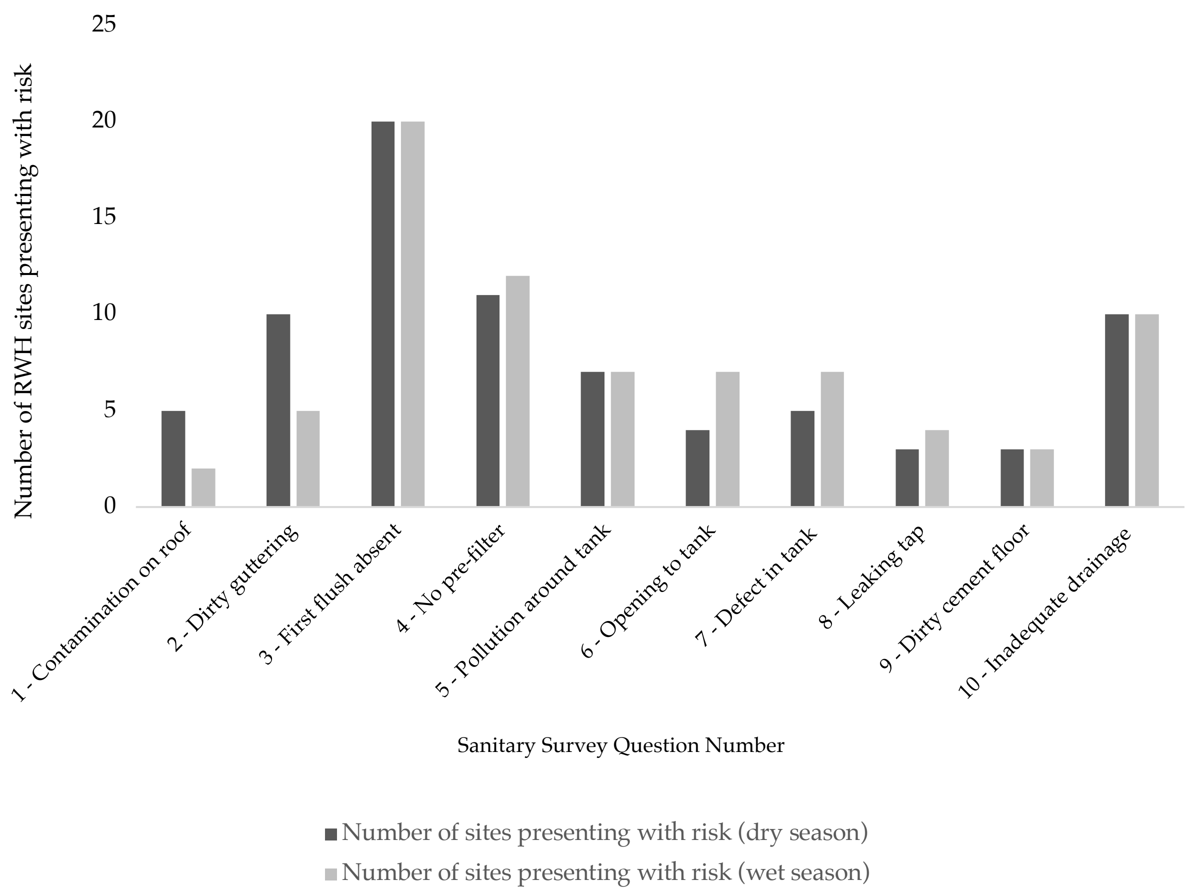
Site #	Urban/ rural	System Installed by	Institution/ Household	Roof Type	Total Catchment area (m^2)	Tank type	Total Tank Volume (m^3)	Number of people served by RWH system	Frequency of RWH system cleaning	Trained in RWH maintenance	Water treatment type
1	Urban	Local Plumber	Institution	Corrugated metal	250	Plastic	68	20	Twice a year	No	Candle filter
2	Urban	Local Plumber	Institution	Corrugated metal	750	Ferrocement	360	85	Never	No	Boiling
3	Urban	Local Plumber	Institution	Corrugated metal	150	Ferrocement	40	40	Twice a year	Yes	UV
4	Urban	Local Plumber	Institution	Concrete tile	900	Ferrocement	180	500	Weekly	No	Chlorine
5	Urban	Local Plumber	Household	Concrete tile	100	Plastic	10	5	Twice a year	No	Candle Filter
6	Urban	Local Plumber	Household	Corrugated metal	150	Ferrocement	180	6	Twice a year	No	Boiling
7	Urban	Local Plumber	Household	Concrete tile	150	Ferrocement	5	4	Twice a year	No	Boiling
8	Urban	Local Plumber	Household	Corrugated metal	75	Plastic	5	5	Weekly	Yes	Boiling
9	Urban	Local Plumber	Household	Corrugated metal	40	Plastic	4	4	Twice a year	No	Boiling
10	Urban	Local Plumber	Household	Standing seam metal	480	Ferrocement	10	35	Twice a year	No	Boiling
11	Rural	KDWSP	Institution	Corrugated metal	100	Ferrocement	10	150	Weekly	Yes	Boiling
12	Rural	KDWSP	Institution	Corrugated metal	264	Plastic	40	700	Monthly	Yes	Boiling
13	Rural	KDWSP	Institution	Corrugated metal	120	Ferrocement	10	100	Monthly	Yes	Boiling
14	Rural	KDWSP	Institution	Corrugated metal	60	Ferrocement	20	150	Monthly	Yes	Boiling
15	Rural	KDWSP	Household	Corrugated metal	30	Ferrocement	4	3	Monthly	Yes	Boiling
16	Rural	KDWSP	Household	Corrugated metal	60	Ferrocement	4	5	Monthly	Yes	Boiling
17	Rural	KDWSP	Household	Standing seam metal	60	Ferrocement	4	8	Weekly	Yes	Boiling
18	Rural	KDWSP	Household	Corrugated metal	32	Ferrocement	4	8	Monthly	Yes	Boiling
19	Rural	Home-owner	Household	Corrugated metal	24	Informal Jar	4	6	Never	No	Boiling
20	Rural	Home-owner	Household	Corrugated metal	48	Informal Jar	4	6	Never	No	Boiling

12 of the 20 sites were domestic, and 8 were community institutions including churches, hospitals, schools and community centers (Table 1). Gutters were either made from HDPE or galvanized sheet metal. 75% (n = 20) of sites used galvanized corrugated metal for roof catchment, 15% used concrete tile and 10% used standing seam metal panels. Catchment areas ranged from 60–900m^2 for institutions and 24–150m^2 for domestic installations. 25% (n = 20) of tanks were plastic, 65% ferrocement and 10% were informal mortar jars, a low-cost, low-volume alternative to formal RWH which are typically constructed by end-users.

Risks of Rainwater Contamination

The most common risks across the test sites were dirty guttering (dry=10, wet=5, n=20), a lack of pre-filtration (dry=11, wet=12, n=20), first-flush (dry=20, wet=20, n=20), and inadequate drainage (dry=10, wet=10, n=20). All of the RWH systems installed by KDWSP had a basic large particle filter: a low-cost, mesh coarse leaf filter at the storage tank opening. No other sites had a pre-filter installed. Quality of construction for the ferrocement tanks was high. Less than 35% (n=20) of all sites presented with defects (wet season). Drainage at water access points was inadequate at 50% (wet & dry seasons, n=20) of sites (Figure 1). Typically, more frequent rainfall in the wet season washes away debris which can account for better condition of RWH systems in the wet season, however, for this set of results, the difference in overall sanitary survey results between the wet and dry seasons was not statistically significant (p = 1.00). Nonetheless, more sites presented with contaminated roofs and dirty guttering during the dry season than wet.

Figure 1 – Dry and wet season sanitary survey results for rainwater harvesting sites in south-West Uganda (n=20)



Rainwater Quality

In total, 80 water samples were tested. The WHO's guidelines on drinking water quality classify TTCs into four risk categories: conforms to guidelines (<1 CFU/100ml), low risk (1-10CFU/100ml), medium risk (>10-100CFU/100ml, and high risk (>100 CFU/100ml) and state that TTC count per 100ml should be zero (WHO, 2008). We found that 75% of sites had acceptable water quality. 25% of sites tested positive for TTCs in the WHO medium risk category: 10 - 100 CFU/100ml (Table 2). All of these sites also had a turbidity greater than 5 NTU in both seasons. WHO guidelines recommend turbidity to be less than 5 NTU (WHO, 2008). There was a statistically significant correlation between median turbidity and the presence of TTCs (dry: p=0.031, wet: p=0.033) indicating that sites than exhibited poor water quality, did so by both metrics.

Presence of TTCs is often related to seasonal influences such as rainfall (WHO, 2008). Nonetheless, 4 of the 5 sites that tested positive for TTCs in the 2018 visit (wet), did so also in the 2019 visit (dry). The pH recorded at each test site lay in the WHO's acceptable range of 6.5 - 8.5. All of the RWH systems installed by KDWSP conformed to WHO guidelines. The two informal RWH rural sites with mortar jars both tested positive for TTCs and had high risk of contamination scores.

*Table 2- Physio-chemical and bacteriological results for rainwater harvesting sites in south-West Uganda (n=20). *Geometric mean*

Site Number	**Site Description**	**Risk of Contamination Score (max = 10)**		**Ph Median (n=2)**		**Turbidity (NTU) Median (n=2)**		**CFU/100ml Mean* (range) (n=4)**	
		Dry season	**Wet Season**	**Dry season**	**Wet Season**	**Dry season**	**Wet season**	**Dry season**	**Wet season**
1	Urban	2	2	6.8	6.9	5	10	<1	<1
2	Urban	7	7	8.2	8.2	20	10	23.2 (12 – 50)	9.9 (6 - 20)
3	Urban	2	2	6.8	6.8	5	10	<1	<1
4	Urban	3	3	6.8	7	0	0	<1	<1
5	Urban	2	2	8.2	8.1	5	5	<1	<1
6	Urban	6	7	8.2	8	5	20	21.6 (12 – 40)	17.1 (8 – 30)
7	Urban	3	4	6.8	6.8	5	5	<1	<1
8	Urban	3	4	6.9	6.8	2.5	10	<1	<1
9	Urban	6	7	7	7	10	15	53.5 (36 – 70)	29.1 (15 - 50)
10	Urban	4	4	7.2	7.2	0	0	<1	<1
11	Rural	2	3	6.8	7	0	0	<1	<1
12	Rural	1	3	7	6.9	0	0	<1	<1
13	Rural	2	3	7.2	7.4	0	0	<1	<1
14	Rural	2	1	8.1	8.2	0	0	<1	<1
15	Rural	4	5	6.9	6.9	0	0	<1	<1
16	Rural	1	1	8.1	8	0	0	<1	<1
17	Rural	2	2	6.8	6.9	0	0	<1	<1
18	Rural	1	4	8.1	8.2	0	0	<1	<1
19	Rural	7	8	6.9	6.9	20	20	25.2 (16 – 40)	39.8 (28 - 50)
20	Rural	7	6	6.9	6.9	0	20	<1	64.67 (36 - 120)

Sites that presented positive for significant turbidity (above 10 NTU) and TTCs all had 'Risk of Contamination' (ROC) scores above 6. This suggests sanitary surveys could provide a good indicator of potential hazards, as was found by Misati *et al.* (2017). Further research and water quality testing should be carried out to establish how sanitary surveys can contribute to the comprehensive risk management of rainwater.

Rainwater Harvesting Management and Maintenance Practices

Institutions vs Household

Trends in frequency of tank cleaning were similar at both institutions and households. At institutional sites, more people were served by each RWH systems, however, responsibility for maintenance fell on individuals charged with general building maintenance. A lack of clearly defined roles of responsibility at institutional sites was cited as a barrier to maintenance. In contrast 'pride of tank' was cited as an incentive to regularly maintain tanks in the household sites.

Maintenance Practices

85% of interviewees stated that either they themselves or a technician maintains and checks on their RWH tanks at least bi-annually. Users of the eight RWH systems installed by the KDWSP reported that they felt well-informed on how to maintain and clean their systems. KDWSP asserted that all installations were carried out in parallel with user-training on tank construction and system maintenance. One interviewee summarized that 'if a repair is needed on a tank, I do it myself. I can even offer my services to my neighbor because I have been trained'. Maintenance practices cited by interviewees included 'washing leaves away', 'cleaning the inside of the tank' and 'cleaning around the tap'.

At sites where users were not trained on maintenance, if blockages occurred, either they would contact the installing plumber to do repairs, or some institutional sites had on-site staff to maintain tanks. The most common repairs required by interviewees were 'replacing guttering' (30%, n=20) and 'replacing filters (25%, n=20). The two users of the RWH mortar jar sites in the rural setting had received no capacity-building support and reported never cleaning their systems. At both sites, users cited 'lack of awareness' and 'high cost' as deterrents to maintaining and repairing their RWH systems.

Users at 3 sites that presented with TTCs reported that they never cleaned their RWH systems and none had been trained in RWH maintenance. No pre-filtration was used at any of these sites and all catchment areas presented with debris. Homeowners/site managers had not been trained on RWH system maintenance and did not have any support from an intermediary organisation with specialism in rainwater-harvesting. This suggests that a lack of training can lead to poor maintenance of systems which in turn can increase the likelihood that rainwater is contaminated. In accordance with findings by Domènech, Heijnen & Saurí (2012), we found that where poor quality rainwater was detected, it was associated with poor cleaning and management of RWH systems.

At all sites where end-users reported either weekly or monthly cleaning of RWH systems and where systematic capacity-building practices had been implemented in parallel with the construction of RWH systems, tests indicated acceptable water quality. This suggests that capacity-building activities have a positive impact on how well systems are maintained and can reduce the ROC. Additionally, all of these sites had a basic pre-filter installed, suggesting that simple interventions such as installing a pre-filter and regular cleaning can improve the likelihood that water meets WHO standards. This filter was often made my end-users themselves, constructed from locally available buckets, pierced with holes and covered with a mesh.

Representativeness

In Rubanda, the Ministry of Water and Environment estimates that only 1908 people or 1% of the population is served by RWH (MWE, 2019). In this region, the KDWSP is the most prominent supporter of RWH, having installed over 800 tanks since the mid-1990s, suggesting that many of the RWH users in the region have been installed in line with the KDWSP approach (Danert & Motts, 2009). In Mbarara, it is estimated that 10275 people are served by RWH, about 4% of the population (MWE, 2020). These users can be differentiated into formal (as are those urban users involved in this study) and opportunistic users, where water is diverted into whatever container is available (MWE, 2020). Given that the participants of the study self-selected, there is potential that the data set of this study does not represent the communities in question, as it is likely that the RWH systems in the study were of better quality, and better maintained than that typical RWH system from the communities in question.

Limitations of Study

The results of this study are limited as surveys and test results were only conducted at two points across an 11-month period in time. The small sample size limits the applicability of the findings. Water was sourced from the tap of the RWH tank and not at the point of consumption, where further contamination could occur. The sanitary survey used in this study weighted all risks equally, but there is research to suggest that some risks are more likely to cause contamination than others (Misati *et al.*, 2017). Further research could identify which risks have the strongest correlation to poor water quality and could look at developing weighted ROC scores. Additional research could analyse further the effectiveness of the interventions highlighted in this study in ensuring good water quality from RWH.

Conclusions

We carried out a mixed-methods evaluation of RWH system monitoring and maintenance practices at 20 installation sites in south-west Uganda to understand the risks to contamination of rainwater and to identify measures that can reduce these risks. The most prevalent risks included a lack of pre-filter or first-flush, dirty guttering and inadequate drainage. Overall, presence of TTCs was low and most sites had low 'risk of contamination' scores. Where high turbidity and presence of TTCs was detected, all sites had high ROC scores.

The sanitary survey, microbiological and physiochemical test results indicate that the presence of an intermediary organisation (KDWSP) that guides installation, while carrying out capacity building on RWH system maintenance, can mitigate the ROC to rainwater. It is not clear whether the good water quality exhibited by the systems installed by the KDWSP was due to the presence of a pre-filter, good maintenance, or training of end-users, but it does appear that overall, the proactive role of the intermediary organisation reduced the ROC of the collected rainwater.

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