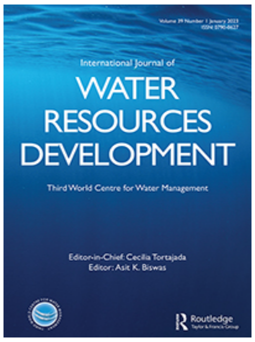

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Conventional and makeshift rainwater harvesting in rural South Africa: exploring determinants for rainwater harvesting mode

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ABSTRACT

In underserved rural areas, domestic rainwater harvesting has been gaining importance as an alternative water source. In rural South Africa, however, less than 1% of households use conventional rainwater harvesting systems. Instead, a household survey in KwaZulu-Natal reveals that many households harvest rainwater in a makeshift manner, using homemade gutters and drums. Statistical analysis shows that high income, a brick house with straight gutters and good water services facilitate conventional rainwater harvesting, while a household with only round huts is easily trapped into makeshift rainwater harvesting. For upscaling rainwater harvesting in rural areas, housing types need to be considered.

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KEYWORDS
Rainwater harvesting; household water insecurity; household survey; round hut; KwaZulu-Natal; Bayesian

Introduction

Rainwater harvesting (RWH) as a water security strategy

Domestic RWH has gained worldwide importance as an alternative water source in the face of increasing water shortages and household water insecurity (HWI) (Haque et al., 2016; Helmreich & Horn, 2009; Musayev et al., 2018; Yannopoulos et al., 2019). Starting from the mid-20th century, RWH systems and techniques have been increasingly implemented in numerous countries around the globe as a strategy to reduce the dependence on surface waters and aquifers (Santos & de Farias, 2017; Yannopoulos et al., 2019). Where climate change will likely aggravate the pressure on freshwater resources, RWH can help reduce HWI even in arid regions (Musayev et al., 2018). The term 'rainwater harvesting' is defined as the concentration, collection, storage and use of rainwater runoff for both domestic and agricultural purposes (Gould & Nissen-Petersen, 1999). Domestic RWH refers to rainwater that is used for domestic purposes, garden-watering and small-scale agriculture (Kahinda et al., 2007).

Previous studies have explored the potential of RWH systems for helping households meet their water demand and cope with water stress (Balogun et al., 2016; Lee et al., 2016). In a climate with seasonal rainfall, RWH can help augment water supply in the dry season

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(Santos & de Farias, 2017; Subba et al., 2017). In rural areas, RWH can serve as the main water source when water availability from other sources is critically low (Balogun et al., 2016; Yannopoulos et al., 2019) and when households are underserved by municipal infrastructure (Elgert et al., 2015; Sámano-Romero et al., 2016). Domestic RWH is one strategy of rural households to increase their range of available water sources (Kahinda et al., 2007; Lopes et al., 2017) and thereby improve their water security and reduce their dependence on water services (Lee et al., 2016). Importantly, RWH reduces the burden of having to collect water at distant public taps, wells or surface water sources (Elgert et al., 2015; Kahinda et al., 2007), and the health risks associated with carrying water (Geere et al., 2010). It is therefore especially advantageous in rural dispersed settlements with an unfavourable topography and underdeveloped infrastructure, such as rural South Africa (Kahinda et al., 2010).

Domestic RWH in rural South Africa

Based on a household survey in rural KwaZulu-Natal (KZN), South Africa, Lebek et al. (2021) found the dominant underlying causes of HWI in the study area to be the unequal provision and unreliability of municipal water services. Water infrastructure is often lacking or not well maintained. Use of alternative, unimproved water sources/surface water (streams, rivers or springs) is not supported by the municipality and such water sources are often highly polluted. Diversification of water sources can enhance water security of households (Kahinda et al., 2007, 2010; MacAllister et al., 2020). In the study area, domestic RWH is an important alternative water source that is valued by rural communities. This is the case in KZN in general, where rooftop RWH is widely used for drinking water (Kahinda et al., 2007).

The South African government and non-governmental organizations (NGOs) have been promoting RWH (Kahinda & Taigbenu, 2011). In the past, the Department of Water Affairs (DWA) has given financial support to indigent households towards the cost of RWH tanks and the implementation of RWH systems (Dobrowksy et al., 2014; Kahinda et al., 2007). However, despite the high potential in rural South Africa, institutional, legal and financial factors have prevented an upscaling of RWH (Kahinda & Taigbenu, 2011). Fewer than 1% of rural households use RWH tanks as their main water source (Kahinda et al., 2010). Still, RWH is part of everyday life for many rural households. In rural KZN, the first author observed a range of different RWH practices that might be considered makeshift. Households collect rainwater in drums or dishes, directly into the containers or from roof surfaces through mostly homemade gutters and waterspouts. Such makeshift RWH practices have been neglected in previous studies on RWH, despite their apparent importance for water security, which is the motivation for the present study.

Exploring makeshift and conventional RWH

We define the way in which a household harvests rainwater as the *RWH mode* (conventional or makeshift RWH). In our case study, *conventional RWH* from rooftops denotes the collection of rainwater with regular, established RWH systems, that is, large, plastic rainwater tanks with a volume of 2000, 4000 or 6000 L and industrially manufactured, off-the-shelf gutters. This corresponds to the understanding of Kahinda and Taigbenu (2011), who define a domestic RWH system as one that collects water from rooftops or other surfaces and stores it in above- or underground tanks for domestic use. We define *makeshift RWH* as the collection and storage of rainwater in drums (usually 210 L) or dishes that are in some cases connected to homemade, improvised gutters and water-spouts made from corrugated iron, plastic bottles or wood.

RWH has implications for household water security aspects, including health and sanitation and water-related productive activities. In particular, RWH can pose a health risk for water users; without the necessary (chemical and biological) treatment, RWH can contribute to the spreading of water-related diseases (Kahinda et al., 2007). These water quality and health concerns are related to dust and chemical pollution washed out of the air, chemical or microbial contamination from rooftops by heavy metals or organic matter such as bird droppings, bacterial growth inside tanks, and insect vectors breeding inside tanks (e.g., mosquitoes that transmit malaria) (Dobrowksy et al., 2014; Kahinda et al., 2007). Whether these risks take effect depends on the design and level of maintenance and cleaning of the RWH system, rainwater use (potable uses versus non-potable uses) and water treatment (e.g., with chlorine). Two studies of rainwater quality in South Africa indicate that water from RWH tanks is not within standards for potable drinking water and needs to be treated before use (Chaplot et al., 2018; Dobrowksy et al., 2014). While flushing the rooftop with the first millimetres of rain and diverting this water would improve physicochemical rainwater quality in the tank (Gikas & Tsihrintzis, 2012), diverting devices have not been installed in rural South Africa (Kahinda et al., 2007). Despite the health risk, however, RWH can greatly improve health and sanitation by contributing to the available water sources of a household (Fry et al., 2010) and enhance small-scale productive activities of rural households, such as gardening and brick-making (Kahinda & Taigbenu, 2011).

Previous studies on the implications of domestic RWH from rooftops for productive activities and health have only considered conventional RWH, while makeshift RWH practices have been neglected. In contrast, we begin with the premise that it makes a difference for water security whether the rainwater was harvested in a conventional or a makeshift manner. Therefore, we ask what role the RWH mode plays for aspects of HWI. In particular, we compare the effects of conventional and makeshift RWH for health and sanitation and agricultural activities.

Moreover, we aim to investigate the underlying reasons for the differences in RWH mode among rural households. Fisher-Jeffes et al. (2017) pointed out the scope for research on social drivers for RWH uptake. Staddon et al. (2018) investigated the reasons for the adoption of domestic RWH in central Uganda. Kahinda and Taigbenu (2011), in their study of the challenges of and opportunities for upscaling of RWH in rural South Africa, ask why only few rural households have implemented RWH systems so far, despite its high potential. The study did not consider makeshift RWH. Yet, our KZN household survey showed that over two-thirds of the participating households *did* practice RWH, but not by use of conventional RWH tanks. Our question therefore is: Which factors determine the RWH mode of a household? We believe that a differentiated view of RWH modes can help one to understand the prospects of and barriers to further dissemination of RWH in rural South Africa.

Data and methods

This study is based on two different household surveys from 2018 that hold data on domestic RWH and aspects of household water security. We use data from the General Household Survey (GHS), which is conducted annually by Statistics South Africa (StatsSA), and from the aforementioned household survey that the first author conducted in rural KZN. While the KZN survey is restricted to 67 households in a small study area, the GHS covers private households in all nine provinces of South Africa. The GHS aims to measure the level of development and performance of government programmes and projects and compile indicators of education, living standards and service delivery. It is not related to a specific season (wet or dry). The GHS comprises 213 questions in 10 different sections on, *inter alia*, health and general functioning, household information, including water and sanitation, health, welfare and food security, and household livelihoods. The KZN survey comprises 52 questions on different aspects of household water security, with a focus on water collection, domestic water use, water treatment, sanitation and hygiene, and water-related health. Information on RWH in the GHS is limited to a question on the main source of *drinking* water, where *RWH tank* is one of the possible answers. It does not hold information on RWH for other purposes, or on makeshift RWH. In comparison, the KZN survey provides data on the presence of any kind of RWH system, whether or not it is the main source of water, the RWH mode (conventional or makeshift), and what the rainwater is used for.

Data and data processing

Study area

The study area is a rural area in Ward 1 of the uMvoti Local Municipality in KZN. It lies within the former homeland KwaZulu and is now officially state-owned under tribal authority. It has a size of roughly 52 km^2 and an elevation range of 600 masl. Land cover in the study area consists mainly of pastures and dispersed settlements with associated small-scale cropland. There are no commercial farms in the area. Close to watercourses, there is natural forest or shrub land. The study area is home to approximately 1320 households.

Data from household survey in KZN in 2018

From 17 January to 5 February 2018, the first author conducted a household survey on household water security with 67 households in the study area. We worked in two teams of one researcher and one translator each. To sample households in this remote setting, we used convenience sampling (Etikan, 2016), a type of non-random sampling. Due to practical constraints, we picked households that were not further away from the road than 15 minutes by foot and that seemed representative of their group of neighbouring households. Beyond the questionnaire, we asked further questions and took photographs of water containers, RWH systems, buildings and crop fields. These photographs were later used to verify and supplement responses and fill in missing data. The household survey is described in detail by Lebek et al. (2021).

In this study we use data from the KZN survey on RWH and rainwater use, primary water source, presence and reliability of water services, and household income. In the field, we observed and recorded whether a household practised RWH at all, whether they owned a large tank for RWH or if they collected rainwater in drums (210 L) or large dishes. We also obtained additional qualitative data on RWH practices of individual households. Moreover, we observed the presence of gutters and, where applicable, the gutter type. Here we distinguished between industrially manufactured gutters, as can be obtained from a hardware store, and homemade gutters. The data on RWH that we present here are related to RWH as an important *alternative* water source in summer, which is the wet season. The three types of *primary* water sources are yard taps, standpipes and unimproved sources/surface water, such as streams, rivers and springs. Regarding water services, we distinguished between no services (users of unimproved sources/surface water), highly unreliable services, unreliable services and reliable services. The household survey data include details on the hours, weekdays and seasonality of water availability, respectively. We aggregated these data in a variable called water services quality. We classify water services as unreliable when a household has water for 12 hours or less a day, on fewer than seven days a week or when pressure decreases in winter. We classify the water services as highly unreliable when one or more of the following criteria hold true: the household has water for fewer than five hours a day, on fewer than four days a week or only in summer. When asked about their total monthly income, households often did not share an exact amount but rather a range or an approximate amount. We therefore aggregated households into three groups regarding their total monthly income: less than ZAR 2000, between ZAR 2000 and ZAR 10,000, and above ZAR 10,000. As per the exchange rate on 31 January 2018, ZAR 1000 = US$84.40.

Round hut fraction (RHF)

For the 67 households in the KZN survey, we determined the RHF, which is the number of round huts divided by the total number of buildings that belong to one household. We counted the buildings and round huts for each household using Google Earth imagery and validated the counts with our field observations.

General Household Survey (GHS) for South Africa, 2018

The data of the GHS can be downloaded free of charge from the Open Data Portal of StatsSA. We used the data from 2018 so they are comparable with our KZN survey data from the same year. The complete data set covers 315 different variables from 20,908 households from all over South Africa. We aimed at a selection of rural households that are comparable with the households we interviewed during the KZN survey and therefore filtered the data set by the following variables: geography type (*GeoType*; original variable name as retrieved from the 2018 GHS, StatsSA Open Data Portal), main source of drinking water (*Q512Drin*), net household income per month in Rand (*Q812Netincome*), main dwelling (*Q51MainD*) and type of living quarters (*Q102LQ*). Filtering reduced the data set to 5752 households. The selected households are located in traditional rural areas or on farms and not in urban settlements (*GeoType* $\neq$ 1). They do not have a tap within their dwelling (*Q512Drin* $\neq$ 1). They live in a private dwelling (*Q102LQ* = 1) and their main dwelling is a separate house or brick structure, traditional or in a back yard (*Q51MainD* = 1 | *Q51MainD* = 2 | *Q51MainD* = 7). Their net household income is equal to or less than 20,000 Rand/month (*Q812Netincome* ≤ 20,000). By the latter criterion, we excluded rural households that owned large commercial farms. The GHS provides data on RWH from tanks as a main source of drinking water (*Q512* = 4), but it does not hold information on RWH for other purposes or makeshift RWH.

Bayesian statistical analysis

We opted for a Bayesian statistical approach, as compared with a classical ('frequentist') approach, because the Bayesian approach gives direct probability statements about the hypotheses or effects of interest without the need to go via the repeat sampling interpretation of *p*-values and arbitrary significance levels. It also translates small sample sizes more coherently into wider uncertainty distributions.

Bivariate analyses and hypothesis-building

Based on the field observations in KZN, we explored a number of bivariate relationships between variables from the KZN survey: RWH mode (conventional or makeshift), measured in the survey by container type (tanks or drums); quality of water services (four classes); income (three classes); RHF (continuous between 0 and 1); gutter type (homemade or off the shelf); and rainwater use for drinking, cooking, washing dishes, bathing, laundry, cleaning and irrigation (binary variables). The models and results of the exploratory analysis are described in the supplemental data online. The juxtaposition of field observations and bivariate relationships led to the conceptual diagram of the drivers of RWH mode shown in Figure 1, which we then proceeded to test statistically by comparing the multiple regression models of RWH mode implied by this diagram. Finally, we repeated the analysis for the GHS data with RWH (practised or not) as the response variable and income (continuous) and quality of water services (three classes) as the predictors; all other variables of the more detailed KZN survey were missing in this case. We now describe both sets of models in turn, zooming in from the GHS level to the KZN level.

Model of RWH in the general household survey

Whether or not a household practised RWH (binary response variable) was modelled by a logistic regression with income and quality of water services as well as their interaction as the predictors. Income (continuous predictor) was standardized by subtracting the mean and dividing by the standard deviation (SD) to facilitate setting priors. Water services (three categories) were treated as an ordered categorical predictor following Bürkner and Charpentier (2020). Uninformative priors were set for all parameters, implying almost nothing about the effects before considering the data. For the effects, we used a uniform distribution over the real numbers. For the intercept, we used a Student's *t*-distribution with 3 degrees of freedom (d.f.), mean = 0 and scaled by an SD = 2.5. For the simplex parameter that models the difference between adjacent categories of water services (ordered categorical predictor), we used a Dirichlet(1,1) distribution, which puts equal probability on all valid simplexes (Bürkner & Charpentier, 2020). The posterior distribution

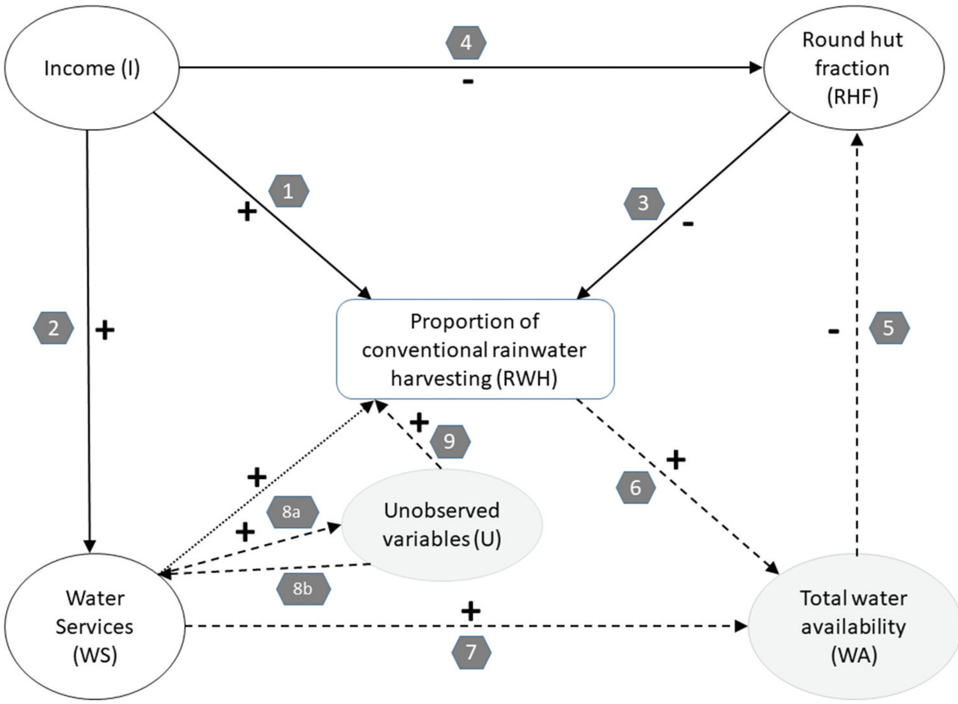

Figure 1. Factors for the probability of conventional rainwater harvesting (RWH mode) and their interrelations. Indices 1–9 are explained in the text. The unobserved variable *U* and links 8 and 9 emerged from the statistical analysis of the diagram and were not part of our initial hypothesis. Arrows and signs stand for positive (+) and negative (–) effects among variables. Solid arrows represent effects that have been confirmed statistically. Dashed arrows are hypothetical. The dotted arrow is a spurious effect explained in the text. Variables in grey bubbles are unobserved.

of the parameters was represented by 4000 samples generated by Markov chain Monte Carlo with the R package *brms* (Bürkner, 2017) that interfaces with the Bayesian inference engine Stan (Stan Development Team, 2019). Convergence was confirmed via the *R* statistic and trace plots of four chains.

Model of RWH mode in the KZN survey

In order to test formally the causal hypothesis depicted in Figure 1, we compared all univariate and multiple regression models that would be consistent with (parts of) the graph, so-called testable implications. We thereby borrowed techniques from causal inference (Pearl et al., 2016). We formulated all possible regression models of RWH mode (conventional or makeshift) with varying combinations of the one to three predictors (income, RHF and water services), but excluding interactions because these could not be identified without more data or stronger prior assumptions. We used logistic regression, modelling the probability of a households to use conventional RWH (RWH = 1). The probability of a households to use makeshift RWH (= 0) is then just 1 minus the probability of RWH = 1. RHF is a continuous predictor between 0 and 1, while income (I) and water services (WS) are ordered categorical predictors.

We used the same uninformative priors as for the GHS model. For the effects, we used a uniform distribution over the real numbers. For the intercept, we used a Student's *t*-distribution with 3 d.f., mean = 0 and scaled by a SD = 2.5. For the simplex parameters that model the differences between adjacent categories of I and WS, we used a Dirichlet(1,1) distribution. Again, we sampled 4000 samples from the posterior distribution using *brms*, confirming convergence as described above in the second section.

Results and discussion

RWH modes

By definition, a RWH system consists of a catchment area, a storage vessel and a distribution system (Nel et al., 2017). Makeshift RWH systems differ from conventional ones in the design of these three components. In the study area, RWH tanks have volumes of 2000, 4000 or 6000 L. They are usually connected to industrially manufactured gutters (see Figure A1 in the supplemental data online). Homemade gutters for makeshift RWH are mostly made of corrugated iron sheets that had been bent in order to route the water towards the container (see Figure A2 online). In some cases, gutters and water spouts were made of plastic bottles (see Figure A3 online) or hollow tree trunks (see Figure A4 online). Drums usually have a volume of 210 L, but households use a variety of containers of different sizes and shapes.

Of all 20,908 households that were interviewed in the GHS 2018, only 3% used rainwater tanks as their main or alternative source of drinking water. Of our reduced set of 5752 rural households with no piped water inside the dwelling, 7.4% used rainwater from a tank as the primary source or an alternative source of drinking water. In the study area in KZN, the first author observed both RWH modes. Of the 67 households from the KZN survey, 92% harvested rainwater in the wet season. A total of 25.4% harvested rainwater in tanks, and 16.4% of the households used rainwater from tanks for drinking. A total of 65.7% of the households harvested rainwater in a makeshift manner, that is, in drums or dishes, and 31.3% used rainwater from drums or dishes for drinking. Households with large RWH tanks may use the remaining rainwater well into the dry season (winter). Although RWH is only a seasonal option for most households, it is an important and beneficial complementary water source; it makes households more independent from unreliable water services and reduces the number of time-consuming roundtrips for water collection.

Factors for the adoption of RWH

Our analysis of the data from the GHS yields insights into the factors for the adoption of RWH in rural South Africa, confirming findings of previous studies. Whether a household uses a conventional RWH system for drinking water depends on the existence and reliability of water services as well as household income (Figure 2). The probability of a household to practice conventional RWH generally decreases with rising water services quality. At average income (ZAR 4700), the probability was 0.05 (median) with a 90% credible interval (CI) of [0.04, 0.06] for good water services, 0.06 [0.05, 0.06] for average/

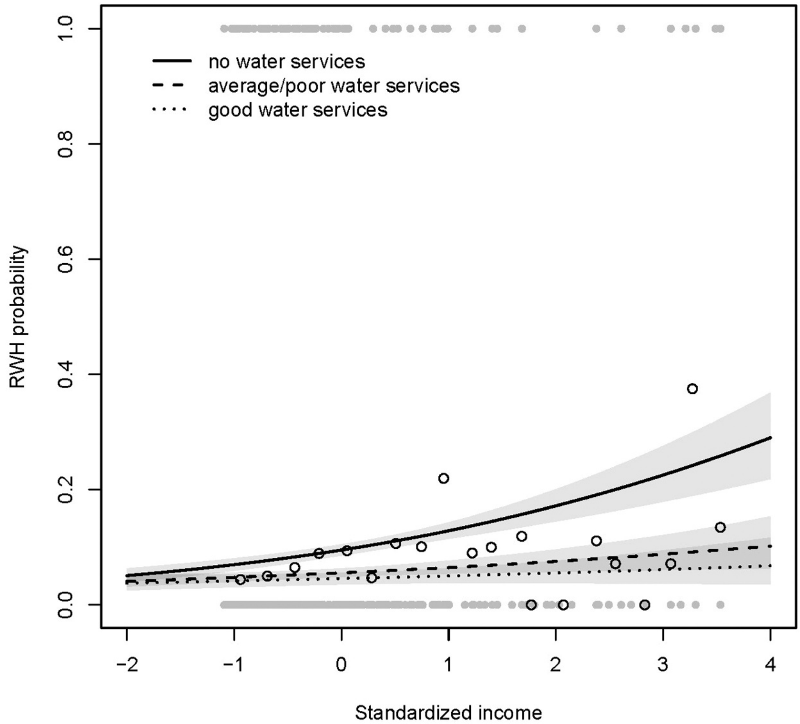

Figure 2. General Household Survey (GHS): probability of a household to practice rainwater harvesting (RWH) as a function of income and quality of water services. Grey points are the original response data from the GHS (1 = RWH; 0 = no RWH). Open circles are those data averaged for 20 equidistant bins for easier reading as the proportion of households practising RWH. Lines are the medians of the posterior distributions; and shaded areas are the central 90% credible intervals. A standardized income of 0 is the mean income in the GHS data (4700 Rand). A change of 1 in standardized income means 1 SD (standard deviation) in the GHS data (4300 Rand). RWH probability generally increases with income and decreases with water services quality, with the income effect itself being strongest for households with no water services.

poor water services and 0.10 [0.09, 0.11] for no water services. We present all estimates as median [90% CI]. It seems that households that have experienced disruptions in water services benefit from an RWH tank as an additional water source. Where households pay for municipal water services, they can use RWH to save money (Dobrowksy et al., 2014).

The probability for conventional RWH generally increases with income, with the income effect itself being strongest for households with no water services. It increased per SD of income (ZAR 4300) by a maximum of 0.03 [–0.01, 0.06] for good water services, 0.04 [0.01, 0.07] for average/poor water services and 0.08 [0.06, 0.11] for no water services. Since households often need to cover the costs of the RWH system themselves, the majority of households cannot afford the cost of a rainwater tank (Kahinda et al., 2007). Hence, whether a household uses RWH as a source of drinking water depends on its income.

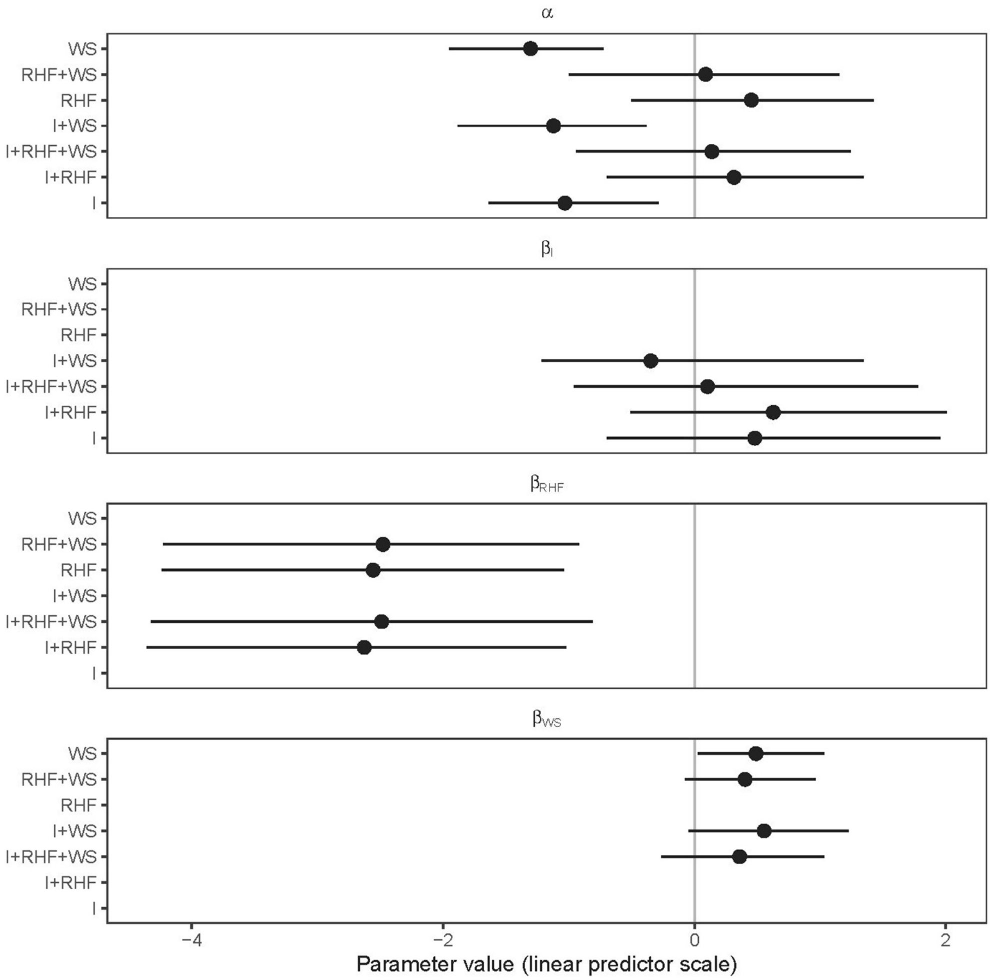

Figure 3. KwaZulu-Natal (KZN) survey: parameter estimates of different model variants of rainwater harvesting mode (RWH). Parameter α is the intercept of the model; and β_{I}, β_{RHF} and β_{WS} are the effects of income (I), round hut fraction (RHF) and water services (WS), respectively. Shown are the medians and 90% credible intervals of the posterior distributions. The rows for each parameter represent the model variants with different sets of predictors. RHF has the strongest effect, though with the largest uncertainty, which changes only minimally when other predictors are switched on or off. The effect of water services (WS) changes also minimally with the choice of other predictors. The effect of income (I) changes most drastically depending on the predictor choice, including change of sign.

Determinants of RWH mode

Beyond the driving factors for the adoption of RWH systems as shown in the results from the GHS analysis, our case study in KZN enables a differentiated view of RWH *mode*. The RWH mode was conceptualized to be embedded in a constellation of household income, housing and water availability (Figure 1), which was statistically tested through a series of univariate and multiple logistic regressions, whose results are depicted in Figure 3. Of interest are the signs and magnitudes of the predictor coefficients (the effects) and how they vary between different model variants. The coefficient values are comparable because ordered categories are modelled just as continuous variables in our case. The causal interpretation is discussed next.

RWH mode and housing

Households in the study area usually comprise more than one building: they either have traditional round huts or brick houses or a mix of both types. Round huts, so-called rondawels, are one-room huts built from a mix of clay, cow dung and grass. Some round huts have thatched roofs, which have a much lower runoff coefficient (about 0.2; Kahinda et al., 2007) than corrugated iron roofs (0.7–0.9; Biswas & Mandal, 2014), which reduces RWH yield.

Housing, and specifically the RHF, is an important factor for RWH mode (Figure 1, index 3); it has the greatest (negative) direct effect on the probability of conventional RWH, no matter which model is used, but with a wide posterior distribution (Figure 3). The little movement we see between model variants means that RHF is only slightly influenced by the other predictors as confounders (of all potential confounders considered in this particular analysis). We do not see much change at all when including I to RHF (model I + RHF), but we will be able to say something about this link in the third section below. Including WS to RHF (model RHF + WS), however, slightly reduced the magnitude of the negative effect of RHF, which suggest a negative influence of WA on RHF (Figure 1, index 5), while WA itself is positively influenced by WS (Figure 1, index 7). WA is unobserved so we cannot confirm this statistically, but it is plausible given our field evidence. Based on the three-parameter model (I + RHF + WS) (Figure 3), the probability of conventional RWH decreases by a maximum of 0.06 [0.02, 0.11] for an increase in RHF of 0.1 (Figure 4 and Table 1). The interrelations between WA, WS and RHF are explained in the third section below.

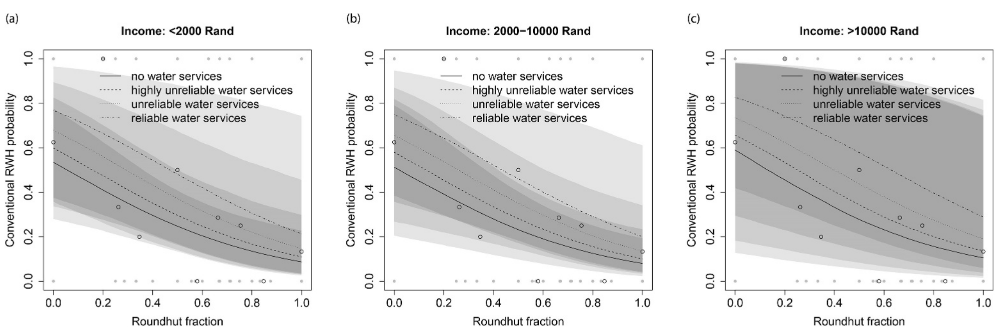

Figure 4. KwaZulu-Natal (KZN) survey: probability of a household to use conventional rainwater harvesting (RWH) as a function of round hut fraction (RHF), quality of water services (WS) and income (I) following the three-parameter model (I + RHF + WS) (see Figure 3). The three panels reflect three different income levels. Grey points are the original response data from the KZN survey (1 = conventional RWH; 0 = makeshift RWH). Open circles are those data averaged for 10 equidistant bins for easier reading as the proportion of households practising conventional RWH. Lines are the medians of the posterior distributions; and the shaded areas are the central 90% credible intervals. Conventional RWH probability generally decreases with RHF (less brick houses) and increases with WS quality and I.

Table 1. KwaZulu-Natal (KZN) survey: probability of a household to use conventional rainwater harvesting (RWH) for various realizations of the three predictor variables following the three-parameter model (I + RF + WS) (see Figures 3 and 4).

	Income: < 2000 Rand		Income: 2000–10,000 Rand		Income: > 10,000 Rand	
	No round huts	All round huts	No round huts	All round huts	No round huts	All round huts
No water services	0.53 [0.28, 0.78]	0.09 [0.03, 0.23]	0.51 [0.21, 0.79]	0.08 [0.02, 0.19]	0.59 [0.13, 0.98]	0.11 [0.02, 0.74]
Highly unreliable water services	0.60 [0.34, 0.83]	0.11 [0.03, 0.30]	0.58 [0.27, 0.82]	0.10 [0.03, 0.23]	0.66 [0.18, 0.98]	0.14 [0.02, 0.75]
Unreliable water services	0.68 [0.38, 0.89]	0.15 [0.04, 0.46]	0.66 [0.36, 0.87]	0.14 [0.04, 0.34]	0.74 [0.30, 0.98]	0.19 [0.04, 0.77]
Reliable water services	0.77 [0.36, 0.97]	0.21 [0.03, 0.74]	0.75 [0.38, 0.95]	0.20 [0.04, 0.61]	0.83 [0.42, 0.99]	0.29 [0.06, 0.82]

Note: Values are median [90% credible interval].

RWH mode (conventional in tanks and makeshift in drums) is related to the gutter type, because RWH tanks are usually connected with off-the-shelf gutters. A much larger proportion of households with homemade gutters thus have drums rather than tanks (difference 0.51 [0.32, 0.68]), while a large proportion of households with off-the-shelf gutters have tanks. RWH tanks can only be used to their full potential with large, off-the-shelf gutters. To attach a straight, long gutter to the roof, a household needs at least one large brick house with straight roofs, hence the positive correlation between conventional RWH (tanks) and brick houses (low RHF) (Figures 1 and 3). A household with only round huts (RHF = 1) cannot efficiently harvest rainwater in a tank.

RWH mode and household income

A household´s income (I) has the most variable effect on RWH mode compared with the other factors. It changes most drastically depending on the choice of other predictors, including change of sign (Figure 3). All these effects are close to zero and with wide posteriors, so if there is a direct effect of I on RWH mode then it is small. In a model without other predictors, I has a medium positive effect on the probability of conventional RWH. When RHF is included as well (model I + RHF) then the positive effect is amplified, which suggests a negative influence of I on RHF (Figure 1, index 4), a 'backdoor' influence of I on RWH that is closed when we condition on I. When WS is included on top of I and RHF as well (model I + RHF + WS), then the amplifying effect of RHF is dampened because part of the positive effect of I on RWH is channelled via WS (Figure 1, index 2). This means when only I and WS are included (model I + WS) then the direct effect of I is actually negative. On balance, with all three predictors included, we conclude that the direct effect of I on RWH is positive but small (Figure 1, index 1). The change in probability of conventional RWH for a change in income class is illustrated in Figure 4 and quantified in Table 1. A relatively high income may enable households to afford large RWH tanks connected with off-the-shelf gutters. This is in line with our findings from the GHS.

RWH mode, water services and total water availability (WA)

The quality of water services is indirectly related to the RWH mode. The effect of water services on the probability of conventional RWH is consistently positive, though not far from zero, with a narrow posterior distribution. It also changes very little when we move between model variants, which again suggests little influence by the predictors we considered acting as confounders. Adding I (model I + WS) has almost no appreciable effect, while adding RHF (models RHF + WS and I + RHF + WS) slightly reduces the positive effect of WS. This is the result of the same effect of WS influencing WA (Figure 1, index 7) and WA influencing RHF (Figure 1, index 5) as described in the third section below.

The *direct* effect of water services is illustrated in Figure 4 and quantified in Table 1. However, the finding that better water services (greater WS) should *directly* increase the proportion of conventional RWH seems illogical to us; if it is not via WA and RHF, but this path is already explicitly included. Hence, we consider the positive direct effect of WS a spurious effect that is generated by an unobserved confounder (Figure 1, unobserved variable *U*). There are two ways this confounder can work causally, either as a 'fork' (Figure 1, indices 8b and 9), that is, influencing both WS and RWH positively, or as a 'pipe' (Figure 1, indices 8a and 9), which is positively influenced by WS and itself positively influences RWH. Our reflection on the spurious effect of WS on RWH has led us to generate two hypotheses on possible unobserved confounders and their relations with WS and RWH.

First, we suppose that households who generally have a reliable WS (i.e., users of yard taps) likely also own an RWH tank. This is supported by an observation in the field; users of yard taps commonly store water from their yard tap in their RWH tank. We hypothesize one of the unobserved confounders to be storage of municipal water. It would work as a pipe that is positively influenced by WS and itself positively influences RWH.

Second, we hypothesize another unobserved confounder to be favouritism of the water provider. Water provision in the study area is highly unequitable and households who lack a reliable provision of water (household with no WS or highly unreliable WS) are disadvantaged by the water provider for specific (sometimes political) reasons (Lebek et al., 2021). We suppose that the water provider also has a say in the provision of RWH tanks to households. This would mean that the water provider is an unobserved confounder that positively influences both WS and RWH. The hypothesized unobserved confounders and their relations with WS and RWH would explain the spurious direct effect of WS on RWH. Both hypotheses and associated questions can, in a next step, be addressed empirically in the field.

The variable total WA refers to the total volume of water that is available to the household, including both water from the primary water source and water from RWH. Depending on the RWH mode, households can enhance their available water volume to different degrees (Figure 1, index 6). Users of conventional RWH can harvest much larger rainwater volumes to supplement their total WA. This positive effect of RWH on WA could not be formally tested here, because cyclic relations cannot really be unpacked using these type of regression models. Nevertheless, we suppose the self-reinforcing effect of RWH is seen as part of the large effect that comes out for RHF.

The availability of water from the primary source is determined by the household's distance from the water source (collection time) and the reliability of the water source. Primary water sources in the KZN study are unimproved water sources such as streams, springs or rivers (for 51% of the households interviewed), public, municipal standpipes (28%), yard taps that had been connected to standpipes illegally (18%) and RWH (3%). This means that over half of the households we interviewed do not benefit from water services at all. Due to mismanagement, over-pumping of groundwater, vandalism and lack of maintenance, most standpipes in the study area are highly unreliable. Generally, yard taps are the only reliable and improved water source (Lebek et al., 2021).

Interrelations between housing, income, water services and total water availability

We have confirmed statistically that RHF, I and WS all play a role for the RWH mode. Moreover, the results show that these three factors are interlinked. This is supported by our observations in the field. Together, they produce the conditions for the use of conventional or makeshift RWH. WS is an indirect factor for the RWH mode via total WA (Figure 1, index 7) and RHF (Figure 1, index 5). While the direct effect of household income on RWH is uncertain, I is a factor for both WS (Figure 1, index 2) and RHF (Figure 1, index 4). These linkages are now discussed in turn.

WS is related to the financial means of a household (Figure 1, index 2). Households with yard taps have the highest reliability of water services, yet installing a yard tap is costly. At the same time, households that can afford the installation of a yard tap are likely able to also afford a conventional RWH system.

To build a brick house, a household needs financial resources to buy bricks, tools and other materials. By contrast, building a round hut requires little financial means because the household can collect most of the building material in their surroundings. Therefore, I is also a factor for RHF (Figure 1, index 4).

Building a round hut requires only small amounts of water. To build a brick house, however, a household needs to allocate large water volumes. Therefore, total WA is a critical requirement for building a brick house and thus has an effect on RHF (Figure 1, index 5). WA depends on the quality of WS from the primary water source (Figure 1, index 7). Most households in the study area are water insecure to different degrees (Lebek et al., 2021). For households that can barely carry enough water home for drinking and washing, building a brick house would be impossible. One of the households we interviewed had bought bricks for building some years previously, but the bricks were piled in the yard unused because the household lacked water for building. We also interviewed a household that was busy at the time building a brick house onsite. The household had an extra tank and over 30 extra containers that were all used for storing and collecting water for building only. It became clear how the household's capacities for water collection and storage were bundled for this endeavour. Lastly, RWH itself facilitates house construction and brick-making (Kahinda & Taigbenu, 2011; Kahinda et al., 2007). Water used for building does not need to be of high quality so increasing total WA through RWH (Figure 1, index 6) can facilitate building.

Those who cannot afford a brick house find themselves trapped in a water insecurity situation where the opportunity to build a brick house is not only limited by the lack of financial resources but also by a lack of water resources which that very brick house would help secure. The interrelation of income, housing, total WA and RWH mode results in the

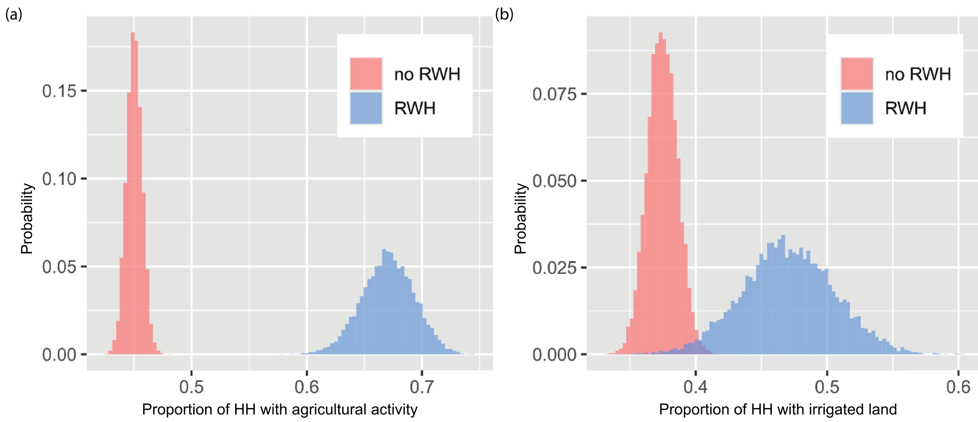

Figure 5. General Household Survey (GHS): (a) proportion of households (HH) with agricultural activity among HH with rainwater harvesting (RWH) and no RWH: HH with RWH are more likely to practice agriculture than households without RWH; and (b) proportion of HH with irrigated land among HH with RWH and no RWH: HH with RWH are more likely to irrigate their land than households without RWH.

accumulation of water resources in the form of reliable water services plus large RWH tanks in some households, while others lack reliable water services as well as conventional RWH systems.

Implications of RWH mode for household water security

Here we explore the implications the RWH mode has on irrigation at the homestead, on domestic water use and on water quality-related health risks. These results are based on the bivariate analyses described in the supplemental data online.

Agricultural activity and irrigation

Agricultural activity and irrigation are related to RWH. We focus on agricultural activity and irrigation related to direct use of rainwater at or around homesteads and not at distant fields. In the GHS data, agricultural activity and RWH are correlated (Figure 5a). Of those households with RWH, a much larger proportion performs agricultural activity compared with those households with no RWH (difference of 0.22 [0.18, 0.26]). Accordingly, of those households with RWH, a larger proportion irrigates their crops compared with those households with no RWH (difference of 0.10 [0.04, 0.16]) (Figure 5b). This is in line with previous studies (Kahinda et al., 2009); RWH facilitates agricultural and other small-scale productive activities (Kahinda et al., 2007).

In the KZN survey, however, there is no clear support for a correlation between RWH mode and irrigation. Rather, irrigation depends on the primary water source of the household. Of those households with a yard tap, a much greater proportion irrigates their crops compared with households that use a public standpipe or an unimproved water source. Few households use rainwater for irrigation. Households that do irrigate their crops use a hosepipe connected to their yard tap. This correlates with our observations in the field.

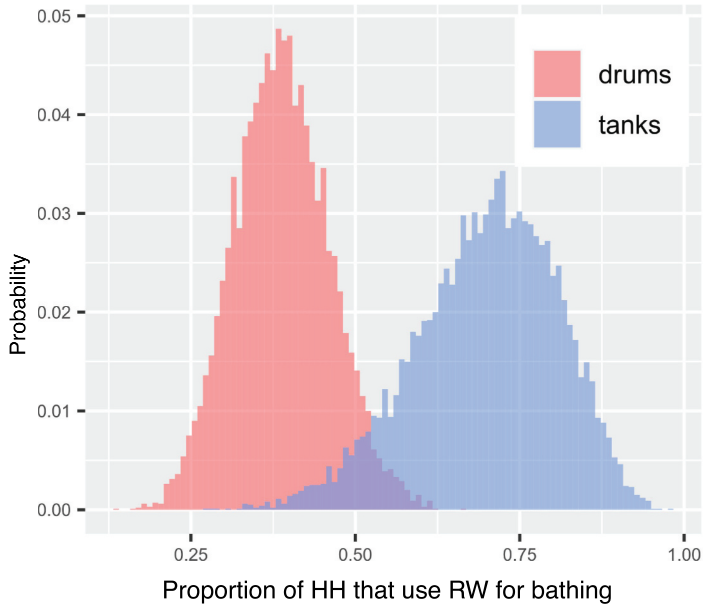

Figure 6. KwaZulu-Natal (KZN) survey: proportion of households (HH) that use rainwater (RW) for bathing among HH with drums and tanks. HH with tanks (conventional RWH system) are more likely to use RW for bathing than HH with drums (makeshift RWH system).

Domestic use of rainwater

For most domestic water uses (drinking, cooking, cleaning, washing dishes and laundry) there is no clear support for a correlation with the RWH mode in the KZN survey. These activities use relatively small amounts of water. However, the RWH mode does make a difference for the use of rainwater for bathing because that requires a larger volume of water than most of the other water-related domestic activities (Figure 6). Of those households with conventional RWH (tanks), far more use their rainwater for bathing compared with those households with makeshift RWH (drums; difference of 0.32 [0.09, 0.52]). Users of tanks benefit from their much larger available rainwater volumes.

The largest water volumes are needed for laundry. However, many households in the study area wash their clothes either in or next to a river or stream, next to a public standpipe or in their yard using their yard tap. Therefore, RWH mode does not make a difference for the use of rainwater for laundry. The difference in rainwater use for bathing shows that conventional RWH is more likely to improve the sanitation of rural households than makeshift RWH.

Quality of rainwater

The qualitative data from the KZN survey yielded additional information on the link between perceived rainwater quality and domestic use of rainwater. If it rained during the day, the rainwater can be taken inside and used for 'inside' purposes, such as drinking, cooking and bathing. If it rained at night/in the dark, the rainwater is said to be of low quality and stays outside for irrigation and laundry. Water quality and health concerns related to pollutants washed out of the air and chemical or microbial contamination from rooftops do not differ among households with conventional and makeshift RWH in our case study. Once the rainwater has reached the tank or drum, however, there may be differences in water quality among conventional and makeshift RWH. Water quality and health concerns for conventional RWH arise from bacterial growth inside tanks, insect breeding and low levels of maintenance of tanks. These risks are likely lower where rainwater is collected in drums because users of drums have more control over the quality of their rainwater. They can move around their RWH container and thus prevent it from being polluted (e.g., by taking it inside the house during the night). Moreover, drums can be easily closed with a lid and cleaned. They are usually emptied much faster than tanks, which reduces the risk of bacterial growth and insect breeding. However, well maintained and closed tanks have the lowest risk of insect breeding. Users of both tanks and drums need to treat rainwater before use, especially where it is used as drinking water.

Conclusions

At the national rural level of the South African GHS, the probability of a household to practice RWH increases as the quality of water services declines. The probability for RWH generally increases with income, with the income effect itself being strongest for households with no water services. The GHS, however, only records conventional RWH and does not consider what we call 'makeshift' RWH. Makeshift RWH has also been neglected by previous studies on rural RWH. Yet, the distinction between conventional and makeshift RWH makes a difference for households' livelihoods, productivity, sanitation and health, as we could show for our local case study in rural KZN. Our study thus extends the scope of RWH research to makeshift RWH and a differentiated understanding of RWH modes.

Of all households in our case study, two-thirds harvested rainwater in a makeshift manner and nearly half of these households used rainwater for drinking. Based on these observations, we hypothesize that makeshift RWH might also be prevalent in rural KZN and beyond in South Africa and elsewhere. In the rural low-income communities of our case study, makeshift RWH plays an important role for rural household water security. Certainly, makeshift RWH is less efficient than conventional RWH systems in terms of volume, but can be advantageous in terms of water quality and affordability. Overall, conventional RWH has greater potential to improve water-related productive activities, health and sanitation than makeshift RWH, where rainwater is used for irrigation and bathing. In order to use their RWH tank to its full potential, households can reduce water quality-related health risks by water treatment and good tank maintenance.

Income, housing, water services and total water availability all determine the RWH mode, that is, whether a household harvests rainwater in a conventional or makeshift manner. The round hut fraction has the greatest direct effect on RWH mode. With an increasing share of round huts, the probability for conventional RWH decreases. The direct effect of income on the probability of conventional RWH is positive, but small. Water services have an effect on RWH mode, supposedly via one or more unobserved variables. The determinants for RWH mode are interrelated; income is a factor for both water services and housing, while the level of water services is related to the RHF.

For upscaling RWH in rural areas, the specific water needs and housing types of households need to be considered. While some households may benefit from new drums and gutters that are tailored to their round huts, other households may need to enhance their RWH capacity and therefore require a transition to conventional RWH with large tanks. In order to transition, they need not only funding but also at least one brick house with straight walls. Development interventions aimed at further disseminating RWH in rural South Africa would need to consider all factors that we established for RWH mode and the ways these factors are interrelated.

This study is an interesting example of an iterative mixed-methods approach where observation-based hypothesizing and statistical analysis alternate and mutually stimulate each other. Our initial hypothesis on the relations between RWH mode and other variables emerged from our field observations and inspired bivariate statistical analyses. We then tested this conceptual model by comparing multiple regression models in the framework of causal inference. This analysis confirmed our hypothesis and helped quantify the direction and strength of the various effects. Importantly, it also raised new questions on unobserved variables related to both water services and RWH mode. In particular, more field observations and future case studies would shed some light on the relation between water storage and RWH mode and the role of favouritism in the provisioning of both water services and conventional RWH tanks.

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Credit author statement

T.K. supervised the research project; developed the code for the statistical analysis; performed the multivariate analysis; and contributed to the methods, results and conclusion. K.L. conceived and designed the analysis; collected the data; performed the bivariate analysis; and wrote a large part of the manuscript

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