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An examination of factors affecting sustainability of domestic rainwater harvesting systems in a rural, semi-arid region of Mexico

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ABSTRACT

Rainwater harvesting (RWH) is increasingly utilized today by populations to alleviate water supply issues, particularly in rural, dry environments. Limited research has considered, simultaneously, the numerous factors that contribute to sustainability – for example social acceptance, water quality, and maintenance needs – of RWH. This research aimed to improve understanding of factors influencing the sustainability of rainwater harvesting systems for domestic use (DRWHS) through examination of social, water quality, and technical feasibility components. We conducted 50 household surveys and 17 rainwater quality analyses in San Jose Xacxamayo a rural, semi-arid community in Puebla, Mexico. Results showed that DRWHS are socially accepted primarily because of the presence of existing local skills and knowledge, as well as critical need for water. Results from most of the water quality parameters measured were within WHO guidelines for human consumption, with the exception of pH, total coliform, and heterotrophic plate count; requiring rainwater treatment prior to consumption. Technical feasibility was the main barrier to the sustainability of DRWHS; highly seasonal rainfall and small roof sizes (averaging 70 m^2) resulted in households unable to meet annual water needs. Increasing roof sizes and providing water treatment could ensure DRWHS sustainability in the studied community.

Key words | climate change, Mexico, rainwater harvesting, reliability, rural, water supply

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INTRODUCTION

Fresh water is essential for life and human well-being, however populations in many regions worldwide lack basic access to a safe and constant supply. The United Nations estimates that, globally, nearly one billion people lack access to an improved source of drinking water (UN 2012). Individually, several countries are facing conditions of water stress, where annual water availability per capita ranges from 1000 to 1700 m^3 (Brown & Matlock 2011). Cumulatively, these countries' water stress conditions currently affect roughly one-fifth of the global population Q1 (Arnell 2004; UN 2007; Neibaur 2015). There is a global decline of water supply and water quality in large part because of a growing population (expected to reach 8 billion in 2025), water pollution from human activities, and effects of climate change (Alcamo *et al.* 2000; Imteaz *et al.* 2012).

In much of the developing world, populations in rural, semi-arid and arid regions often are more vulnerable to the challenges of access to water because they reside in areas of little rainfall and may face economic, political, or technological barriers to pipe and distribute surface or groundwater (UN 2007; Neibaur 2015). Because of current and future water challenges, there is a need for alternative water supplies that can sustain populations in rural semi-arid or arid areas, enable economic development, and conserve existing surface and groundwater resources (Fuentes-Galván *et al.* 2015; Lizárraga-Mendiola *et al.* 2015).

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Rainwater harvesting (RWH), an ancient technology used to capture and store rain, dates back over 4,000 years. Evidence shows that RWH originated in the Middle East and Asia, and several countries – notably India, Japan, China, and Turkey – have adopted this practice for Q2 over 2,000 years (Gould & Nissen-Peterson 1999; Neibaur 2015). Historically, RWH has been utilized to respond to both agricultural and domestic water supply needs. RWH is currently being revived and utilized in several dry, poor, and rural regions of the world for domestic water provision, as an alternative technology to satisfy populations' present and future water demands under climate change uncertainties (Gould & Nissen-Peterson 1999; Meera & Ahammed Q3 2006; Barron 2009; Mun & Han 2012). Several international development agencies, such as the United States Agency for International Development (USAID) and the U.S. Peace Corps, fund RWH system implementation by working directly with the communities to help facilitate social acceptability of RWH. Furthermore, RWH has been applied as an adaptive measure to address climate change impacts on precipitation variability in places where human populations are heavily dependent on rain-fed local water resources (Ndiritu *et al.* 2011). Numerous RWH studies have demonstrated improved livelihoods and increased water supply through the implementation and use of DRWHS (Mutekwa & Kusangaya 2007; Barron 2009). Additionally, the utilization of DRWHS, which operate at a household level, is currently being acknowledged as a contemporary, sustainable solution to meet household domestic water demands (Gould & Nissen-Peterson 1999; Mun & Han 2012; Lizárraga-Mendiola *et al.* 2015).

Numerous factors affect the sustainability of DRWHS. These factors can include social acceptability, water quality, and ability to meet household demands given spatial and temporal variability of rainfall (Neibaur 2015). Social factors, for example, can strongly influence a rural population's willingness to adopt DRWHS, even where there is high need for improved water supply (Fuentes-Galván *et al.* 2015). Social factors include local beliefs and attitudes, customs, gender roles, economic benefits or costs, local knowledge, materials and technical capacity, among others (Fuentes-Galván *et al.* 2015). Acceptance of rainwater for potable use can also be dependent upon the user's perception of taste, odor, and appearance (Doria 2010). Further, local customs can impact the reliance on senses to select a water source that can lead to the continued use of more contaminated water, foregoing the opportunity to change behavior and opt for a more reasonable and improved supply option, possibly through RWH (WHO 2004; Neibaur 2015).

Water quality is an additional important factor that affects feasibility of DRWHS, as it directly relates to human health (Baguma *et al.* 2010). Much literature shows that rainwater alone is typically of high quality; once rainwater interacts with the atmosphere, roof, or storage tank, contamination can occur (Choudhury & Vasudevan 2003; WHO 2008; Helmreich & Horn 2009; Schets *et al.* 2010). Previous studies generally have concluded that the physiochemical properties of rainwater are within WHO guidelines with the exception of pH (Pushpangadan & Sivanandan 2001; Chang *et al.* 2004; Neibaur 2015). Heavy metal Q4 contamination of rainwater is highly dependent on the roof and tank material (Chang *et al.* 2004; Ward *et al.* 2010). Zinc, copper, and metallic roofs are reported to negatively affect water quality (as considered for human potability), while water collected from concrete, tile, and aluminum roofs typically is acceptable for potable use (Ward *et al.* 2010; Mendez *et al.* 2011). Several other studies of RWH have reported that stored rainwater is contaminated with bacteria that exceed WHO guidelines, a problem which can be attributed to poor system design and infrequent maintenance (Ward *et al.* 2010; Domènech *et al.* 2012).

Technical feasibility and reliability of DRWHS refers to the capacity of these systems to meet household water demands. Factors that influence DRWHS efficiency include temporal distribution of rainfall, user demand, catchment size, and storage capacity (Lizárraga-Mendiola *et al.* 2015). Several studies have examined various optimization methods for DRWHS on the capacity to meet household water demands (Youn *et al.* 2012; Wallace & Bailey 2015). The behavioral method, developed by Jenkins *et al.* (1978) and later adapted by Fewkes & Butler (2000), is used to compute volume yield of a tank in a given time, which is a function of rainfall, catchment size, runoff losses, tank size and user demand. The behavioral method can provide accurate and continuous results for the DRWHS input, output and volume in a defined period of time (Fewkes & Butler 2000; Liaw & Tsai 2004; Imteaz *et al.* 2012). The applied simulation method (Imteaz *et al.* 2012) aims to determine the rainwater supply delivered by the tank in meeting the users demand over a given time. Reliability determines the frequency that the demand is met and can be examined on Q5 a time-based scale (Liaw *et al.* 2004; Palla *et al.* 2011).

Climate change is projected to affect future precipitation patterns and therefore the feasibility of DRWHS. In 2025, it is estimated that 2.9 to 3.3 billion people worldwide will be affected by water stress (Arnell 2004). Understanding the long-term feasibility of DRWHS as an alternative to meeting water supply needs for human populations requires evaluation of future precipitation trends and projection of the ability to meet a household's year-round demands (Lizárraga-Mendiola *et al.* 2015). It also requires an understanding of criteria for social acceptance of DRWHS (Fuentes-Galván *et al.* 2015).

Numerous studies have examined individual components of DRWHS and their feasibility, however, few studies have investigated social, environmental, technological, and climate factors simultaneously (Youn *et al.* 2012; Wallace & Bailey 2015). Therefore, considering potential interactions between these factors, current understanding of the reliability of DRWHS for human populations is limited. In the present study, we aimed to address these limitations by examining the sustainability of the DRWHS in a semi-arid, rural community near Puebla, Mexico, through an analysis of social, water quality, and technical feasibilities of the systems. Additionally, we considered how future precipitation patterns could affect the ability of DRWHS to deliver adequate water supply.

METHODS

We conducted this study in San Jose Xacxamayo, which is a small community located in the municipality of Puebla, the fourth most populous city in Mexico. The community had a total of 827 residents in 2010 (INEGI 2010; OECD 2013). Average annual precipitation is 724 mm, with most falling during the rainy season between May to October (CONAGUA 2012). Our methods for the present study included: (i) surveys with DRWHS users (ii) water quality sampling of stored rainwater and (iii) water balance modeling to determine current and future reliability of DRWHS under future climate conditions.

This project was conducted as a part of Peace Corps Volunteer work by E. Neibaur in San Jose Xacxamayo (2012–14) that involved the installation of DRWHS of 10,000 liters each in 82 households. Of those 82 households, 50 were randomly selected for in-person surveys. All survey questions were developed and conducted in line with the study's objectives, relevant literature, and approved by the International Review Board (IRB) of Florida International University. Surveys were conducted through personal interviews with questions related to: socio-economic characteristics of households, current water supply sources, economic costs of water, household water demand, understanding of RWH, and the durability and required maintenance of existing DRWHS. Survey questions aimed to understand social acceptability factors, behaviors, attitudes, and skill level of household users with respect to DRWHS. In addition, surveys were used to calculate the DRWHS current and future potential storage capacity and reliability as determined by the roof size, current domestic water demand, and monthly rainfall input. Descriptive statistical tests of survey data were conducted using the Statistical Package for Social Science (SPSS).

Water quality analyses examined whether stored rainwater met conditions for potable human use. From August to October 2014, during the final phase of E. Neibaur's Peace Corps Volunteer assignment, 17 rainwater samples were collected from select DRWHS. Households surveyed confirmed that DRWHS sampled had been cleaned out prior to the rainy season and were used only for storage of pure rainwater (no cross source contamination). Physiochemical and bacteriological analyses were performed on water from the 17 DRWHS. Most water samples were tested and collected directly from stored water in the DRWHS, however, there were a few cases where the water levels were low and a bucket (the usual methods of extraction by households) was utilized. All samples taken were stored in sterilized polyethylene plastic containers. Some water quality parameters were analyzed *in situ* (temperature, pH, total dissolved solids, electric conductivity (EC)) and other water quality samples (ammonium, phosphorus, heterotrophic plate count (HPC), and total coliform count) were stored in a cooler at 4 °C and transported the same day for analysis at a laboratory facility the Meritorious Autonomous University of Puebla (BUAP). Water quality data were compared against the World Health Organization's (WHO) standards for water use and human consumption. For absence of criteria standards from WHO, information from previous studies of rainwater quality was compared against our data (Domènech 2012; Adler Q6 *et al.* 2013). Q7

As part of the survey, domestic water demand for weekly use was calculated as reportedly used for: drinking, cooking, washing clothes, bathing, washing dishes, washing the house, and watering plants. Initially, our question considered all domestic uses for the household per week. For the initial 8 surveys conducted, responses were conservative and with high uncertainties. Thus the additional 42 surveys recorded the weekly domestic water demand separately for each domestic use per household, allowing a more precise response by the participant. The total domestic water use for each household was used to calculate the water volume required to be captured and stored given the monthly precipitation in order to meet the family's need. In addition, monthly demands and roof sizes of all surveyed users were averaged to calculate the sample populations overall average feasibility and reliability of RWH. Rainfall data were extracted from the nearest meteorological station, Balcon Diablo A. Texaluca (18 °89′75″N, −98 °13′22″W) from 1951 to 2010, a 49 year time period (INEGI 2010).

Calculating the volume of potential rainwater collection is important to optimize the size of the rainwater tank for sustainable water use. The key component to a DRWHS is the catchment area, where the rainwater is captured. In San Jose Xacxamayo the rainwater is captured from the households' roofs, with the majority having concrete roofs. The roof runoff volume of a system can be calculated with the following equation:

Equation (1) Roof runoff volume

Q13
$$Q_t = RC \times R \times A \tag{1}$$

where:

$Q_t =$ Quantity of monthly rainwater harvested (m^3),
$RC =$ Runoff coefficient,
$R =$ Total monthly rainfall, and
$A =$ Roof area or catchment area (m^2).

The inflow, Q_t, is calculated using the net monthly rainfall, storage catchment size, and the runoff coefficient for the concrete material used as adopted for this study is 0.80 (Biswas & Mandal 2014). To calculate the feasibility of DRWHS for capturing sufficient water for current and future domestic household demand the water mass balance model was applied based on an approach developed by Fewkes (1999):

Equation (2) Water Mass Balance Equation

$$V_t = V_{t-1} + Q_t - D_t;\ 0 \le V_t \le S \tag{2}$$

where:

$V_t =$ Volume (m^3) of rainwater,
$V_{t-1} =$ Volume (m^3) of rainwater in storage system at end of monthly interval, t,
$Q_t =$ Inflow (m^3) during monthly time interval, t,
$D_t =$ Demand (m^3) during monthly time interval, t,
$S =$ Maximum Storage Capacity.

Time is taken for the monthly storage capacity using the demand of all surveyed users. Each user's current roof size was considered in the calculations. The water balance model was calculated to understand the tanks' monthly inflow, outflow, and total volume. The performance of DRWHS (reliability) was adapted from Karim *et al.* (2013) Q8 and calculated by taking the total number of users that met their domestic water demand in the monthly time period as described in the following equation:

Equation (3) Reliability of RWHS

$$R_e = 1 - \frac{n}{N} \times 100 \tag{3}$$

where:

$R_e =$ Probability of the tank supplying the monthly demand of the users (%),
$n =$ Number of households that did not met their water demand for that month,
$N =$ Total number of users.

RESULTS AND DISCUSSION

This study provided one of the first integrated assessments of the sustainability of DRWHS, considering social, environmental, technological, and climate factors that affect

DRWHS. The results reflect social, water quality, and technical feasibility of DRWHS based on 50 surveys conducted, 17 water analyses, and current and future potential tank storage capacity under a 10%, 15%, and 20% decrease in precipitation for 49 users. Overall, we found that roof sizes were the determined limiting factor of DRWHS to meet year-round water demands for domestic use in a rural, semi-arid area of Mexico. In addition, results of the study suggested that social acceptance, an important factor in DRWHS sustainability, can be achieved with local acceptance of the RWH technology and by acquiring the local skills needed to construct and maintain the systems. In addition, the DRWHS tanks were shown to be economically feasible for many community members to self-finance their own system where existing knowledge and skills are available.

Our study included 100% participation and 100% response to the requests for the 50 surveys. However, some participants did not answer all questions within the survey. Table 1 reports the key socio-economic characteristics of surveyed users. Females made up the majority (96%) of the survey respondents; this was a result of the fact that men were largely unavailable during the time when surveys were carried out. Out of the respondents, 96% identified as one of the heads of household. The average age of the participants was 39 years old and the mean household family size was 4.3 people.

Table 1 | Selected socio-economic characteristics of San Jose Xacxamayo

Characteristics	Description	N	%
Gender	Male	1	4
	Female	49	96
Age group	18–64	47	42
	>64	3	6
Household Size	1–4 people	31	38
	>5	19	66
Occupation	Construction	33	66
	Agricultural	13	26
	Other	4	8
Income	<$1.25/day	24	48
	>$1.25/day	26	52
Potable Water	No	50	100
Bathroom Type	Improved	6	12
	Unimproved	42	88

The main economic activity in the majority of the households was construction (66%). Agriculture was second, accounting for 26%, and 8% responded that other sources of income were dominant in their households, such as selling embroidered napkins, weaving palm boxes, selling wood or running a local store. Thus, over half the populations surveyed had at least one household member with knowledge and skills in construction, which are useful to construct and maintain the DRWHS. Monthly income reported (in U.S. dollars) included any government assistance; 64% of participants did receive such aid. Just over half (52%) of the monthly household income of respondents was over $1.25/day/capita. The other 48% reported income levels below the international poverty line of $1.25/day/capita. All respondents (100%) stated they had no access to running potable water in their homes. As related to type of bathroom, 12% of households reported improved sanitation facilities (flush toilets) and the other 88% reported unimproved sanitation facilities (open air and unventilated latrines).

Our results indicated that there were five water sources from which the community could obtain water: wells, a *chorro* (excess clean water that spills from a tank that transports clean water to a neighboring community), a community cistern of piped water from a nearby source (called the *headwater*), purchased trucked water, *jaguey* (community mountain rainwater collection system of 700,000 liter capacity implemented in 2005 by the local government), and household RWH collection systems. All 50 surveyed households reported that for three months out of the year their household does not collect water by foot. The weekly travel frequency to obtain water was answered by 49 out of the 50 respondents: days traveled per week to collect water varied from only 1 day to all 7 days. Most frequently, users travelled once or twice a week to obtain water from local sources. Respondents also noted that most of the weekly travel was done in the dry season (November–April). This result implied that in the rainy season most of the surveyed users were able to capture enough rain for household needs and reduce work time required to obtain water from local sources.

All participants had a DRWHS, and only one user did not collect rainwater because of their roof type (woven palm thatch). Participants ranked dependency of their available water sources (*jaguey*, wells, purchased water, *chorro*, headwater, and rainwater) in order of reliance and usage for domestic purposes as follows: 26 (52%) of respondents ranked rainwater as number 1 (the most used), 18 (36%) ranked it second, 5 (10%) ranked it third, and 1 respondent said they did not use it. Out of all users, 34 respondents reported that they used rainwater for drinking purposes and the other 12 responded that they did not. In terms of the perception of rainwater, the majority of respondents stated that the smell, appearance, and taste were average or above average. One of the users had a bad perception of the rainwater but that user declared that they did utilize rainwater for drinking.

Table 2 shows select characteristics from the existing systems that participants had (age and cost of tank, user contribution to tank construction, and required maintenance). The two types of cisterns that were utilized in the community are concrete and ferrocement. There were more concrete tanks (69) compared to ferrocement tanks (7). Construction of over half of the tanks (55%) was supported by external national and international funds, although a considerable number of participants were financially responsible for their own tank (37%). Construction of all of the ferrocement tanks was supported by external national funds. These types of tanks required more frequent number of repairs at a younger age in comparison to the concrete cistern. Our survey results also suggested that the community did not prefer ferrocement cisterns and that the organizations that promoted their construction did not adequately involve the community members in the planning and implementation process. The lack of social acceptance and limited input of the community in project development of ferrocement tanks could affect the longevity and sustainability of those DRWHS systems. Most households had to contribute with time and/or money regardless of the financial funding source of the tank. The average reported cost contribution by the user per tank was ~$221, excluding labor. In most cases the household participated in the construction process by digging the hole and constructing the tank, or by helping with construction. The average number of days for digging the hole needed to construct a concrete cistern (12.6) was higher than that of a ferrocement (2.33), since ferrocement are aboveground structures and only require a minimum of 0.5 m to be dug for the foundation as opposed to 1.9 m for concrete cisterns. The construction process for both averaged about 13 days for each system. Our survey results suggested that length of time to implement a RWH tank was not a determining factor in

Table 2 | DRWHS characteristics

Category	**Description**	**Concrete**	**Ferrocement**	**Total**
Number of Cisterns	DRHWS	69	7	76
Government Aid	No Aid	28	0	28 (37%)
	International Aid	6	0	6 (8%)
	Federal Aid	35	7	42 (55%)
Economic Costs for Construction	<$100	24	0	24
	$100–$500	14	3	17
	$501–$1000	6	0	6
	>$1000	1	0	1
Household Labor Contribution (*Avg. No. Days)	Digging	12.6	2.3	
	Construction	12.3	15	
Tank Age (Years)	<1	5	1	6
	1–5	35	6	41
	6–10	19		19
	11–18	10		10
Maintenance	No. of tanks repaired	6 (9%)	3 (42%)	10 (13%)
	Avg. repaired tank age	9	1.6	5.3
	Avg. total repairs	1.8	1.5	1.6
	Avg. repair costs	$50	$12	$31

the social adoptability of these systems. The tank age ranged from <1 year to 18 years, with 38% of tanks having been in existence for over 6 years (all concrete tanks). The number of concrete tanks that required maintenance to fix for leaks over their lifespan was low (9%). The average tank age that requires maintenance was 9 years and average total spent on repairs was $50. The ferrocement tank had a higher maintenance requirement (42%) with an average tank age of 1.6 years and average total spent on repairs of $12.40. The higher repair of the ferrocement tank implied that there could have been inadequate training to the community members in the construction of these types of systems. Out of the 46 who responded to maintenance capability, all reported that their family was capable of maintaining their DRWHS if there were to be a malfunction (i.e., leak).

Rainwater quality analysis

Water quality was examined through analysis of physicochemical and bacteriological quality (Table 3). The average water temperature was 19.81 °C. The pH ranged from 7.70 to 10.42, with an average pH recorded value of 8.74. In all DRWHS, the pH tended to be more alkaline, likely because of the concrete material on the roofs and tanks. The WHO recommends a pH of 6.5–8.5 for drinking water, however low alkalinity is not considered a human health hazard (Gould & Nissen-Petersen 1999; WHO 2004; Domènech *et al.* 2012). The TDS of samples ranged from 23 ppm to 123 ppm with an average of 68 ppm. EC ranged from 33 to 176 μS/cm with a mean of 97 μS/cm. There is no WHO standard for TDS or EC, however, it is generally recommended for TDS to be between 100 and 1,200 ppm for drinking water, of which two of the samples exceeded 100 ppm. Ammonia ranged from less than 0.01 mg/l to 0.245 mg/l with a mean of 0.069 mg/l. Ammonia levels greater than 0.2 mg/l can interfere with the effectiveness of chlorine, and two participants' tanks reported water with ammonia greater than 0.2 mg/l. Additionally, two household tanks' results were undetectable, signifying level lower than 0.1 mg/l. The phosphate ranged from 0.30 mg/l to 0.90 mg/l with an average of 0.55 mg/l. Of participants, 5 users' tanks had undetectable phosphate values, implying levels lower than 0.5 mg/l. The HPC count was high amongst all users' tanks. Only one user's tank had below 100 CFU/ml at a value of 70 CFU/ml. There are no WHO recommended HPC levels, however seasonal fluctuations in HPC can indicate maintenance frequency of the user. Four out of the 17 users had coliform bacteria present in their drinking water. Of those with coliform bacteria present, three did not use treatment in the storage tank; one treated with chlorine.

Technical feasibility

Based on results of the survey, the average domestic weekly water demand of all households surveyed was 1693.17 liters, which equates to 56.78 l/c/d (21.4 m^3/capita/year). This was below the WHO recommended minimum of 100 l/c/d and just above the WHO poverty threshold 50 l/c/d. Washing clothes and bathing combined made up over half (60%) of household water use.

Table 3 | Water quality parameters

Parameter	Range	Mean	WHO guidelines
Temp (°C)	17.1–22.2	19.8	–
pH	7.70–10.42	8.74	6.5–8.5
Conductivity (μS/cm)	33–176	97	–
TDS (ppm)	23–123	68	100–1200
Ammonia (mg/l)	<0.01–0.245	0.069	<0.2[a]
Phosphate (mg/l)	0.3–0.90	0.55	–
Total Coliform (CFU/100 ml)	0–500	82	0
HPC (CFU/ml)	57–10780	1209	–

[a] Recommended level with chlorine present.

Figure 1 shows the reliability of the DRWHS systems for both current and future use of the 49 users. A 10%, 15%, and 20% decrease in the current monthly rainfall was taken to project future reliability of the systems under climate change uncertainty. Current and future reliability projections were seasonally variable, with the highest reliability falling in the months of June to September. The variability between different precipitation percent decrease was not substantial. Overall, in the peak rainy season a little less than half of the DRWHS users were able to meet their households' monthly current water demand.

CONCLUSION

The success and sustainability of DRWHS as a water supply source is highly dependent on factors related to social acceptance, local technical capacity, water quality, and technical feasibility of the DRWHS. Overall, we found that DRWHS were socially acceptable in San Jose Xacxamayo, Mexico, and that water collected generally was fit for human consumption. Our results also suggested that community involvement and contribution in the diagnostics, design, and implementation of water provisions was crucial in order to meet the social acceptance, minimize health risks, and reduce possibilities of failure of projects that promote DRWHS to increase access to water supply for domestic needs. Our water quality analyses indicated that rainwater could provide quality drinking water as long as additional treatment was performed prior to consumption. There exists a technical feasibility barrier to provide sufficient water supply under current and future precipitation patterns, primarily due to the small average roof size of the participants (70.4 m^2), which was not sufficient to capture and store adequate year round water supply of the average annual demand (87.9 m^3). It is recommended to have a roof size of at least 150 m^2 for rural, semi-arid communities that aim to rely on DRWHS, to supply sufficient quantity of water for annual household domestic demands.

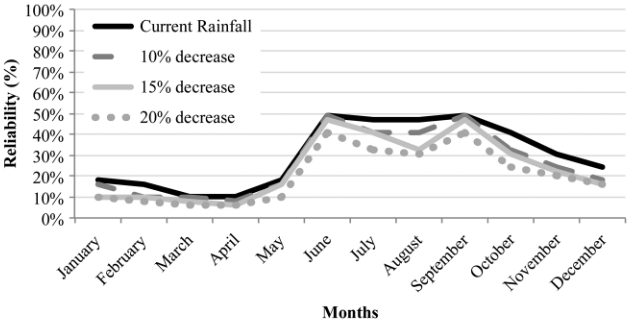

Figure 1 | Current and Future Reliability of DRWHS at San Jose Xacxamayo (considering 1951–2010 monthly rainfall data from the nearest meteorological station, Balcon Diablo A. Texaluca approximately 9 km distance to San Jose Xacxamayo).

Future research should examine possible heavy metal contamination of DRWHS, to further expand the knowledge and understanding of the role of concrete roofs and storage tanks on rainwater quality. In addition, we recommend future sampling across the year to examine potential seasonal variability, including variability in people's perceptions of the DRWHS and therefore social acceptability. Additionally, more substantial evidence on the economic and social benefits that DRWHS could be garnered through studies that examine conditions before and after their implementation. Future projects would benefit from having regional scale models for small communities to predict future precipitation under different climate change scenarios, as this information could provide for more accurate technical feasibility assessments.

Finally, much of DRWHS project's success in San Jose Xacxamayo was attributed to the developed trust between the Peace Corps Volunteer and the community, something that is somewhat difficult to quantify. Nevertheless, organizations that implement similar projects in the future should consider this factor, and particularly the influence on social acceptance and feasibility of DRWHS. In addition, for those who do not benefit from an external funding source, DRWHS projects should aim to provide and empower the community members with all the tools that can enable successful implementation.

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REFERENCES

Adler, I., Hudson-Edwards, K. A. & Campos, L. C. 2013 Evaluation of a silver-ion based purification system for rainwater harvesting at a small-scale community level. *Journal of Water Supply: Research and Technology – AQUA* **62** (8), 545–551.

Alcamo, J., Henrichs, T. & Rosch, T. 2000 *World Water in 2025*. Center for Environmental Systems Research, University of Kasse. Q9

Arnell, N. W. 2004 Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change* **14** (1), 31–52.

Baguma, D., Loiskandl, W., Darnhofer, I., Jung, H. & Hauser, M. 2010 Knowledge of measures to safeguard harvested rainwater quality in rural domestic households. *Journal of Water and Health* **8** (2), 334–345.

Barron, J. 2009 Rainwater harvesting: a lifeline for human well-being. UNEP/Earthprint.

Biswas, B. K. & Mandal, B. H. 2014 Construction and Evaluation of Rainwater Harvesting System for Domestic Use in a Remote and Rural Area of Khulna, Bangladesh. *International Scholarly Research Notices*. Q10

Brown, A. & Matlock, M. D. 2011 A review of water scarcity indices and methodologies. White paper, 106.

Chang, M., McBroom, M. W. & Beasley, R. S. 2004 Roofing as a source of nonpoint water pollution. *Journal of Environmental Management* **73** (4), 307–315.

Choudhury, I. & Vasudevan, L. 2003 Factors of biological contamination of harvested rainwater for residential consumption. In: *Hawaii International Conference on Social Sciences*. University of Hawaii, Honolulu, HI. June 2003. [WWW document]. Available from: http://www.watercache.com/docs/rwquality1.pdf.

CONAGUA 2012 National Meteorological Service. Secretariat of Environment and Natural Resources of Mexico. Available from: http://www.smn.cna.gob.mx/.

Domènech, L., Heijnen, H. & Saurí, D. 2012 Rainwater harvesting for human consumption and livelihood improvement in rural Nepal: benefits and risks. *Water and Environment Journal* **26**, 465–472. Doi: 10.1111/j.1747-6593.2011.00305.x

Doria, M. D. F. 2010 Factors influencing public perception of drinking water quality. *Water Policy* **12**, 1–19.

Fewkes, A. 1999 Modelling the performance of rainwater collection systems: towards a generalised approach. *Urban Water* **1**, 323–333.

Fewkes, A. & Butler, D. 2000 Simulating the performance of rainwater collection and reuse systems using behavioural models. *Building Services Engineering Research and Technology* **21** (2), 99–106.

Fuentes-Galván, M. L., Delgado-Galván, X., Charcas-Salazar, H., Mora-Rodríguez, J., Flores, J. L. F. & Benavides, A. C. 2015 Rooftop rainwater harvesting acceptance in three localities of Guanajuato, central Mexico. *Interciencia* **40** (6), 403.

Gould, J. & Nissen-Petersen, E. 1999 *Rainwater Catchment Systems for Domestic Supply: Design, Construction and Implementation*. Intermediate Technology Publications, London, UK.

Helmreich, B. & Horn, H. 2009 Opportunities in rainwater harvesting. *Desalination* **248** (1), 118–124.

Imteaz, M. A., Adeboye, O. B., Rayburg, S. & Shanableh, A. 2012 Rainwater harvesting potential for southwest Nigeria using daily water balance model. Resources. *Conservation and Recycling* **62**, 51–55. ISSN 0921-3449.

INEGI 2010 Censuses of population and housing. Available from: http://www.inegi.org.mx/est/contenidos/proyectos/ccpv/.

Jenkins, D.,, Pearson, F.,, Moore, E.,, Sun, J. K. & Valentine, R. 1978 *Feasibility of rainwater collection systems in California*. Contribution No 173, Californian Water Resources Centre, University of California. Q11

Karim, M. R., Rimi, R. A. & Billah, M. S. 2013 Reliability analysis of household rainwater harvesting tanks in the coastal areas of Bangladesh using daily water balance model. In: *20th International Congress on Modelling and Simulation*. pp. 2639–2645. Q12

Liaw, C. H. & Tsai, Y. L. 2004 Optimum Storage volume of rooftop rainwater harvesting systems for domestic use. *Journal of the American Water Resources Association* **40**, 901–912.

Lizárraga-Mendiola, L., Vázquez-Rodríguez, G., Blanco-Piñón, A., Rangel-Martínez, Y. & González-Sandoval, M. 2015 Estimating the rainwater potential per household in an urban area: case study in Central Mexico. *Water* **7** (9), 4622–4637.

Meera, V. & Ahammed, M. M. 2006 Water quality of rooftop rainwater harvesting systems: a review. *Journal of Water Supply: Research and Technology, AQUA* **55**, 257–268.

Mendez, C. B., Klenzendorf, J. B., Afshar, B. R., Simmons, M. T., Barrett, M. E., Kinney, K. A. & Kirisits, M. J. 2011 The effect of roofing material on the quality of harvested rainwater. *Water Research* **45** (5), 2049–2059.

Mun, J. S. & Han, M. Y. 2012 Design and operational parameters of a rooftop rainwater harvesting system: definition, sensitivity and verification. *Journal of Environmental Management* **93** (1), 147–153. ISSN 0301-4797.

Mutekwa, V. & Kusangaya, S. 2007 Contribution of rainwater harvesting technologies to rural livelihoods in Zimbabwe: the case of Ngundu ward in Chivi District. *Water SA* **32** (3), 437–444.

Neibaur, E. 2015 Sustainability Analysis of Domestic Rainwater Harvesting Systems for Current and Future Water Security in Rural Mexico. Master's Thesis. Florida International University.

Ndiritu, J., Odiyo, J. O., Makungo, R., Ntuli, C. & Mwaka, B. 2011 Yield–reliability analysis for rural domestic water supply from combined rainwater harvesting and run-of-river abstraction. *Hydrological Sciences Journal–Journal des Sciences Hydrologiques* **56** (2), 238–248.

Organisation for Economic Cooperation, Development (OECD) 2013 Improving Education in Mexico- A State -Level Perspective from Puebla.

Palla, A., Gnecco, I. & Lanza, L. G. 2011 Non-dimensional design parameters and performance assessment of rainwater harvesting systems. *Journal of Hydrology* **40**, 65–76.

Pushpangadan, K. & Sivanandan, P. K. 2001 Technology, quality and cost of water from DRWH -a case study in Kerala, India.

Schets, F., Italiaander, R., Van Den Berg, H. H. J. L. & de Roda Husman, A. 2010 Rainwater harvesting: quality assessment and utilization in The Netherlands. *Journal of Water and Health* **8** (2), 224–235.

United Nations (UN) 2012 The Millennium Development Goals Report.

Wallace, C. D. & Bailey, R. T. 2015 Sustainable rainwater catchment systems for micronesian atoll communities. *JAWRA Journal of the American Water Resources Association* **51** (1), 185–199.

Ward, S., Memon, F. & Butler, D. 2010 Harvested rainwater quality: the importance of appropriate design.

WHO 2004 *Guidelines for Drinking-water Quality*. World Health Organization, Geneva.

WHO 2008 *Guidelines for Drinking-water Quality-Incorporating First Addendum. Recommendations*, 3rd edn. Vol. 1. World Health Organization, Geneva, Switzerland.

Youn, S. G., Chung, E. S., Kang, W. G. & Sung, J. H. 2012 Probabilistic estimation of the storage capacity of a rainwater harvesting system considering climate change. *Resources, Conservation and Recycling* **65**, 136–144.

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