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Empirical evidence on the potential of rainwater harvesting for residential water supply in Accra

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We evaluate the potential of rainwater harvesting for residential water supply by estimating, analysing and comparing the per capita water consumption accessible from rainwater harvesting (RWH) systems and that acquired from water tanker services (WTS) for single-family households in Accra, Ghana. Although the values from WTS stochastically dominates those from RWH over a wide range, the difference in their mean values does not appear to be statistically significant, and the probabilities that the per capita water consumption, of a household selected at random, exceeds the WHO service levels of {5, 20, 50, 100} lpcd are {1.000, .937, .239, .0474} for RWH, compared to {1.000, .994, .555, .0467} for WTS. We conclude that for single-family dwellings in Accra, the WHO service levels for water consumption and hygiene obtainable from RWH is appreciable and comparable to those from WTS providers. Therefore, households can satisfy their current water consumption levels with RWH alone.

Introduction

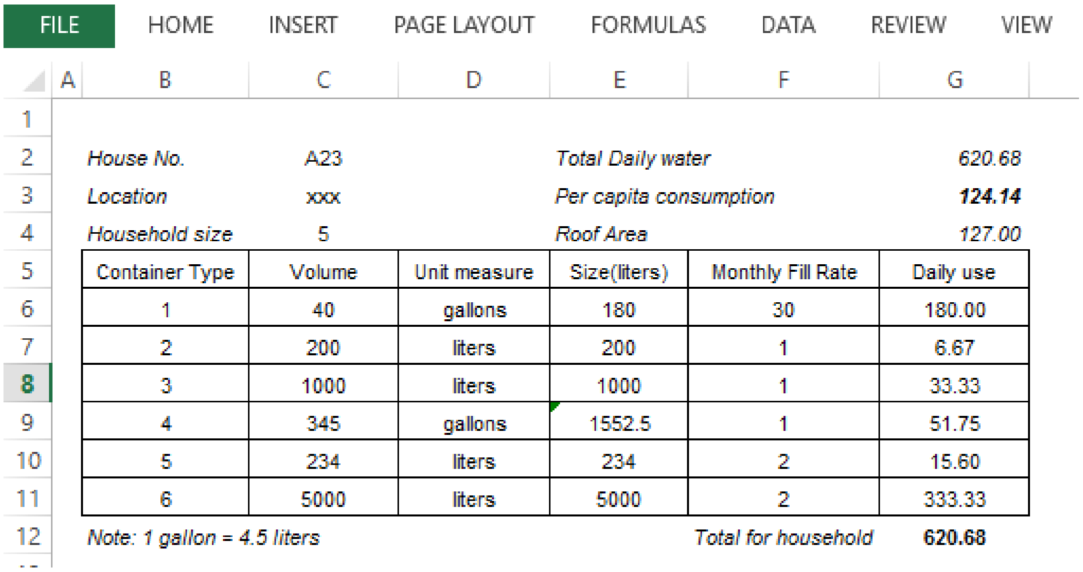
Inadequate water supply threatens livelihoods and poses a public health risk to households not served by pipe-borne water systems (Howard & Bartram, 2003). For such households, rainwater harvesting (RWH) systems and water purchased from water tanker service (WTS) providers are among the alternative but complementary sources of water supply that can contribute different quantities towards meeting the WHO service levels for water consumption (hydration and food preparation) and hygiene (Howard & Bartram, 2003). For example, in Accra, residents of single-family dwellings—those constructed and sold by real estate developers—who are not reliably served by pipe-borne water tend to depend on RWH and WTS providers. However, the availability of water from each of these sources is not limitless; the potential of RWH can be constrained by perceived quality, amount of rainfall and size of roof (Ahmed, 1999; Domènech & Saurí, 2011), while that from WTS is constrained by purchase costs relative to a household's income and vendor service reliability. Studies on the potential of RWH for domestic use therefore tend to focus on comparing prescribed household water demand with available supply from rooftops, and form the basis for recommending the storage capacity to install (Oke & Oyebola, 2015; Oteng-Peprah, Osei-Marfo, Duncan, & Sitsofe, 2014; Silva, Sousa, & Carvalho, 2015). Results of such studies are beautifully summarized in Ghana's Water Policy document: "Rainwater harvesting has a great potential to increase water availability…[and]…could provide a reasonable amount of water for household and other institutional water needs thereby reducing demand on the pipe-borne system and therefore the resource" (MWRWH, 2007, p. 3). Is there any empirical evidence in Accra to support this claim? Our purpose is to answer this question, using an approach unprecedented in the existing literature.

Unlike the current approach of using design or prescribed per capita water consumption values to evaluate the potential of RWH, we use the existing level of consumption obtained from WTS as a measure of the "demand" to be met through RWH. We then compare the per capita water supply from RWH with the per capita water consumption from the existing WTS, and also with the WHO standards for water consumption and hygiene. Here, we were especially interested in making probabilistic estimates—known in probability theory as exceedance values—of the extent to which the per capita water values from each source (RWH and WTS) exceeds the WHO threshold values of 5, 20, 50 and 100 lpcd. Thus, we are able to evaluate the potential of RWH, not only in comparison with existing consumption levels, but also with demand thresholds that define the level of health risk associated with various levels of water consumption Such a comparison might be important to at least households and to water policy makers. Although both alternatives require an investment in storage capacity, water from RWH is virtually free compared to the cost of purchasing from WTS providers (Nnaji, Eluwa, & Nwoji, 2013). If comparable quantity (and, to a large extent, quality) of rainwater can be assured, then there should be little economic motivation for overdependence on water from vendors. Consequently, households should prefer RWH as a main source of water supply, supplemented by water from tanker services where necessary. At the policy level, information on the amount of water obtainable from RWH in comparison with those from WTS, as well as the exceedance values, may be useful in providing the evidence needed to justify and/or to initiate promotional campaigns, as well as legislating and providing incentives for the adoption of RWH systems.

Methods

We surveyed 30 households from Ashongman Estate, a peri-urban community in Accra with a population of about 1500 to 2000. The area was selected for the study because, although water infrastructure exists, supply is infrequent, forcing residents to rely on other sources of water supply such as tanker services, neighbours and rainwater. Our data consists of 10 yrs of monthly rainfall data (1993-2002, which is long enough for studies that might have informed the RWH policy statement published in 2007). It also includes household-level variables such as household size, per capita water consumption and roof area—variables that determine the potential of RWH (Campisano & Modica, 2012; Ghisi, 2010). We obtained household size from a head count of persons in each house and roof area was measured as the plan area of the roof. *Household size* ranged between 1 and 10 persons per household with a median value of 7. *Roof Area* ranged between 93-178 m^2, with a median value of 127.4 m^2.

Per capita water consumption from WTS is not directly observable since metered records do not exist for such services in our study area. To enable us estimate this variable, we collected data on the number and capacities of water storage facilities for each respondent. We conducted interviews to estimate the frequency with which each of these containers is filled for use in a month. We multiplied the monthly fill rate by the container volume and divided the result by 30 to obtain the daily water available from each tank. We summed these daily values to obtain an estimate of daily water consumption per household. We then estimated the per capita water consumption by dividing the total household water use by *household size*. Figure 1 is a screenshot of an Excel model we created to implement our estimation procedure.



House No. A23
Location xxx
Household size 5

Total Daily water 620.68
Per capita consumption ***124.14***
Roof Area 127.00

Container Type	Volume	Unit measure	Size(liters)	Monthly Fill Rate	Daily use
1	40	gallons	180	30	180.00
2	200	liters	200	1	6.67
3	1000	liters	1000	1	33.33
4	345	gallons	1552.5	1	51.75
5	234	liters	234	2	15.60
6	5000	liters	5000	2	333.33

Note: 1 gallon = 4.5 liters

Total for household **620.68**

Figure 1. Model for estimating a households' per capita water consumption based on water obtained from water tanker service providers.

Source: Author's construction

To estimate the potential per capita water supply from RWH, we re-arranged the variables shown in equation (1), which equates annual household water demand to annual water supply from roof-tops. Here, q measures the per capita water consumption in lpcd; N is the size of the household; c is the run-off coefficient, taken as 0.8 here; A is the roof area, measured in m^2; and R is the average annual rainfall for Accra, estimated at 816 mm.

$$q*N*360 = c*A*R \ldots \qquad (1)$$

Our interest in making probabilistic statements about the differences in the service levels offered by RWH and the existing water use required that we fit probability distributions to the per capita water consumption data for both sources. We tested alternative distributions to determine which one fits the data best. We examined the Normal, Lognormal and Generalized Extreme Value (GEV) distributions, using the log likelihood estimates in Matlab as our criterion. As indicated in Table 1, the normal distribution was a poor fit while the GEV distribution was the best fit. Our probabilistic assessment was therefore made using the GEV distribution, although we also compared our results with those from the lognormal distribution. We computed these exceedance values at the WHO service levels for water consumption and hygiene.

Table 1. Log likelihoods for alternative models fitted to per capita water consumption data for RWH and for water tanker services (WTS)

Table cell heading	RWH	WTS
Normal	-153.67	-135.83
Lognormal	-132.17	-132.45
GEV	-128.40	-132.38

Results

Statistical analysis of our data (see Table 2) shows that generally the per capita water consumption from RWH are lower but more varied than those from WTS (also see Figure 2). Ignoring the inferior fit of the normal distribution, the 95% confidence intervals of the mean values are as shown in Table 2. The overlapping nature of the intervals (see also Figure 3) is a suggestion that the mean values of the two variables are not statistically different.

Table 2. Statistics of per capita water consumption data: RWH & WTS, Accra. N = 30

Source of water	Min	Max	Median	Mean	s.d	95% Confidence interval	
						LB	UB
RWH	17	240	36.50	45.30	41.27	29.88	60.71
WTS	21	117	51.89	56.74	22.77	48.24	65.24

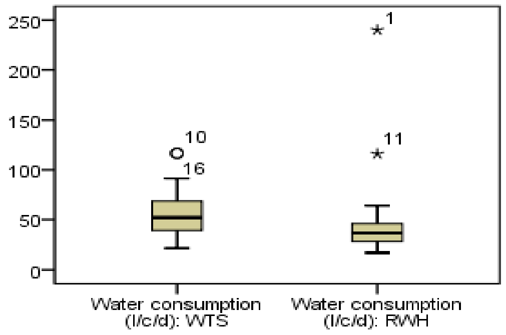


Figure 2. Distribution of per capita water consumption
Source: Author's construction

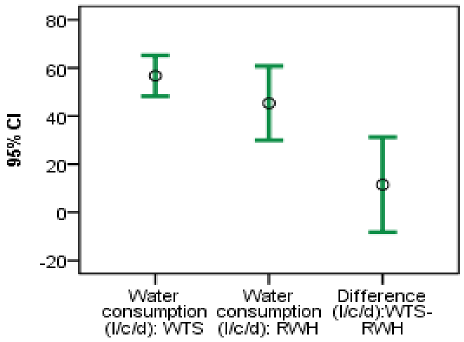


Figure 3. 95% Confidence intervals of per capita water consumption data
Source: Author's construction

The probability distributions and the survival curves for the two per capita water consumption values are shown in Figure 4 and Figure 5 respectively. The distribution for WTS is less picked and is generally shifted to the right of the distribution of RHW. The survival curves depicted in Figure 4 indicates that the exeedance probabilities for WTS are generally larger than those for RWH at all levels of per capita water consumption, except for values above about approximately 100 lpcd. Thus, the per capita consumption values for WTS stochastically dominates those of RWH.

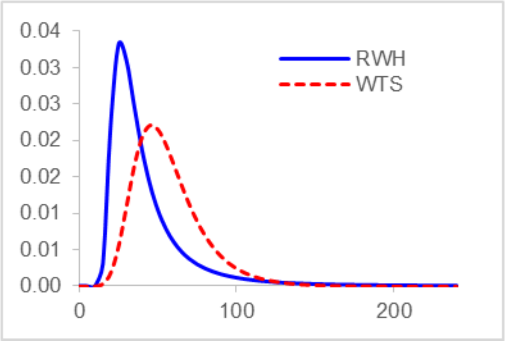


Figure 4. Probability distributions of per capita water consumption
Source: Author's construction

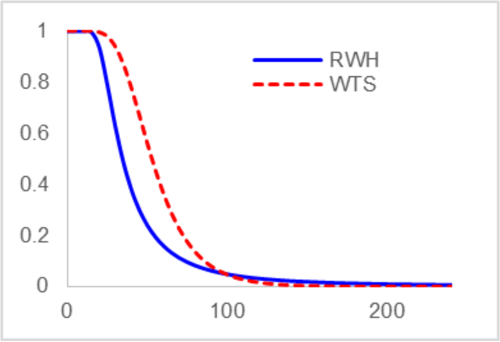


Figure 5. Survival curves of per capita water consumption
Source: Author's construction

The exact exceedance probability values computed with Matlab are presented in Table 3, both for the lognormal and GEV distributions. As expected, these probabilities decrease with increasing service level, but the lognormal distribution generally underestimates the probabilities for RWH, except for the 50 lpcd service level. From the GEV distribution, WTS produce higher exceedance probabilities compared to RWH at all service levels except the Very Low Risk category.

Table 3. Exceedance probabilities for WHO's service levels for water consumption and hygiene

WHO service level	Lognormal Distribution		GEV Distribution	
	RWH	WTS	RWH	WTS
5 lpcd: Very High Risk	99.99%	100%	100%	100%
20 lpcd: High Risk	88.10%	99.40%	93.70%	99.40%
50 lpcd: Low Risk	29.78%	55.60%	23.90%	55.50%
100 lpcd: Very Low Risk	3.41%	4.87%	4.74%	4.67%

Discussion

In this study, we have evaluated the potential of rainwater harvesting for residential water supply by comparing the per capita water consumption (supply) levels accessible from rainwater harvesting (RWH) systems with what is actually obtained from water tanker service (WTS) providers for single-family households in Accra. We fitted probability distributions to our data set, enabling us to obtain and to compare exceedance probabilities at the service levels for water consumption and hygiene, as defined by the WHO. Our results showed that although the per capita consumption values arising from WTS providers ("demand") stochastically dominated those from RWH, the difference did not appear to be statistically significant. Expectedly, the choice of probability distributions affected our results on exceedance probabilities: compared to the GEV distribution, the lognormal distribution generally underestimated the exceedance probabilities for RWH. The difference in the per capita consumption values can be explained by the fact that RWH is a function of household size, roof area and quantity of annual rainfall. The relatively lower rainfall values for Accra, located in the south-east of Ghana, might be responsible for the lower per capita water consumption values obtained from RWH. Therefore, given the same housing and household conditions in any replicated study, we would expect the positions of the survival curves to be reversed in the south-west, where annual rainfall is around 2,000 mm.

Since we found no empirical evidence to reject the MWRWH (2007, p. 3) claim on the potential of RWH, we conclude that for single-family dwellings in Accra, the combination of roof and household sizes, and the level of annual rainfall is such that water from rainwater harvesting is (1) sufficient to contribute immensely to, if not completely satisfy, present levels of water consumption from tanker service providers, and (2) has enough potential to increase water availability for meeting the WHO service levels for water consumption and hygiene. Because water from RWH systems, which though may have quality issues, is inexpensive compared to WTS providers, households who wish to minimize their expenditure on water purchases and to increase availability of water, should therefore consider greater dependence on RWH.

This recommendation has several implications: (1) It suggests the need for installing adequately sized storage tanks, but whether in practice this is actually the case in Accra is yet to be empirically examined. We explore this question on storage capacity decision in a subsequent study; (2) Water from RWH and tanker service providers are complementary alternative sources for meeting the water supply needs of a household, and when used together may contribute substantial shares of a households water demand. Future research could therefore look at how water from these sources could be blended to meet the quality and quantity needs of households, given the cost of purchasing water from WTS and constraints on the quantity of rainfall; (3) Increasing water availability through RWH to meet the WHO service standards has implications for real estate development. For any given part of the country, installed roof sizes must be large enough to ensure a service level that should be prescribed by policy, enforced by legislation for compliance, and incentivised for adoption.

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