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Demand-side water management using alternative water sources based on residential end-use

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ABSTRACT

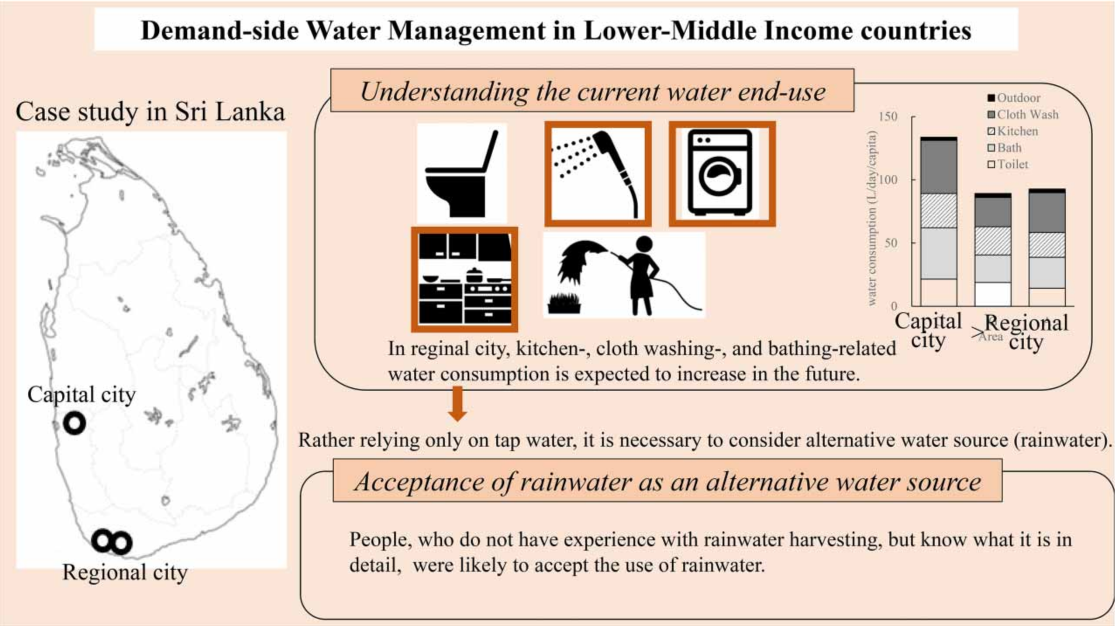
Demand-side water management in developing countries should ideally involve controlling the use of piped water supply and securing water sources that complement it to ensure sustainable use. To investigate the feasibility of incorporating these factors, we conducted a survey in Galle, Sri Lanka. First, an end-use survey was conducted to understand current and near future water use. The results indicated that the toilet, kitchen, clothes washing, and bathing related per capita water consumption in Galle was significantly lower than that in Colombo. The results also suggested that increases in indoor water needs cannot be supplemented via piped water supply only; it is necessary to consider alternative water sources, such as rainwater. Second, the residents' acceptance of rainwater usage for each indoor use was surveyed and it was found that acceptance depended on knowledge levels regarding rainwater harvesting.

Key words: alternative water sources, demand-side water management, knowledge level, LMI countries, rainwater acceptance, water end-use

HIGHLIGHTS

- Residential water end-use in some places in Sri Lanka was investigated.
- People in the capital city use more water than those in the regional city.
- Toilet, kitchen, clothes washing, and bathing water usage varied based on region.
- Tap water supply alone may not be sufficient to meet increasing water demand.
- Rainwater acceptance was influenced by the knowledge level about its specific use.

GRAPHICAL ABSTRACT



INTRODUCTION

Demand-side water management has gained significant attention worldwide as a means to ensure the sustainable use of water in residential areas. In this regard, developed economies have implemented demand-side water management policies to reduce and control consumption, and achieve a greater level of sustainability (Inman & Jeffrey 2006; Willis *et al.* 2011; Daniell *et al.* 2015; Tortajada *et al.* 2019). Subsequently, substantial knowledge of pricing and non-pricing measures has been accumulated (Nauges & Whittington 2010). Among developing economies, water use scenarios differ between upper-middle income (UMI) and lower-middle income (LMI) countries, as classified by the Development Assistance Committee (DAC) List (Organisation for Economic Co-operation and Development (OECD) 2021).

South Africa, a UMI country, successfully changed water use behavior and achieved efficiency in water-use through pricing (water tariffs) and non-pricing (restrictions and water conservation campaigns) measures after a serious drought in 2015 (Brick & Visser 2017; Booysen *et al.* 2019; Matikinca *et al.* 2020). However, demand management, which aims to control the use of piped water, cannot be directly applied in developing countries below the LMI threshold, because the water-supply situation is different and the reality of water use is unclear. For instance, not all residents have access to piped water supply, and when they do, it is only available for a limited time. Furthermore, the quantity of water used in each household is also unclear.

Although water demand is expected to increase in cities due to population growth and urbanization, it is unrealistic to plan to meet future water demand using only piped water-supply systems, which require advanced technologies, vast organizational and operational knowledge, and substantial financial resources (Lawens *et al.* 2019). Considering the implementation of water management policies in LMI countries, the primary requirement is to secure sufficient clean water and respond to the increasing demand, while improving living standards and changing consumption patterns to promote sustainability (Vörösmarty *et al.* 2000; Ercin & Hoekstra 2014; Hussien *et al.* 2016). Therefore, demand-side water management in LMI countries is not only to control piped water use, but also to secure other water sources that can supplement the piped water supply.

In particular, regional cities (i.e., cities other than the capital) in LMI countries have poor water supply. The limited resources available are allocated to the development of infrastructure in the capital and for the industrial sector. Investment to develop regional infrastructure is often left for later, creating pressure on the services in these cities (Straub 2008). In many regional cities, piped water supply cannot be expected to satisfy the increasing domestic demand, and it is necessary to consider secondary sources to supplement the water supply. Potential secondary sources that can complement piped water supply in LMI countries include groundwater, followed by rainwater depending on rainfall conditions. However, groundwater in regional cities of LMI countries is sometimes associated with water quality issues due to poor or limited domestic wastewater treatment methods (e.g., poor solid waste management and the use of onsite sanitation facilities) (Rao *et al.* 2013; Andersson *et al.* 2016; Martinez-Santos *et al.* 2017). Rainwater can be considered as an alternative water source where there is sufficient rainfall. As the quality and quantity of the secondary source varies from region to region, it is necessary to understand the end-use and to consider which secondary sources can be used for which purposes.

Galle, a regional city in Sri Lanka (an LMI country), South Asia was used as a case study for demand-side water management. The Asian Development Bank (ADB) indicates that household and urban water security in Sri Lanka is worse than that in other Asian countries (ADB 2013; Arfanuzzaman & Rahman 2017). First, an end-use survey was conducted to understand the reality of water use. The survey obtained information regarding domestic water use, such as for toilet, kitchen, clothes washing, bathing, and outdoor purposes. Then, by comparing water use in Galle with that in Colombo, the capital, which is characterized by a more modern and urbanized lifestyle, we attempted to predict how water use in the regional city will change in the medium term.

METHODS

Figure 1 is a flow diagram for the study in Galle. Where consumption is excessive, the aim is to identify usage control methods. In case of insufficient water consumption, the aim is to investigate residents' acceptance of alternative water sources, given that it is difficult to meet all future increases in demand with piped water supply alone.

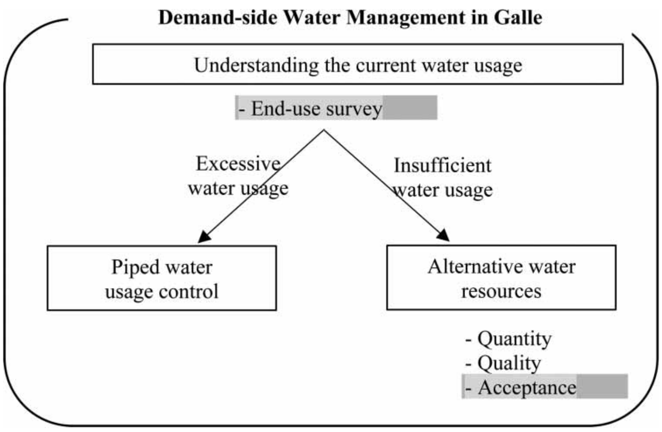


Figure 1 | Study flow diagram.

Study site

Sri Lanka has two major climatic regions – the wet and dry zones (Domroes & Ranatunge 1993). In this study, Galle, one of the cities in the wet zone, was chosen as the study site to investigate the potential of rainwater harvesting. Taking into account its average annual precipitation, catchment area (i.e., estimated from the total area of house roofs) and the average household size (Burt & Weerasinghe 2014; Takagi *et al.* 2018), the usable rainwater is calculated to be 93.2 L/capita/day, making rainwater harvesting feasible in Galle. A previous study also indicated that, given the practicality of installing rainwater tanks, rainwater could serve as a water source for current toilet-related water consumption (Takagi *et al.* 2019). Moreover, it has been reported that groundwater in Galle is associated with health risks because of inadequate wastewater treatment, among other reasons, (Otaki *et al.* 2021) making it suitable only for toilet-flushing and outdoor-related uses.

End-use survey

An end-use survey on domestic water consumption was conducted in three areas (Figure 2). The first area was an urban area around Colombo, and was surveyed between June and November 2018 (25 households; Area C). The second was an urban area around Galle, surveyed from June to October 2017 (32 households; Area G). The third was a peri-urban area around Galle, surveyed from June to October 2017 (70 households; Area A). Sri Lanka comprises 25 districts. It is worth noting that the mean size of households in the three areas is about the same. Piped water supply is accessible to 64.8% and 19.8% of the population in the Colombo and Galle districts,

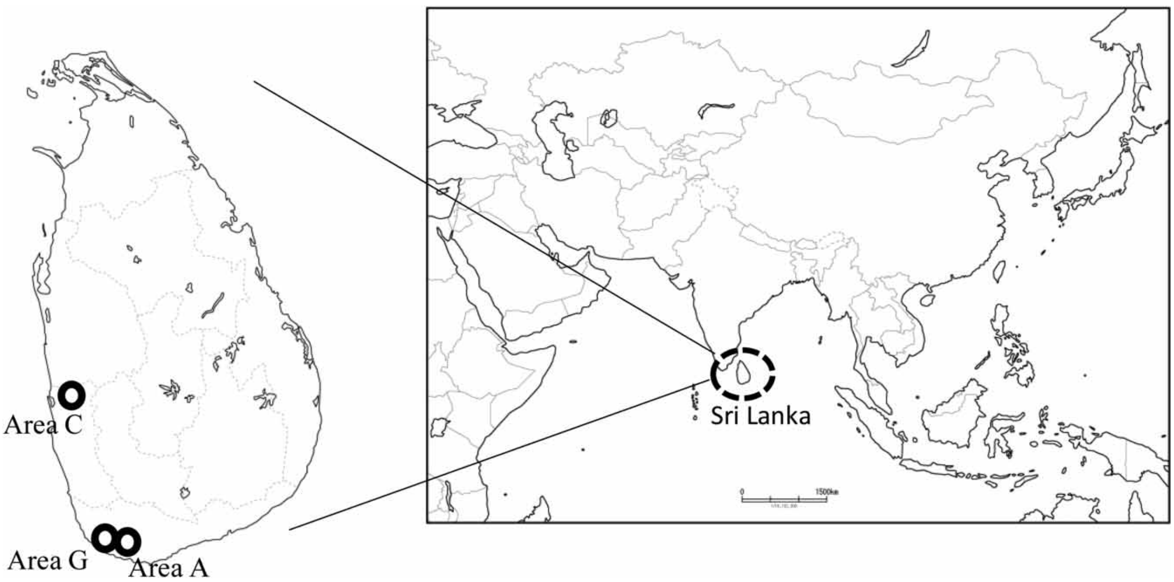


Figure 2 | Geographical setting.

respectively. Although piped water supply is available in the surveyed areas, most households have storage tanks on the roof given that the supply is intermittent and has low pressure. The National Water Supply and Drainage Board (NWSDB), which is responsible for water supply throughout Sri Lanka, plans to provide 140 L/capita/day in urban areas and 110 L/capita/day in rural areas (Department of Census & Statistics Sri Lanka 2012). However, actual per capita water consumption is not clear, because there is no statistical data.

To determine the end-use water consumption, an impeller-type integrating flow meter (DigiFlow 6710M; Savant Electronics Inc., Taiwan) was attached to all faucets in the surveyed households. The households were selected via snowball sampling, one of the non-probability samplings. After these installations, weekly meter readings were recorded for 2–3 weeks, after which the average per capita daily water consumption was calculated (L/capita/day) as a function of use (i.e., toilet, kitchen, clothes washing, bathing, and outdoors). Due to the limited number of flow meters as well as the time and labor required for installation, only 3–8 households could be surveyed simultaneously. Naturally, this then increased the duration for the completion of the survey. There were concerns regarding seasonal variations in water use due to the prolonged duration of the survey, but no such significant impacts were observed due to small, inter-seasonal temperature fluctuations and low outdoor water use, which was affected by precipitation (Figure 3).

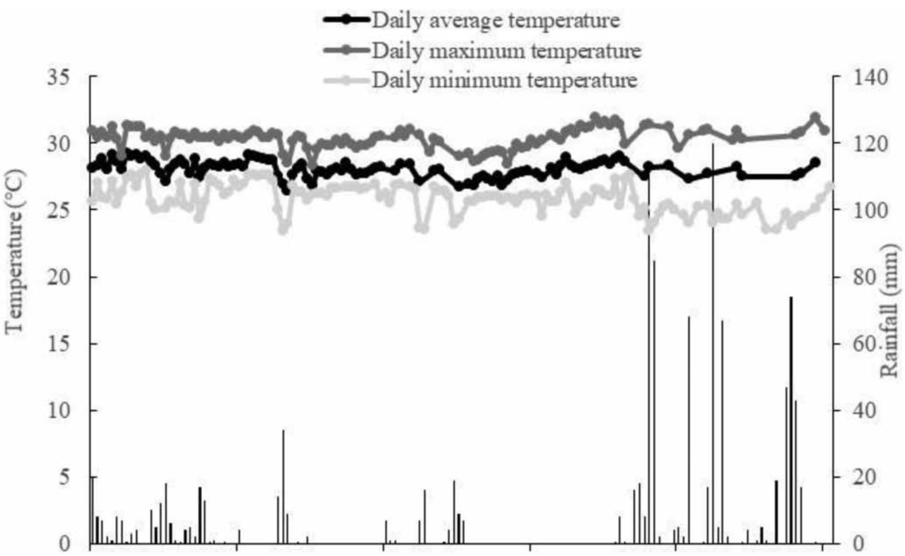


Figure 3 | Variation of temperature and rainfall in Galle.

Acceptability of rainwater usage

An interview survey was conducted in Area G between December 2019 and March 2020. This included 46 households with piped water supply that were selected via snowball sampling. First, the households were asked whether they would accept rainwater harvesting as an alternative water source for each indoor use ('acceptance'). Second, to investigate their knowledge of rainwater harvesting, they were asked to describe what they knew about it. Their responses were categorized into four knowledge levels: (1) know nothing; (2) have heard of it; (3) have detailed knowledge but no experience; and (4) have experience. Respondents were also asked what they thought the amount and duration of piped water supply would be after 10 years. Their responses were categorized on an 11-point scale (amount: 0 [insufficient] to 10 [sufficient], duration: 0 [shorter] to 10 [longer]).

R version 3.6.3 (R Core Team 2021) was used for all the statistical analyses.

RESULTS AND DISCUSSIONS

End-use water consumption

Given that the water consumption was log-normally distributed, the analysis was performed using logarithmically transformed values. The mean and standard deviation corresponding to each end-use by area are shown in Table 1. These values were calculated using the logarithmic values, which were then transformed again to normal values. Figure 4 shows the average water consumption, summing the mean value of each end-use. People in Area C use approximately 140 L/capita/day, which is the target of NWSDB, while those in areas G and A (urban and peri-urban) use less water, approximately 90 L/capita/day. This suggests that the demand-side water management in the regional city should focus more on considering alternative water sources than on controlling water use. Regarding the mean water consumption of each end-use, the Turkey–Kramer multiple

Table 1 | End-use mean and standard deviation by area

		Area		
		C	G	A
Toilet	Mean	21.52	18.90	14.31
	SD	1.88	1.98	1.89
Bath	Mean	40.57	21.67	24.39
	SD	1.89	1.98	1.97
Kitchen	Mean	27.06	22.31	19.69
	SD	1.58	1.77	1.80
Clothes washing	Mean	42.06	23.13	31.47
	SD	2.06	2.16	1.78
Outdoor	Mean	2.46	3.20	2.89
	SD	2.59	5.40	1.46

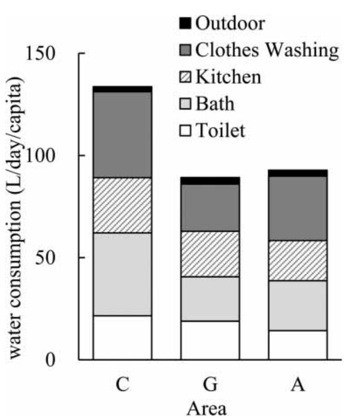


Figure 4 | Average per capita water consumption by area.

comparison test was carried out to see if there were statistically significant differences between the means of each end-use in the three target regions. The results indicated that toilet, kitchen, clothes washing, and bathing related water use varied on a regional basis (Table 2). Figure 5 illustrates a comparison of the means, showing significant differences in multiple comparisons.

Table 2 | Results of Turkey-Kramer multiple comparison test

	***p* value**		
	A vs G	**A vs C**	**G vs C**
Toilet	0.113	0.026**	0.742
Kitchen	0.553	0.048**	0.413
Clothes washing	0.077*	0.155	0.003***
Bath	0.697	0.014**	0.006***
Outdoor	0.935	0.877	0.761

***: $p<0.01$, **: $p<0.05$, *: $p<0.1$.

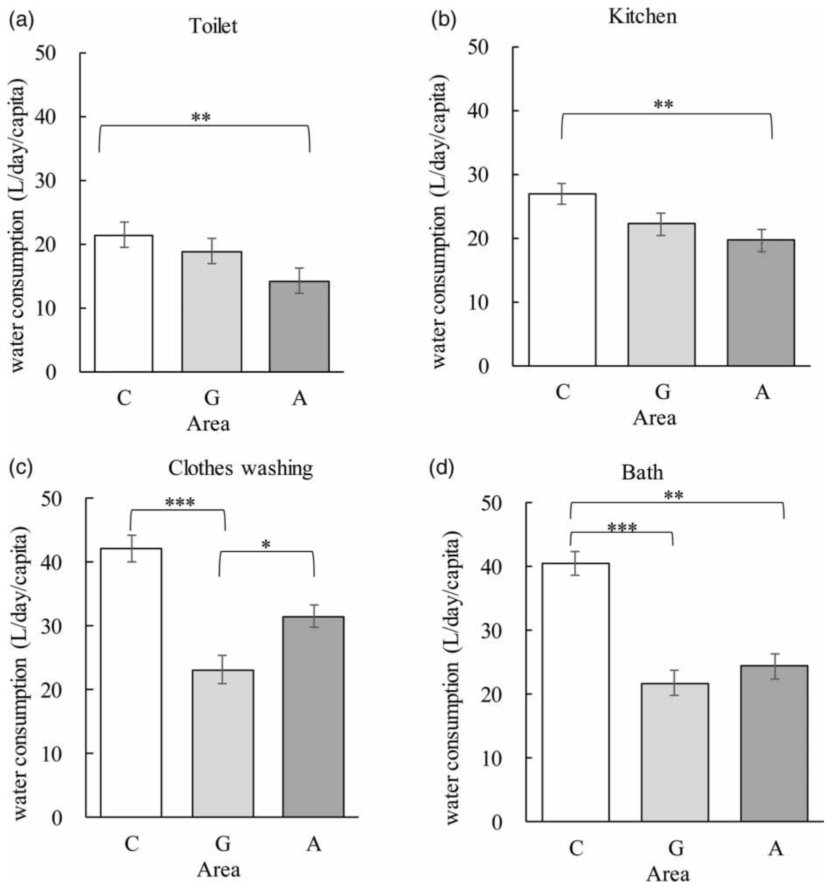


Figure 5 | Comparison of means corresponding to water consumption as a function of end-use. (a) Toilet, (b) Kitchen, (c) Clothes washing, and (d) Bathing uses.

Toilet-related water consumption was significantly higher in Area C than in Area A. This could be attributed to the use of different toilet types owing to modernization. In Asia, people have been flushing toilets with water from a hand tub (i.e., water bucket); however, in recent years, flush toilets have become popular in urban areas, and in the surveyed areas, the percentage of households that primarily use flush toilets in Areas C, G, and A were 80, 75, and 10%, respectively. This indicates that, while flush toilets are prevalent in the cities, they are not yet widespread in peri-urban areas. Therefore, while toilet-related water use may not be significant in the present urban areas of Galle, it may increase in the future owing to urbanization and the increasingly widespread use of flush toilets in peri-urban areas. In such a situation, demand-side water management could promote (i) installing water-saving devices along with new flush toilets; and (ii) considering alternative water sources for toilet use.

Kitchen, clothes washing, and bathing-related water consumption in Area C was also significantly higher than those in other areas; particularly for bathing-related use. Previous research has demonstrated that the per capita water consumption is inversely correlated with the household size (Keshavarzia *et al.* 2006; Fan *et al.* 2013; Sadr *et al.* 2016). The results of the survey showed that the mean family sizes of households in areas C, G, and A, were 4.56, 4.25, and 4.04, respectively, which are not significantly different (F=2.03, p=0.16). Therefore, the differences in water consumption could not be attributed to differences in household size. The difference might arise from differences in the equipment and facilities used in the different areas. For example, in areas where residents have more modern lifestyles – such as Area C – the households have more convenient cookware, washing machines, and shower facilities.

When considering future water consumption in a regional city, it can be assumed that the lifestyles and economic situation will try to catch up with those in the capital. Average water consumption in Colombo, the capital, is currently approximately 1.5 times that in Galle, with particularly large differences in consumption for bathing and clothes washing. This implies that, rather than relying only on piped water supply, alternative water sources must be considered in Galle. Additionally, even if groundwater alone is used for outdoor purposes, covering future increases in indoor water needs via piped water supply remains infeasible. Therefore, residents' acceptance of the use of rainwater for indoor purposes was therefore examined in Galle.

Acceptance of rainwater as an alternative water source

Rainwater harvesting is recognized as a complementary water source to piped water supply in developing countries and has been considered in previous studies (Helmreich & Horn 2009; Karim *et al.* 2015; Amos *et al.* 2018). The acceptance of rainwater as an alternative source for each end-use is shown in Figure 6. While more than 90% of the respondents accepted the use of rainwater for outdoor purposes, few respondents accepted it for indoor use, especially for kitchen-related purposes. Therefore, the relationship between rainwater acceptance for toilet, bath, and clothes washing purposes and the knowledge level regarding rainwater harvesting was analyzed. Between 30 and 50% of respondents accepted the use of rainwater for these purposes (Figure 7). Additionally, there was a significant difference (Fisher's exact test, p=0.034) in the acceptance of rainwater use for bathing depending on the knowledge level. Multiple comparisons revealed that respondents with knowledge level 3 (i.e., no experience with rainwater harvesting but know about it in detail) showed a higher acceptance of rainwater use for bathing than did respondents with knowledge level 2 (i.e., have heard about rainwater harvesting). These findings indicate that the acceptance of rainwater as an alternative water source increases as the knowledge level of rainwater harvesting increases. Acceptance of rainwater use as an alternative for toilet and clothes washing purposes measured as a function of knowledge was also marginally significant (Fisher's exact test; p=0.097 and 0.072, respectively). This indicates that providing more detailed knowledge of rainwater harvesting, such as its collection from roofs and storage in tanks, may have a positive effect on its acceptance.

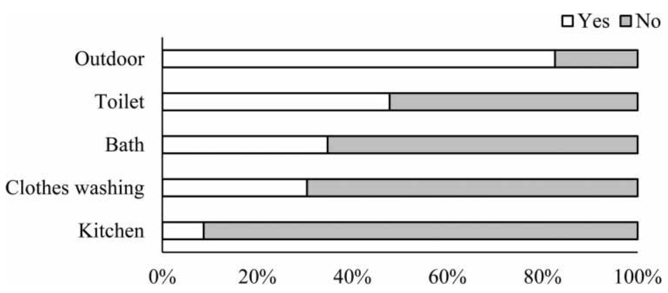


Figure 6 | Acceptance of rainwater for each end-use.

Medium-term water availability

Regarding the future of piped water supply, many residents expressed a conservative view of its amount and duration (Figure 8). Thus, if rainwater is accepted as an alternative source, it may be possible to eliminate concerns regarding future water scarcity and improve the quality of life. This study revealed differences in the initial

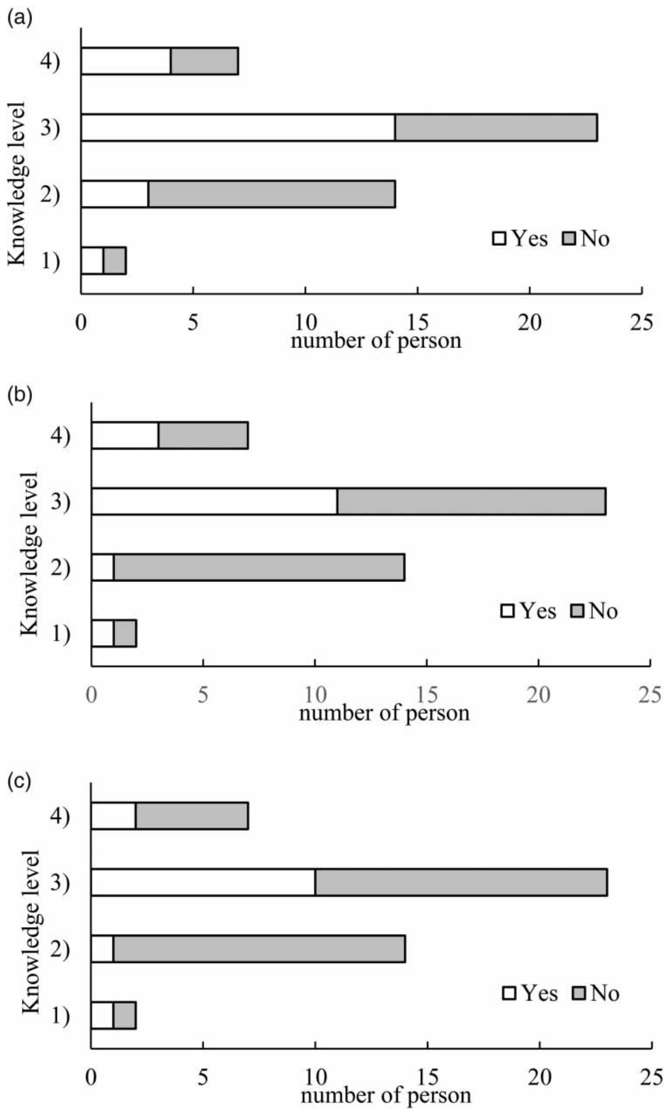


Figure 7 | Relationship between rainwater acceptance and knowledge level of rainwater harvesting for (a) Toilet-, (b) Bathing-, and (c) Clothes washing-related uses.

acceptance of rainwater depending on knowledge level – that is, having knowledge of more specific ways to use rainwater led to an increase in its acceptance. Takagi *et al.* (2019) demonstrated that the provision of information on rainwater harvesting – such as cost, quality, availability, and the natural water cycle – increases its acceptance to some extent. However, given that residents have varying levels of knowledge regarding rainwater harvesting, it is not clear in what cases acceptance would increase and which item(s) of information, if shared, would be effective.

Limitation

This study has certain limitations. As evaluating the end-use of water in households is time-consuming and labor-intensive, it was not possible to include a large number of households in the surveys. Some studies have successfully disaggregated water end-use by machine learning of water-flow patterns (Nguyen *et al.* 2019; Meyer *et al.* 2020). However, application of this method in LMI countries remains a challenge, as stored water is often used. Therefore, it was not possible to have a concrete quantitative discussion on whether there is a shortage of water and, if so, to what extent.

Additionally, there is a gap between self-proclaimed and actual knowledge (Sloman & Fernbach 2017) and it was not possible to identify the actual knowledge level regarding rainwater harvesting using simple methods such as the Likert scale (Koutiva *et al.* 2015). It would be necessary to conduct in-depth interviews to understand the

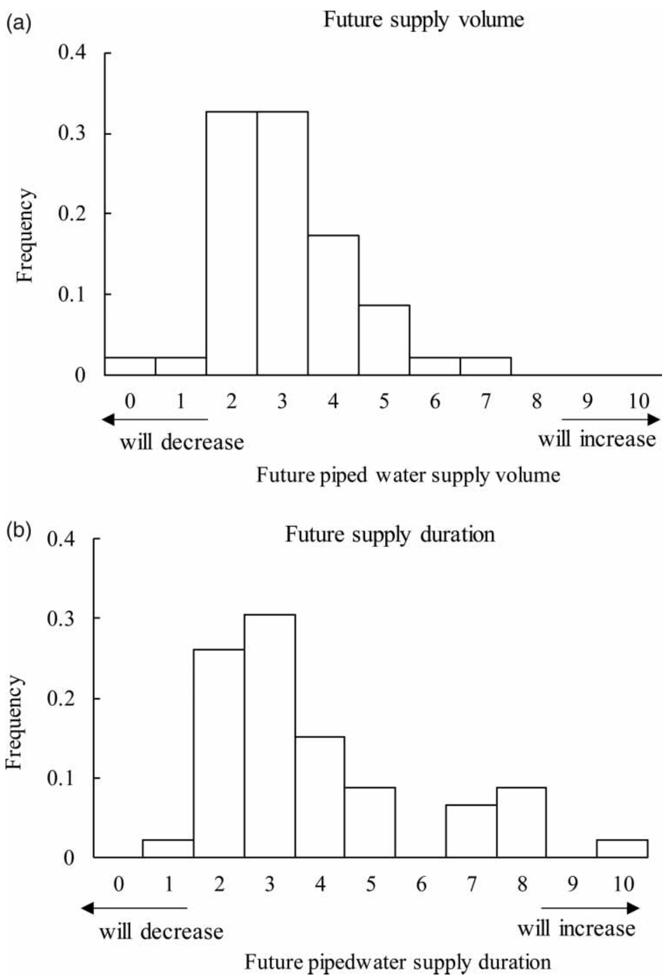


Figure 8 | Residents' views regarding future piped water supply. (a) Volume and (b) duration.

true knowledge level. Interviews were conducted in this study to determine the level of knowledge, but as they were still time-consuming, it was not possible to obtain a large sample.

CONCLUSIONS AND RECOMMENDATIONS

This study investigated the end-use of water in the residential areas of Galle, Sri Lanka. It was observed that piped water supply alone may not be sufficient to meet the increasing water demand in the medium term given that bathing water use as well as kitchen and clothes washing water use are likely to increase significantly. In current urban areas, an increase in toilet-related water use is not expected. However, as urbanization increases, its increase is expected. Therefore, residents' potential acceptance of rainwater as a complementary source to piped water was examined, and it was found that people are likely to accept the use of rainwater for toilet, bathing, and clothes washing purposes depending on their knowledge level of rainwater use. Therefore, to promote its future use, it is important to teach specific rainwater harvesting and usage methods.

In Galle, which was the target area for this study, as well as in other cities in LMI countries, it is difficult to utilize groundwater owing to the absence of the proper treatment of human excrement and wastewater (Otaki *et al.* 2021). Thus, it is hoped that the findings of this study will serve as a reference for the development of alternative solutions to water-supply related problems faced by many such cities in LMI countries.

ACKNOWLEDGEMENTS

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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