Research Paper

Urban household water resilience and source selection in Nepal pre- and post-disaster

Sadhana Shrestha, Yoko Aihara, Arun P. Bhattarai, Niranjan Bista, Naoki Kondo, Kazama Futaba, Kei Nishida and Junko Shindo

ABSTRACT

Urban areas in low- and middle-income countries are under chronic water stress, and multiple water source use (MWSU) is common. A detailed study on MWSU is necessary for strengthening water security and enhancing household water resilience to natural disasters which is defined as the ability of a household water system that is exposed to a disaster to resist, accommodate, and recover efficiently in a short time. Surveys were conducted in the Kathmandu Valley, Nepal, before and after the 2015 Gorkha earthquake. A classification of resilient and non-resilient households was based on respondents' perception scores of their water systems before the earthquake and one month after. Around 80% of households used two to three water sources, and 70% of households were classified as water resilient. Three characteristics of a water resilient household were: (i) use of greater number of water sources, (ii) use of multiple reliable water sources such as piped water, groundwater, and (iii) use of effective adaptive strategies such as water storage in a bigger container. Since the study showed the practice of MWSU enhanced the resilience, protection and management of local water sources (well, spring, stone spouts) by initiatives of local government or communities or both is recommended.

Key words | adaptive strategies, earthquake, household, multiple water sources use, natural disaster, water security

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HIGHLIGHTS

- The research examines the change in use of multiple water sources in low- and middle income countries after a natural disaster.
- It distinguishes the water sources being used for consumptive and non-consumptive purposes.
- It examines status of household water resilience after a natural disaster in urban area of a low-income country.
- It provides water-related characteristics of households that were water resilient.
- It provides evidence of utilizing the common characteristic of 'multiple water source use' for increasing water security and enhancing water resilience against natural disaster.

INTRODUCTION

Many low- and middle-income countries have intermittent water supply due to poor management and financial and technological constraints (Nazarnia *et al.* 2015). Consequently, multiple water source use (MWSU) is commonly practised by households to meet their domestic water demand (Howard *et al.* 2002; Ozdemir *et al.* 2011;

doi: 10.2166/washdev.2020.042

Yoden 2012; Evans *et al.* 2013; Tucker *et al.* 2014; Shrestha *et al.* 2015; Elliott *et al.* 2017; Foster & Willetts 2018). A wider disparity between water demand and supply is evident in cities due to the increasing water demands from incessant urban migration; this situation contributes to the problem of chronic water stress (Ozdemir *et al.* 2011; Elliott *et al.* 2017; Shrestha *et al.* 2017).

Global agendas, including the previous Millennium Development Goals (goal 7, target c) and current Sustainable Development Goals (goal 6.1) focus on primary drinking water sources for substantially improving people's access to water. However, when MWSU is commonly practised, prioritizing primary drinking water sources seems to have a narrow focus (Elliott *et al.* 2017), particularly because there is a marked difference in the sources used for consumptive (drinking/cooking) and non-consumptive purposes (bathing, handwashing, etc.). There are potential public health risks from using poor-quality water for non-consumptive purposes (Aihara *et al.* 2014; Shrestha *et al.* 2015), and neglecting water sources other than those used for drinking fails to address the impacts of household water on health and development (Elliot *et al.* 2019). MWSU is a complex phenomenon as water sources, their combination, and the purpose of use are diverse and are driven by different factors, including the performance of the piped water supply, the availability of water sources, the socio-economic situation of the household, and seasonal influences on supply. Although MWSU is a diverse, widespread and essential practice (Elliot *et al.* 2019), the availability of literature that describes and quantifies its details and mechanisms and examines the relationship between water sources used for consumptive and non-consumptive purposes (Elliott *et al.* 2017) is limited.

Resilience, in the context of a social system, has been defined as 'the ability of a system, community, or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner' (United Nations Office for Disaster Risk Reduction 2009). In the context of natural disasters, such as earthquakes, the resilience of the water supply system is of utmost importance to protect public health and maintain well-being (Howard *et al.* 2010). It is recommended that water system infrastructures are strengthened to mitigate the adverse effects of disasters (Cutter *et al.* 2003; Aihara *et al.* 2018). However, in areas where communities rely on alternative sources to piped water, the complete resilience of households may depend both on the water supply infrastructure and other factors, including MWSU. Household resilience to climate change could potentially be boosted by MWSU (Howard *et al.* 2010). Thus, investigating the role of MWSU in enhancing household resilience to natural disasters is beneficial.

Mostafavi *et al.* (2018) assessed water infrastructure resilience in the Kathmandu Valley after the 2015 Gorkha earthquake. They considered the resilience as a process acting under the presence of a chronic stressor, i.e., chronic water scarcity. Their study highlighted that the resilience of the Valley's water system was positively reinforced by the adaptive capacity of the area's social system. Owning a piped water connection and using groundwater from wells were also associated with stronger household perceptions of water system resilience against the 2015 Gorkha earthquake (Aihara *et al.* 2018). These results indicate that MWSU and other adaptive strategies against chronic water scarcity could be linked to households' water resilience to disaster.

In this context, the objectives of this study were as follows: (1) to examine the status of household MWSU pre- and post-disaster, (2) to identify the distinction between the water sources used for consumptive (drinking and cooking) and those used for non-consumptive (bathing, laundry, cleaning and gardening) purposes, and (3) to identify the characteristics of households that were water resilient to the disaster.

METHODOLOGY

Study area

This study selected the Kathmandu Valley, Nepal, as representative of a water-stressed urban area in a low- and middle-income country that is prone to natural disasters, such as earthquakes. Kathmandu Valley is the capital city of Nepal (a low-income country in South Asia) and has a population of 2.51 million (CBS 2011). Kathmandu Upatyaka Khanepani Limited (KUKL) supplies 69 million litres of water per day (MLD) in the dry season and 115 MLD in the wet season against a water demand of 370 MLD (KUKL 2015). Water supply is intermittent (<4 hours per week in the dry season) (Guragain *et al.* 2017; Shrestha *et al.* 2017). Therefore, residents exploit multiple water sources (Shrestha *et al.* 2017) and have developed coping strategies, such as collecting, pumping, treating, storing and purchasing (Pattanayak *et al.* 2005). Globally, Nepal is among the top 15 countries in the world that are exposed to multiple natural hazards including earthquakes and floods (Dilley 2005). On April 25th, 2015, an earthquake of 7.8 M struck Nepal, and the Kathmandu Valley was one of the most affected areas (NPC 2015). The water service was disrupted by damage due to landslides, power outages (which affected water extraction by pump) and damage to household connections (Mostafavi *et al.* 2018).

Study design

A two-stage cluster survey design was used with probability proportional to household size sampling technique. The sampling unit was a household and the lowest administrative unit was a ward. Our study area has 93 wards consisting of more than 40,000 households in total. At the first stage, 37 wards were selected for sampling 50 clusters and a random geographical location was chosen for each cluster using geographic information system. At the second stage, the interviewers were provided with the detail of geographical location of each cluster and they chose 30 households closest to each cluster location randomly before conducting the survey. The details of this longitudinal study design have been explained previously (Shrestha *et al.* 2017). A baseline survey of 1,139 households was conducted between January and April 2015. After the 2015 Gorkha earthquake on April 25th, 2015, a follow-up survey of the same households was conducted between December 2015 and February 2016, which is considered a post-earthquake survey. The inclusion criteria for respondents were being a member of the household and aged 15–60 years. The trained interviewers conducted face-to-face interviews with the selected participants. Out of the 1,139 households in the baseline survey, nine households were excluded due to an invalid respondent age. Of the remaining 1,130 households, 144 could not be contacted in the post-earthquake period, resulting in 986 households. In this study, the administrative divisions refer to those established before January 2017. The data set was previously used in a study on the dynamics of water consumption (Shrestha *et al.* 2017).

Questionnaire

A structured questionnaire was developed, and data were collected via face-to-face interviews. The questionnaire included socio-demographic, economic and water source questions (water quantity, the purpose of use, water storage, water expenditure, etc.). The different types of water sources included in the questionnaire were piped water, private groundwater, rainwater, jar water, tanker water, neighbour's piped water, neighbour's well, public well, surface water and stone spout. Piped water is defined as a municipal water supply provided by a utility company; private groundwater is water extracted from underground via tube wells and dug wells and is present within the household compound; jar water is water marketed in 20 L jars, and tanker water is defined as sources marketed by private vendors who supply water from a truck or tanker. Depending on the ownership, the neighbour's piped water, the neighbour's groundwater, and public wells are considered different water sources in this study. The per capita daily water consumption in litres (LPCD) was calculated by dividing the daily household consumption by the size of the family. The questionnaire also included a water insecurity scale (WIS), which consisted of 15 items rated on a six-point Likert-type scale. The six answers of never, rarely, sometimes, often, mostly, and always were scored from 0 to 5, respectively. Total scores ranged from 0 to 75, and a higher score indicated a higher perception of water insecurity. Aihara *et al.* (2015) validated the scale used in the study area.

During the follow-up survey, respondents were asked to score their perceptions of their own household's water system (quality and quantity combined) before the earthquake (T1) and one month after the earthquake (T2). The score options ranged from very unsatisfied (0), unsatisfied (1), neither satisfied nor unsatisfied (2), satisfied (3), very satisfied (4), and ideal situation (5). Water resilience to the disaster was measured by calculating the difference between the T1 and T2 scores. The households with a negative result were considered to be non-resilient and the households that returned a score of 0 were deemed resilient. Positive results were obtained for the households with a perceived improvement in their water systems, which is less expected in the disaster-hit areas; therefore, they were excluded from the analyses whenever necessary.

The questionnaire was developed in English, translated into Nepali, and translated back into English. Separate groups of Nepalese people in the field of water research were involved in the translation and back-translation processes. After revising the Nepali questionnaire, it was pretested in 30 households, and additional modifications were made based on the results.

Statistical analysis

This study included a group of 986 households that were surveyed before and after the 2015 Gorkha earthquake. Paired sample t-tests were used to compare household characteristics pre- and post-earthquake, such as the number of MWSU used by households along with WIS scores. Phi coefficient of correlation was estimated to examine the relationship between the use of a particular source for cooking and drinking purposes and cooking and non-consumptive purposes. A McNemar's test was applied to determine a change in household behaviour in the use of different water sources and their purpose of use in the post-earthquake period. Independent sample t-tests were used to compare water-related characteristics (volume of household water used in terms of private groundwater, rainwater, jar water, tanker water, etc., and the LPCD and WIS scores) and the number of MWSU used by non-resilient and resilient households separately for the pre- and post-earthquake periods. A chi-square test of independence was applied to examine water storage behaviour and resilience. A generalized estimation equation (GEE) with a binary logistic model was used to identify the water sources that were associated with resilience to disaster using pre-earthquake data. The association of MWSU (used as a continuous variable) with resilience was determined using a univariate GEE model. The GEE model was specially selected to account for the clustering effect resulting from the two-stage cluster sampling design. To examine the changes in water-use storage behaviour, and WIS scores of both non-resilient and resilient groups post-earthquake, McNemar's tests and paired sample t-tests were used, respectively. The IBM SPSS Statistics version 23.0 (IBM Corporation, Armonk, NY, USA) statistical program was used for all statistical analyses.

Ethical consideration

The ethical review board of the University of Yamanashi and the Nepal Health Research Council reviewed and approved the study protocol (Shrestha *et al.* 2017). The participants were informed about the study's objectives and procedures and were assured of their anonymity and confidentiality. They were then requested to participate voluntarily. Those who agreed to the terms and conditions gave their informed consent. Omitting questions and withdrawing from the study were permitted at any time during the interview.

RESULTS

Use of multiple water sources

In this study, the households reported to use a total of ten different water sources: piped water, private groundwater, rainwater, neighbour's piped water, neighbour's well, public well, surface water (lake/pond), stone spout, jar water, and tanker water. The mean number of water sources used per household significantly increased from 2.30 to 2.46 after the earthquake (P-value <0.001). Pre- and post-earthquake, 74 and 84% of the households used two to three water sources, respectively. Figure 1 illustrates the percentage of households using multiple water sources before and after the earthquake. Before the disaster, 171 (18%) households reported using a single water source; this reduced to 76 (8%) households after the earthquake. The maximum number of sources used was five before, which rose to eight after the disaster.

We have reported the percentage of households using multiple water sources along with their purpose of use in pre- and post-earthquake and the percentage point changes after the disaster, in this study. In Figure 2, the percentage

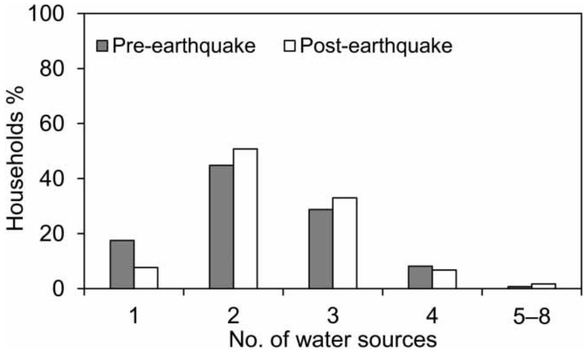

Figure 1 | Multiple water sources used per household for domestic purposes.

of users of the five different water sources (piped water, groundwater, rainwater, jar and tanker water) before and after the earthquake are plotted in x and y axes, respectively, and the size of the bubble denotes the percentage point changes after the disaster. The bigger the size of the bubble, the larger was the percentage change. The percentage of households using private groundwater and jar water increased after the earthquake and this change was larger for jar water (Figure 2(a)). But the percentage of households using rainwater and tanker water declined after the earthquake. Interestingly, the percentages of households using piped water, groundwater and tanker water for drinking purpose declined considerably after the earthquake and this change was larger for tanker water compared to the other sources. But the percentage did not change at all for the jar water. Figure 2(c) shows that except for jar water, the percentage of households using other water sources for cooking purposes declined post-earthquake. The percentage of households using piped water for bathing and laundry purposes declined considerably compared to that of groundwater and tanker water (Figure 2(d) and 2(e)). These details about the other sources are shared in the Supplementary material (Table S1).

To identify the distinction between water sources used for consumptive (drinking and cooking) and those used for non-consumptive purposes (bathing, laundry, cleaning and gardening), we estimated phi correlation coefficient between the use of a water source for cooking and drinking purposes and between the use of a water source for cooking and non-consumptive purposes (Table 1). The use of a water source for cooking was strongly and positively correlated with the use of that source for drinking. But the use of a water source for cooking was not correlated or very weakly negatively correlated with the use of that source for non-consumptive purposes. The pattern of the relationships was similar across the water sources and before and after the earthquake except for the 'neighbour's piped water'. Before the earthquake, the use of the 'neighbour's piped water' for cooking was not correlated with the use of that source for drinking: however, was positively correlated with the use of that source for non-consumptive purposes, but these relationships reversed after the earthquake and aligned with the results of other water sources.

Household water resilience to disaster

Household water resilience to disaster, in this study, is defined as the ability of a household water system that is exposed to a disaster to resist, accommodate and recover efficiently in a short time. This study classified households as water resilient and non-resilient based on the participants' perception scores of their household's water systems before the earthquake and one month after. From a total of 980 households (six households were excluded due to missing answers), 246 (25.1%) were classified as water non-resilient, while 685 (69.9%) were determined to be water-resilient households. Increased perception of their water systems after the earthquake was evident in 49 (5.0%) households and these were excluded from the analysis. Since this classification of household water resilience was based on the respondents' perception scores, we further compared LPCD, household water consumption from different sources, and water insecurity perception between the resilient and non-resilient households to validate this classification. The underlying assumption was that the resilient households will have higher LPCD, lower water insecurity and will use a higher volume of water from different sources (e.g., piped water, groundwater, jar water and tanker water) in comparison to the non-resilient households.

As expected, a greater volume of piped water, groundwater and tanker water (L/day) was used by resilient households both before and after the earthquake compared with non-resilient households (Figure 3). Before the earthquake, the average LPCD of resilient households

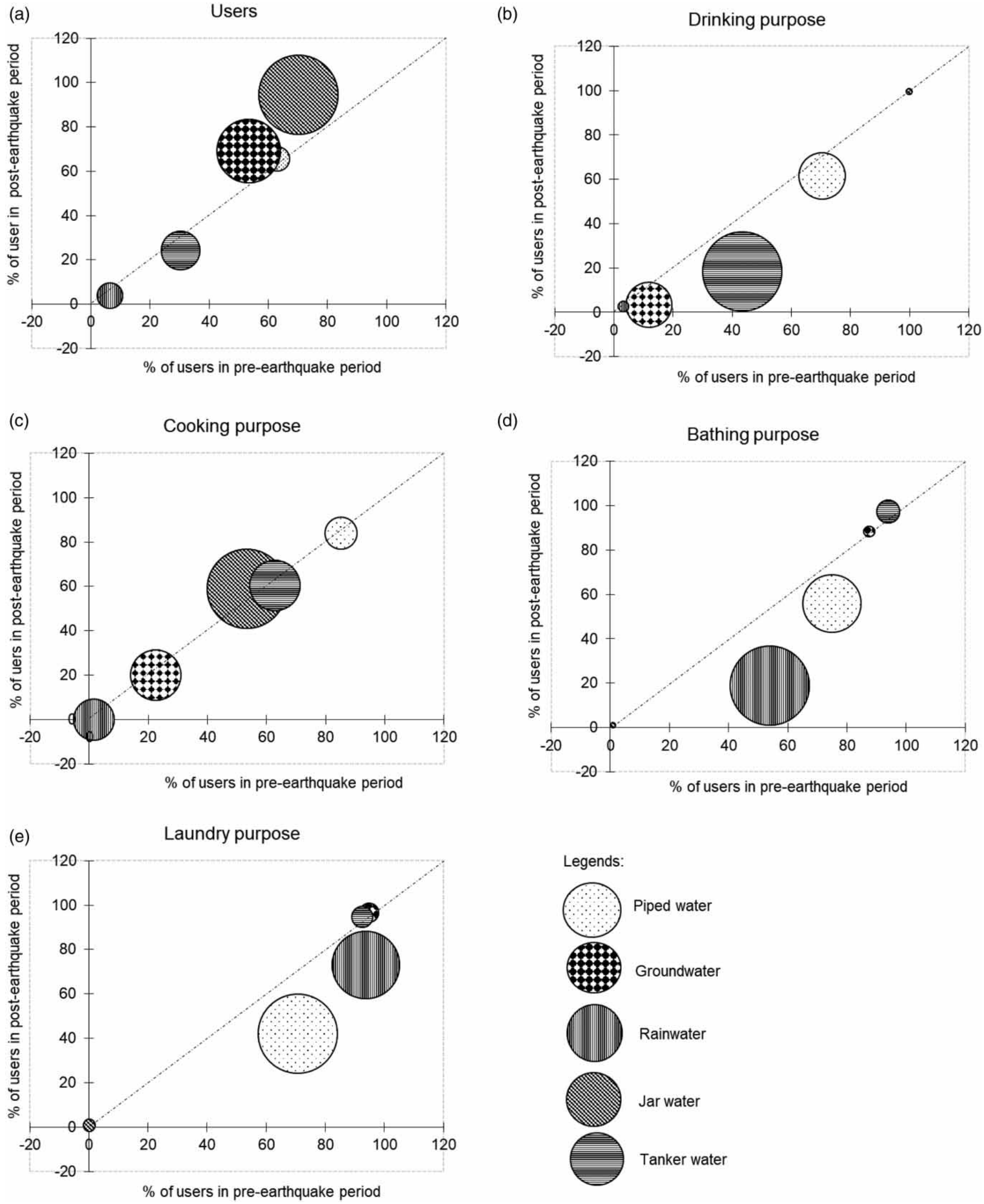

Figure 2 | Percentage of households reporting use of water sources (a) and the purpose for which they use those sources (b)–(e) during pre- and post-earthquake periods. The size of the bubble represents the relative change in the percentage after the disaster.

Table 1 | Relationships between the sources used for consumptive purposes and those used for non-consumptive purposes

	Pre-earthquake period				Post-earthquake period			
	Cooking and drinking		Cooking and non-consumptive use		Cooking and drinking		Cooking and non-consumptive use	
Sources	ϕ	***P*-value**	ϕ	***P*-value**	ϕ	***P*-value**	ϕ	***P*-value**
Piped water	0.48	<0.001*	−0.06	0.187	0.34	<0.001*	−0.14	0.001*
Groundwater	0.68	<0.001*	−0.03	0.524	0.33	<0.001*	0.01	0.870
Tanker vendor water	0.60	<0.001*	−0.01	0.903	0.36	<0.001*	0.04	0.598
Neighbour's piped water	−0.20	0.402	0.60	0.013*	0.80	<0.001*	−0.47	0.021*
Neighbour's well water	0.83	0.002*	−0.44	0.101	0.53	0.047*	Could not be computed	

ϕ: phi correlation coefficient; *: statistically significant *P*-value, i.e., <0.05.

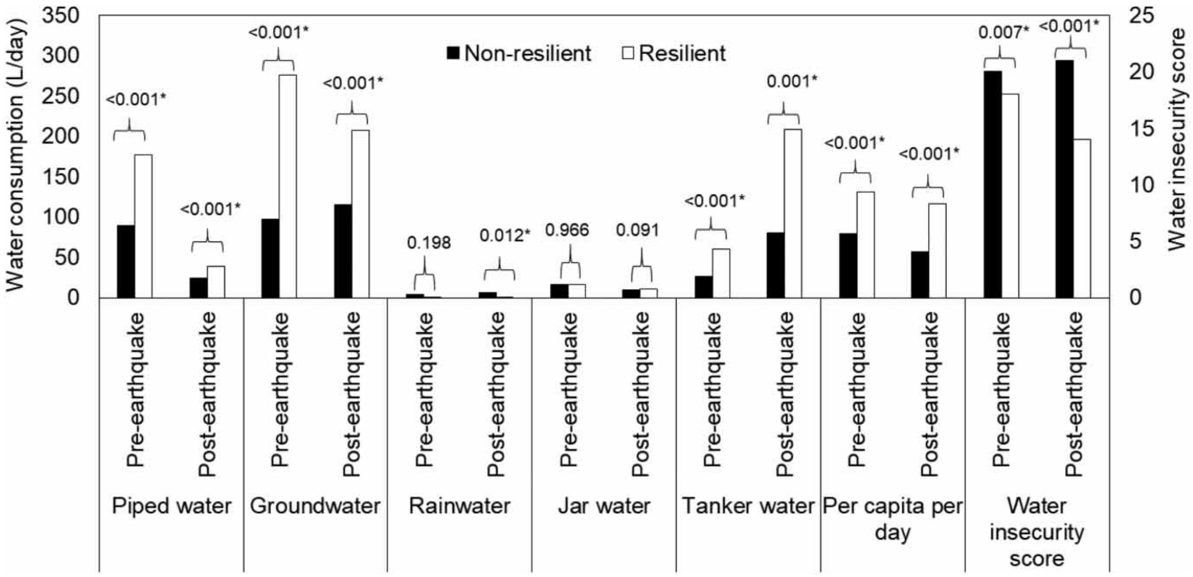

Figure 3 | Comparison of water consumptions and water insecurity scores between the non-resilient (black bar) and resilient (white bar) households during pre- and post-earthquake periods. A number above the bars is a *P*-value from the paired sample t-tests conducted to examine the difference between pre- and post-disaster values for each parameter. * denotes the *P*-value that is statistically significant (<0.05).

(131 ± 142 L) was higher compared with that of non-resilient households (79 ± 103 L) (*P*-value < 0.001). The average post-earthquake LPCD of resilient households (116 ± 205 L) was also higher compared with that of non-resilient households (57 ± 106 L) (*P*-value < 0.001). The non-resilient households perceived higher water insecurities than the resilient households in both the pre- (*P*-value = 0.007) and post-earthquake (*P*-value < 0.001) periods. These results indicate that resilient households always have higher water consumption and lower water insecurity compared with non-resilient households. These results validated the classification of households on water resilience based on the respondents' perception scores. Hence, we have used this classification of water resilience for further data analysis.

Household characteristics for water resilience to disaster

The pre-earthquake data were analysed to explore the household water-use characteristics that influenced resilience to disaster. Of all the non-resilient households, 30% used one water source, 30% used two, 19% used three and 21% used more than three water sources. Among the resilient households, 13% used one water source, 42% used two, 33% used three and 12% used more than three water sources.

Water storage is an adaptive strategy used to combat water scarcity. More resilient households (95%) than non-resilient households (90%) stored groundwater (P-value = 0.035). However, there was no considerable difference between the two groups regarding piped water (resilient = 98% vs non-resilient = 96%; P-value = 0.206) and rainwater storage (resilient = 97% vs non-resilient = 100%; P-value = 1). Since tanks (overhead and underground) have larger storage capacities (usually $\geq$ 500 L) compared with vessels (jar, pot, bucket, bottles, jerry can, etc.) (usually $\leq$ 30 L), this study explored the differences in the use of water containers between resilient and non-resilient households. The use of vessels for storing piped water (non-resilient = 59% vs resilient = 42%; P-value = 0.001) and groundwater (non-resilient = 75% vs resilient = 41%; P-value <0.001) was higher in non-resilient households compared to resilient households. More resilient households (70%) stored groundwater in overhead tanks than non-resilient households (43%) (P-value <0.001). These results indicated that non-resilient households had the characteristic of storing water in smaller containers such as vessels, but resilient households had the characteristic of storing water in larger containers such as overhead tanks.

Figure 4 summarizes the results of the GEE, which was conducted to identify the association between water sources and household water resilience. Those households with a piped water connection (AOR = 1.87, 95% CI: 1.35–2.60) or had private groundwater well (AOR = 1.73, 95% CI: 1.25–2.38) or purchased tanker water (AOR = 1.67, 95% CI: 1.15–2.42) were more likely to be water resilient during a disaster than the households that did not use these water sources. The use of rainwater, jar water, a neighbour's well and a public well was not associated with resilience. The number of MWSU was positively associated (β = 0.28, 95% CI: 0.07–0.49) with household water resilience. The details of the result from the analysis can be found in the Supplementary material (Table S2).

Post-earthquake water-use behaviour of resilient and non-resilient households

We conducted a post hoc analysis to understand the post-earthquake changes in the water-use behaviours (water source use, purchasing behaviour and storage) of

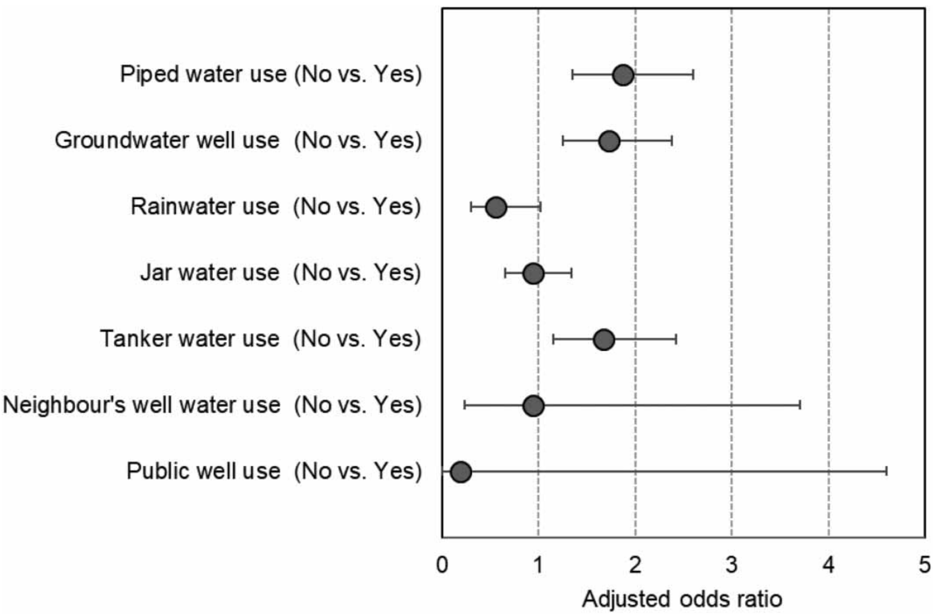

Figure 4 | Water sources associated with household water resilience to disaster. The closed circle denotes the adjusted odds ratio and bar represents a 95% confidence interval.

non-resilient and resilient households. During the post-earthquake period, the number of households using private groundwater considerably increased in both groups (each P-value <0.001), while the use of tanker water considerably decreased in both groups ($P_{resilient}$-value = 0.002; $P_{non\text{-}resilient}$-value = 0.005). Interestingly, more non-resilient households started buying jar water, using neighbour's piped and well water and public wells; however, there was no change in the use of these sources in resilient households. The water-buying behaviour (the purchase of jar water, tanker water or both) of both resilient and non-resilient households also increased after the earthquake (each P-value <0.001). Before the earthquake, there was no meaningful difference in the purchase of water between the non-resilient (64%) and resilient (65%) households (P-value = 0.933). However, after the earthquake, more non-resilient households (92%) bought water compared with resilient households (78%) (P-value <0.001). During the post-earthquake period, the number of households storing piped water in overhead tanks increased in both groups (each P-value <0.001). There was an increase in the number of non-resilient households storing groundwater in overhead (P-value <0.001) and underground tanks (P-value <0.001) as well. Regarding the average water insecurity scores, a noteworthy decrease from the pre-earthquake (18 ± 9) to the post-earthquake (14 ± 9) periods was evident among the resilient households (P-value <0.001), while, for the non-resilient households, the score considerably increased from the pre-earthquake (20 ± 10) to the post-earthquake (21 ± 12) periods (P-value = 0.031).

DISCUSSION

This study examined the situation of MWSU pre- and post-disaster. Moreover, the properties of water-resilient households have been identified, and the changes in the water-use behaviours of resilient and non-resilient households after the earthquake have been highlighted.

The Kathmandu Valley is one representative urban area among many in low- and middle-income countries that suffer from chronic water scarcity. This study revealed that most (three-quarters) of the households in the Kathmandu Valley used two to three water sources with a distinct division between the sources used for consumptive and non-consumptive purposes. These findings are consistent with the results from the Pacific Island countries (PIC) (Elliott *et al.* 2017) and have provided additional evidence against the prioritization of the primary drinking water source by global agendas (Elliot *et al.* 2019). This study revealed that after the earthquake, household water-use behaviour changed considerably. More households used groundwater, jar water and public wells. The mean number of water sources used per household also increased in response to acute water stress induced by the disaster. In this way, the occurrence of disasters further complicates the water source issue and creates more challenges to formulating comprehensive and effective water-intervention programs. Hence, for disaster-prone areas, it is advisable to consider disasters in the development of intervention programs and policies.

The water supply system is the utility highly vulnerable to earthquake damage (EPA 2018); therefore, much importance is given to the creation of resilient water infrastructure. However, in low-income countries, like Nepal, where residents partially rely on water utilities and on self-supply, household water resilience to disaster could be influenced by a multitude of household characteristics. Understanding these issues could help develop water resilience programs and policies. This study identified three main characteristics of households that were water resilient to disaster: (i) use of a greater number of water sources, (ii) use of multiple reliable water sources and (iii) use of effective adaptive strategies against chronic water stress.

The first characteristic of resilient households is the use of greater number of water sources. The practice of MWSU is one of the recommended technical adaptations to enhance household resilience to climate change (Howard *et al.* 2010). Water sources might have a differential vulnerability to disaster as they have for climate change (Elliot *et al.* 2019); therefore, households with larger MWSU could have access to a sufficient number of water sources, even after a disaster. Having access to sufficient resources (such as food and water) helps households to cope with natural disasters, e.g., households with sufficient food easily coped with the Vietnamese flood disaster (Nguyen & James 2013). To maximize benefits, it is recommended that MWSU is incorporated into water supply interventions and local water resources are well managed and protected.

The second characteristic of resilient households was the use of multiple reliable water sources. Those households that used piped water/groundwater/tanker water were more likely to be resilient compared with other households that did not (Figure 4). The majority of households in Kathmandu Valley used piped water, private groundwater and tanker water for non-consumptive purposes for which large volumes of water are required. Furthermore, the use of these three sources was associated with an increased per capita water consumption in the area (Shrestha *et al.* 2017). These sources are relatively reliable, as they can supply a large volume of water. Moreover, groundwater (from a tube well) is highly resilient to most of the impacts of climate change that affect freshwater (Howard *et al.* 2010). Regardless of the poor performance of the utility, piped water is highly preferred by the residents in the valley (Shrestha *et al.* 2017). The use of a neighbour's piped water supply and well were not associated with the resilience, as these arrangements largely depend on the balance of the social relationship; therefore, borrowed supplies are considered to be unreliable sources. The use of jar water and public wells were also not associated with resilience, which could be attributed to the minimal contribution of these sources to the total domestic water supply.

The third characteristic of resilient households was the use of effective adaptive strategies to cope with prevalent chronic water stress, such as storing water in a larger container. Domestic in-house water storage is a common adaptive strategy (Pattanayak *et al.* 2005) that helps to reduce the adverse impacts of water disruption after disasters and positively reinforces the resilience of the system (Mostafavi *et al.* 2018). This study identified a link between resilience, the larger capacity of storage containers and the storage of water from reliable sources. A higher percentage of resilient households stored groundwater compared with non-resilient households. Moreover, resilient households used large containers, such as overhead tanks, but non-resilient households used smaller containers, such as vessels, for groundwater storage. The storage of rainwater in large containers has been linked to the household's ability to use more water, while households that stored rainwater in small containers quickly shifted to less secure sources during the dry season, in PIC (Elliott *et al.* 2017), in Vietnam (Ozdemir *et al.* 2011) and on the PIC atolls (Wallace & Bailey 2015).

Following the earthquake, a greater number of non-resilient households used larger capacity water storage containers. Before the earthquake, a similar percentage of resilient and non-resilient households purchased water. Interestingly, after the earthquake, a higher percentage of non-resilient households purchased water, resulting in an increased economic burden on the household. Following the disaster, the number of non-resilient households using jar water, a neighbour's piped/well water and public wells increased. Conversely, there was no important change in the number of resilient households using these sources. This indicates that non-resilient households accessed as many water sources as possible to manage their domestic water supply after the earthquake, which was reflected by an increased perception of water insecurity in the post-earthquake period.

Our findings should be interpreted in light of certain limitations. The results specifically represent the phenomena in urban areas facing chronic water scarcity. Consequently, water-use behaviour, water source availability and use, and resilience processes and pathways could be different in rural areas. Although these results support the rational classification of resilient and non-resilient households, the use of a robust method/scale incorporating several items to measure resilience is recommended. Additionally, the follow-up survey was conducted around nine months after the earthquake. Hence, recall bias could be possible regarding the perception of the water system before the disaster. Despite these limitations, this study has provided important findings for use by disaster risk managers and policymakers.

CONCLUSION

This longitudinal study revealed that the practice of MWSU is central for household water management in urban areas in the low-income country regardless of the occurrence of disaster and for acquiring household water resilience. Before the earthquake, most households used two to three water sources and the number further increased after the earthquake. Regardless of the occurrence of the earthquake, a clear division was evident between the sources being used for consumptive and non-consumptive purposes. Three characteristics of the household that were water resilient to the disaster were: (i) they used a greater number of water sources; (ii) they used multiple reliable water sources such as piped water, groundwater and tanker water; and (iii) they had adopted more efficient adaptive strategies, i.e., storing in larger containers. After the earthquake, non-resilient households had an increased economic burden from having to purchase water compared with resilient households. The non-resilient households accessed as many water sources as possible, which increased their water insecurity perception. This study recommends utilizing MWSU practices to improve water security and strengthen household resilience to disaster via intervention programs and policies. Furthermore, it provides further advice for formulating initiatives to manage and protect local water sources and to endorse efficient local adaptive strategies.

ACKNOWLEDGEMENTS

We express our sincere gratitude to the Science and Technology Research Partnership for Sustainable Development Program (SATREPS) project, led by Professor Futaba Kazama of University of Yamanashi, co-funded by Japan International Cooperation Agency and Japan Science and Technology Agency. We are grateful to The Small Earth Nepal (SEN) for carrying out the survey smoothly and on time. Lastly, we appreciate the interviewers for their hard work and the participants for providing their valuable time and information.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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First received 21 January 2020; accepted in revised form 26 June 2020. Available online 30 July 2020