Waterborne diarrhoeal infection risk from multiple water sources and the impact of an earthquake

Yuri Ito, Sadhana Shrestha Malla, Arun Prasad Bhattarai, Eiji Haramoto, Junko Shindo and Kei Nishida

ABSTRACT

In the Kathmandu Valley of Nepal, locals depend on multiple water sources due to the limited access to safe water, which is a great global concern regarding its impact on human health. This study aimed to compare the infection risk of diarrhoea from multiple water sources with different concentrations of *Escherichia coli* among water supply areas and evaluate the impact of changing water sources due to the Gorkha earthquake on the infection risk. The concentration of enteropathogenic *E. coli* was estimated in samples of piped water, jar water, groundwater, and tanker water, which were collected in the Valley. The volume of each water ingestion was determined based on a questionnaire survey and considering drinking and bathing sources. The highest estimated risk was observed for households drinking groundwater from shallow dug wells, followed by tanker water. The estimated risk implied the regional disparity due to various water sources with different quality. After the earthquake, the ratio of households drinking only jar water increased, and the estimated risk decreased. The damage on piped water supply, the decrease of tanker water availability and the decrease of residents' trust in groundwater quality presumably enhanced the consumption of jar water despite its high price.

Key words | Gorkha earthquake, household, Kathmandu Valley, QMRA, supply area, waterborne infection

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INTRODUCTION

Sustainable Development Goal 6 ensures access to water and sanitation for all people. Currently, water scarcity affects more than 40% of the global population and is expected to increase (United Nations, Sustainable Development Goals, Goal 6). In the capital of Nepal, the Kathmandu Valley, the total water demand is 370 million litres per day (MLD), while Kathmandu Upatyaka Khanepani Limited (KUKL), which is responsible for the management, operation and maintenance of water supply and sewerage services in the Valley, provides about 144 MLD during the wet season and about 86 MLD during the dry season (Tamrakar & Manandhar 2016). To confront water scarcity, locals have to depend not only on KUKL water supply but also on various alternative water sources, such as jar water, tanker water and groundwater. Groundwater is chemically and microbiologically polluted (Warner *et al.* 2008; Pant 2011; Haramoto 2018), while more than half of the Valley's households use groundwater (Shrestha *et al.* 2017). Maharjan *et al.* (2018) reported that 92% of the jar water samples and 77% of the tanker water samples collected in the Valley exceeded the limits for the total coliform count, as defined by the Nepal Drinking Water Quality Standards. Moreover, Subedi & Aryal (2010)

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indicated that untreated jar water is risky for drinking purposes, based on bacteriological analysis results. Therefore, the use of alternative water sources remains of great concern regarding their effects on human health.

Diarrhoea is the second leading cause of death among children under five years old worldwide, with over 1,300 young children dying every day (World Health Organization (WHO) 2017; UNICEF 2018). In Nepal, it is a leading cause of death, and its incidence in children under five was 400 per 1,000 in 2016 (DoHS 2016/2017). According to WHO (2017), diarrhoea can be prevented by safe drinking water and proper sanitation and hygiene.

Quantitative microbial risk assessment (QMRA) has been applied in several countries, where the piped water supply service is evenly spread (Rose & Gerba 1991; Bichai & Smeets 2013; Teunis & Schijven 2018), as a scientific approach to assess the microbial risk for drinking water (Haas *et al.* 1999). Recently, QMRA studies have been reported on alternative water sources in developing countries and focus especially on groundwaters (Shrestha *et al.* 2015; Briggs *et al.* 2018; Daniels *et al.* 2018). In fact, locals have access to a variety of water sources and, although there are many similar regions around the world, few studies have reported risk assessment using QMRA that targets multiple water sources. Also, in regions with diverse water use, the difference between local areas should be considered when adopting QMRA. In addition, the 7.6 magnitude Gorkha earthquake that occurred in the Kathmandu Valley on April 25, 2015 significantly affected the infrastructure and building of the area, completely damaging 498,852 houses (NPC 2015). After the Gorkha earthquake, the volume of KUKL water supply decreased by almost 40%, and the damage from the earthquake varied among the different supply areas (Thapa *et al.* 2016). In addition, the water supply frequency decreased from 4 h to 2.3 h per week (Shrestha *et al.* 2017).

Therefore, this study aimed to compare the waterborne infection risk of diarrhoea from multiple water sources using *Escherichia coli* as the reference, which is a known hazard in this region, among neighbouring residential areas in the Kathmandu Valley of Nepal. Furthermore, since it has been reported that long-term disasters, such as flood and drought, increase the infection of diarrhoea (Mollah *et al.* 2009; Emont *et al.* 2017; Zhang *et al.* 2019), we evaluated the impact of changing water source due to a natural event on the predicted risk.

MATERIALS AND METHODS

Study area

The Kathmandu Valley lies between the latitudes 27°32′13″ and 27°49′10″ north and longitudes 85°11′31″ and 85°31′38″ east. The Valley has an area of 665 km^2 and encloses 85% of the Kathmandu district, the entire Bhaktapur district, and 50% of the Lalitpur district. It is situated at a mean elevation of about 1,300 m above sea level (Pant & Dongol 2009). The population of the Valley increased from 2.51 million in 2011 to 3.2 million in 2015, and the population growth rate was 4.3% in the last decade (Tamrakar & Manandhar 2016). Although KUKL has provided water from ten branch offices as of 2015, this study excluded the Bhaktapur branch due to lack of data and targeted nine branches (Figure 1), which were considered as the supply areas.

Questionnaire survey

The data of the questionnaire survey were collected by trained interviewers through face-to-face interviews in households. The households were selected using a two-step, cluster sampling method. In the first step, 50 clusters were selected, applying the probability proportional to household size method in wards. In the second step, geographical locations were randomly selected from each cluster, and the interviewer visited the 30 households that were closer to the selected locations. Although there is usually more than one household in a single house, data were collected from only one household per house. A structured questionnaire included socio-demographic, health condition and water use (water source, possible treatment and purpose of use) parameters. The questionnaire surveys were conducted in two dry seasons. The first survey was conducted from January to April 2015 only in 39 clusters (1,130 households), due to the Gorkha earthquake. The second survey was conducted from December 2015 to February 2016, 8–11 months after the earthquake, in 50 clusters

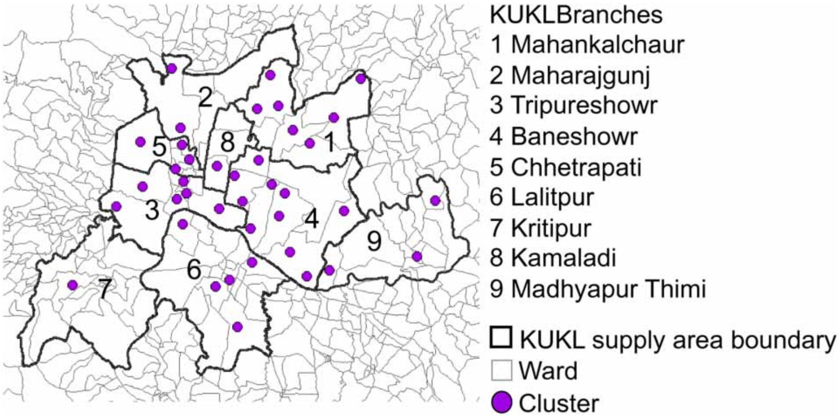

Figure 1 | Locations of the questionnaire survey point in the Kathmandu Valley.

(1,500 households). The data collected from households with inconsistent answers, such as answering positively to water consumption without using water, were excluded from the study. Hence, valid data from 919 households in 39 clusters were used for the analysis (Figure 1 and Table 1).

Water quality survey

Separately from the questionnaire survey, a series of water quality surveys was conducted. Six, 30 and 63 samples were collected for microbial analyses from piped water in 2015 (Malla 2019), jar water in 2014 (Malla *et al.* 2015) and tanker water in 2016 (Malla *et al.* 2019), respectively. Groundwater samples were collected from three well types: deep tube, shallow tube and shallow dug wells, and the total number of samples from each well type from 2009 to 2015 used for the following statistical analysis was 34, 194 and 227, respectively. After the sample collection, the *E. coli* concentrations were immediately measured in a laboratory located in the Kathmandu Valley by the most probable number method using Colilert reagent, as previously reported (Haramoto *et al.* 2011; Shrestha *et al.* 2014). Analysis of variance (ANOVA) was performed to confirm the difference in the microbial concentrations among the water supply areas by using SPSS Statistics Version 26 (IBM, Armonk, NY, USA).

Table 1 | Number of households in each supply area

Supply area	No. of households
1	165
2	56
3	165
4	255
5	97
6	89
7	30
8	26
9	36
Total	919

Water ingestion

This study considered drinking and bathing as the two main water exposure pathways. Regarding the drinking pathway, the water volume of daily ingestion was assumed to be 1,040 mL per person (Shrestha *et al.* 2015). Regarding the bathing pathway, Dufour *et al.* (2017) reported that swimmers ingest an average of 32 mL per hour during swimming activities. We, therefore, assumed that the volume of water ingestion from the bathing pathway is 8 mL per event, supposing that the bathing time is approximately 15 min. The results of the questionnaire survey indicated that several households used multiple water sources for drinking and bathing; mainly piped water, jar water, groundwater, tanker water and their combination. We then tried to estimate the ingestion volume (*Vs*) of each water source for household groups with the same water source combination. For the multiple water source users, the ingestion volume of each source was estimated by dividing the total amount of water (1,040 mL per day for drinking and 8 mL per event for bathing) by the number of water sources used because the ingestion volume data for each source were not available. In addition, a telephone survey was conducted in January 2019 for 177 households – approximately 20 households in each supply area – to obtain information about their well type. Although the abundance rates of well types were different among supply areas, shallow dug wells were the most common (Supplementary material, Figure A1). The volume of groundwater ingestion was calculated based on the abundance ratio of well types in each area.

Risk estimation

Waterborne infection risk was calculated through QMRA, which consisted of four steps: hazard identification, exposure assessment, dose-response assessment and risk characterisation (Haas *et al.* 1999).

Hazard identification

In the Kathmandu Valley, enteropathogenic *E. coli* (EPEC) was the most prevalent pathogen among the bacterial isolates for diarrhoea (Ono *et al.* 2001). We set, therefore, EPEC as a hazard and estimated the annual infection risk of diarrhoea caused by EPEC. According to previous reports, EPEC constitution ratio ranged from 0.74% to 8% (Levine 1987; Balière *et al.* 2015; Cho *et al.* 2018; da Silva *et al.* 2019; Swedan & Alrub 2019) of *E. coli* in water. The value of 8% (Levine 1987) was selected to estimate maximum infection risks and the estimation of EPEC concentration in the current study was based on the concentration of *E. coli*. Additionally, the best-fitted probability distribution of the EPEC concentration was determined for each source and supply area, and 1,000 random numbers were generated based on the distribution by Monte Carlo simulation (MCS) for the subsequent risk calculation. These procedures were performed using the EasyFit 5.6 professional software (MathWave Technologies, Washington DC, USA).

Exposure assessment

The frequency and the magnitude of exposure to pathogens were determined for each water source combination. Drinking and bathing were considered as two different exposure pathways. The results of the questionnaire surveys before and after the earthquake indicated that 84 and 71% of the surveyed households treated drinking water, while 69 and 62% of them, respectively, used a ceramic filter. In addition, according to a previous report (Shrestha *et al.* 2018), 75% of the households in the Kathmandu Valley habitually treated drinking water, and 64% of them used a ceramic filter. However, the effectiveness of the ceramic filter is undermined if it is not regularly cleaned, and the flow rates decrease with use (Sobsey *et al.* 2008). Herein, we assumed that all the examined households used a ceramic filter for drinking water and the removal efficiency for EPEC was 0.2 log (37%) (Bielefeldt *et al.* 2009), taking also into account the undermined effectiveness of the filter. Since the questionnaire surveys indicated that only a few households treated water for bathing (before the earthquake: 4%, after the earthquake: 2%), we assumed that no household treated water for bathing. Thus, the EPEC dose per exposure of each source (D_s) was calculated by Equation (1):

$$D_s = Cs \times Vs \times 10^{-R} \tag{1}$$

where Cs is the concentration of EPEC generated by MCS for each water source that is assumed to be temporally constant, Vs is the average volume of water ingestion per person and per day of households in each water supply area, and R is the removal efficiency of water treatment (0.2 log for drinking and 0 for bathing). Subsequently, the total EPEC dose (number of pathogens ingested per day or event: D_p) was calculated by summing up (Equation (2)) the doses of each source (D_s) included in a water source combination:

$$D_p = D_{pipe} + D_{jar} + D_{deep\,tube} + D_{shallow\,tube} + D_{shallow\,dug} + D_{tanker} \tag{2}$$

Dose-response assessment

The infection risk per day by drinking or per event by bathing (P_d) was calculated using a beta-Poisson dose-response model, as in Equation (3) (Haas *et al.* 1999):

$$P_d = 1 - [1 + D_p/N_{50} \times (2^{1/\alpha} - 1)]^{-\alpha} \tag{3}$$

where N_{50} is the average infecting dose (8.6×10^7) and α is the parameter of probability function (0.1778) (Haas *et al.* 1999).

Risk characterisation

The annual risk of infection (P_a) was calculated using Equation (4):

$$P_a = 1 - (1 - P_d)^N \quad (4)$$

where N is the exposure frequency per year: 365 for the drinking pathway and 104 (twice a week) for the bathing pathway, based on a previous study (Shrestha *et al.* 2015). The annual risks of each water source combination were then used to calculate the annual risk in each supply area (P_{area}):

$$P_{area} = (P_{a,1} \times n_1 + P_{a,2} \times n_2 + \ldots + P_{a,i} \times n_i)/\Sigma n_i \quad (5)$$

where n_i is the number of households using combination i. Finally, the total annual risk (P_{total}) due to both pathways was calculated by Equation (6):

$$P_{total} = 1 - (1 - P_{area,\ drinking}) \times (1 - P_{area,\ bathing}) \quad (6)$$

where P_{total} was considered as a representative value in each area.

Risk calculation before and after the earthquake

The annual risks were calculated by considering the combination of water sources for drinking and bathing in each water supply area. The risks were compared among the nine water supply areas and the impact of changing water source due to the earthquake on the risk was evaluated. Due to the limitation of data availability, the same data set of *E. coli* concentration collected from the several water quality surveys was applied to the risk calculation before and after the earthquake.

RESULTS

Combination of used water sources

In the present study, we identified 13 combinations of water source for the drinking pathway and seven combinations for the bathing pathway. Table 2 presents the number of households that used each combination, and it is clear that many used piped and jar water for drinking and groundwater for bathing purposes. After the earthquake, the number of households that combined multiple water sources for both purposes decreased. The number of households drinking jar water increased, while that of drinking piped water, tanker water and groundwater decreased. In contrast, the use of groundwater for bathing purposes increased.

Estimated and simulated concentrations of EPEC

E. coli was detected in 35% of the examined deep tube wells ($n = 34$), in 30% of the shallow tube wells ($n = 46$), in 79% of the shallow dug wells ($n = 115$), in 55% of the tanker water samples ($n = 20$), in 17% of the piped water samples ($n = 6$) and in 10% of the jar water samples ($n = 30$). These *E. coli* concentrations exceeded the WHO guidelines for drinking

Table 2 | Combination of used water sources and the number of households that used them before and after the earthquake

		No. of household	
Purpose of use	Combination of water source	Before	After
Drinking	① Pipe	177	161
	② Jar	377	525
	③ Ground	16	13
	④ Tanker	26	15
	⑤ Pipe + Jar	152	153
	⑥ Pipe + Ground	6	2
	⑦ Pipe + Tanker	16	8
	⑧ Jar + Ground	31	6
	⑨ Jar + Tanker	32	8
	⑩ Pipe + Jar + Ground	2	1
	⑪ Pipe + Jar + Tanker	45	6
	⑫ Jar + Ground + Tanker	2	0
	⑬ Pipe + Jar + Ground + Tanker	1	0
	Total	883[a]	898[a]
Bathing	① Pipe	197	178
	② Ground	226	407
	③ Tanker	105	90
	④ Pipe + Ground	109	77
	⑤ Pipe + Tanker	80	33
	⑥ Ground + Tanker	53	58
	⑦ Pipe + Ground + Tanker	34	14
	Others	98	49
	Total	902[a]	906[a]

[a]The total number of households was less than 919 because of data unavailability.

water (0 MPN/100 mL) (WHO 2011). Table 3 presents descriptive statistics of the EPEC concentration, such as the sample number, the mean, maximum and minimum concentration, and the best-fitted probability distributions of each water source in each supply area and across the whole area. Although more than five samples were required to generate 1,000 random numbers by using MCS, the sample number of deep tube wells was <5 in seven areas. Therefore, several samples in these areas were created from the EPEC concentration of shallow tube wells multiplied by the ratio of the mean EPEC concentrations of shallow and deep tube wells. The value of non-detected samples was set to 0.04 (MPN/100 mL). As a result of statistical tests to show a variation of EPEC concentrations among water supply areas, EPEC concentrations in shallow dug wells and tanker water samples had significant differences ($P < 0.05$); however, those in deep tube wells and shallow tube wells had no significant differences ($P = 0.27$ and 0.19, respectively).

Baseline risk from different drinking water sources and ingestion pathways

Figure 2 shows the estimated risks of households drinking each combination and groundwater from each well type across the whole area before the earthquake. The median infection risk of households drinking groundwater was the highest, followed by tanker water, while that of households drinking jar water was the lowest, followed by piped water, among single source users. The estimated risk of households drinking tanker water varied greatly due to the large variety of its concentrations. Regarding groundwater sources, the estimated risk of households drinking a shallow dug well was significantly higher. When households drink the combinations including both low-risk (piped water or jar water) and high-risk (groundwater or tanker water) water sources, the risk was greatly influenced by the high-risk water source. For this reason, the median infection risk of households drinking combinations including groundwater was higher than the acceptable limit ($<10^{-4}$ infection/person-year), as proposed by the United States Environmental Protection Agency.

Figure 3 displays the estimated risks from each individual pathway and the combined pathway in each supply area before the earthquake. The estimated risk from the drinking pathway was significantly higher than that from the bathing pathway, and the total risk was mostly determined by the drinking pathways. However, in supply area 7, the estimated risk from the bathing pathway was higher than that from the drinking pathway, and the 75th percentile value of the bathing pathway exceeded the acceptable limit.

Estimated risk in different supply areas before and after the Gorkha earthquake

Figure 4 shows the estimated risks from the combined pathway, and Table 4 outlines the number of households drinking each combination of water sources in different supply areas, before and after the Gorkha earthquake. Before the earthquake, the estimated risks varied among the supply areas, and they were higher than the acceptable limit in half of them. The highest estimated risk was observed in supply area 6, followed by supply areas 3, 5 and 2, where the rate of households drinking tanker water was relatively high, as shown in Table 4. On the other hand, 75 percentile risk did not exceed the acceptable limit in supply areas 1 and 4, although some households drank tanker water and groundwater.

Similarly, the median risk was different in each supply area after the earthquake, as shown in Figure 4. The estimated risk remained almost unchanged in supply area 7, where all the examined households drank only jar water in both periods. However, after the earthquake, the estimated risk significantly decreased in all areas, except for supply areas 7 and 9. Moreover, the number of households drinking tanker water or groundwater drastically decreased, while households drinking only jar water increased in supply areas 1, 2, 4, 5 and 6. Especially, in supply area 6, the rate of households drinking tanker water decreased significantly from 69% to 16%, and that of households drinking only jar water increased from 15% to 41%. Water supply area 8, which had the second greatest decrease in estimated risk, was excluded from the discussion because it consisted of only 25 household samples. In supply area 2, where the third largest decrease of the estimated risk was observed, the rate of households drinking piped water was seriously reduced from 71% to 33%, and that of households drinking only jar water increased from 27% to 61%. On the other

Table 3 | Concentration of EPEC and its probability distribution

Supply area	Sources[a]	No. of samples	Estimated EPEC (MPN/100 mL) Min	Max	Mean	No. of calculated data[b,c]	Simulated EPEC (MPN/100 mL) Min	Max	Mean	Fitted distribution
Area 1	DT	2	0.04	0.69	0.36	14	0.05	4.51	0.36	Pareto ($\alpha = 3.04$, $\beta = 0.05$)**
	ST	14	0.04	3.97	0.32					Pareto ($\alpha = 3.05$, $\beta = 0.04$)**
	SD	13	0.04	194	18.2					Lognormal ($\sigma = 2.68$, $\mu = -0.67$)**
	TK	20[d]	0.04	11.4	0.76					Log-Logistic ($\alpha = 1.14$, $\beta = 0.09$)*
Area 2	DT	4	0.04	0.33	0.11	17	0.04	1.13	0.14	Pareto ($\alpha = 2.38$, $\beta = 0.04$)**
	ST	17	0.04	161	15.9					Lognormal ($\sigma = 2.67$, $\mu = -0.98$)**
	SD	7	0.26	1,200	180					Lognormal ($\sigma = 2.58$, $\mu = 1.93$)**
	TK	8[d]	0.04	727	214					Lognormal ($\sigma = 4.26$, $\mu = 1.17$)**
Area 3	DT	6	0.04	12.6	2.18					Pareto ($\alpha = 0.73$, $\beta = 0.04$)**
	ST	26	0.04	2,330	106					Gamma ($\alpha = 0.05$, $\beta = 1{,}956.00$)*
	SD	41	0.04	19,400	684					Lognormal ($\sigma = 3.58$, $\mu = 2.48$)**
	TK	6[d]	3.36	139	54.7					Lognormal ($\sigma = 1.39$, $\mu = 3.30$)**
Area 4	DT	3	0.04	0.04	0.04	59	0.04	1.10	0.07	Pareto ($\alpha = 6.50$, $\beta = 0.04$)
	ST	59	0.04	89.6	3.25					Gamma ($\alpha = 0.06$, $\beta = 57.73$)*
	SD	15	0.04	12.8	2.21					Log-Logistic ($\alpha = 0.62$, $\beta = 0.22$)*
	TK	2	0.04	0.04	0.04					
Area 5	DT	1	–	–	0.08	20	0.04	0.50	0.10	Gamma ($\alpha = 0.71$, $\beta = 0.14$)*
	ST	20	0.04	2.04	0.33					Gamma ($\alpha = 0.42$, $\beta = 0.78$)*
	SD	7	0.04	7,130	1,110					Lognormal ($\sigma = 3.80$, $\mu = 2.85$)**
	TK	5[d]	0.04	727	184					Lognormal ($\sigma = 3.82$, $\mu = 1.78$)**
Area 6	DT	14	0.04	6.71	0.68					Pareto ($\alpha = 0.99$, $\beta = 0.04$)**
	ST	34	0.04	65.3	3.79					Pareto ($\alpha = 0.59$, $\beta = 0.04$)**
	SD	82	0.04	9,630	204					Lognormal ($\sigma = 3.13$, $\mu = 1.07$)*
	TK	7[d]	10.8	314	91.0					Lognormal ($\sigma = 1.20$, $\mu = 3.81$)**
Area 7	DT	3	0.04	0.04	0.04	1	–	–	0.04	–
	ST	1	–	–	104					–
	SD	23	0.04	2,090	257					Lognormal (σ=2.98, $\mu = 2.93$)*
	TK	12[d]	0.04	19.9	6.02					Gamma ($\alpha = 0.65$, $\beta = 9.22$)*
Area 8	DT	0	–	–	–	22[c]	0.04	0.24	0.05	Pareto ($\alpha = 12.28$, $\beta = 0.04$)**
	ST	22	0.04	20.9	1.04					Pareto ($\alpha = 1.83$, $\beta = 0.04$)**
	SD	18	0.04	328	32.2					Lognormal ($\sigma = 2.80$, $\mu = 0.66$)**
	TK	14[d]	0.04	727	138					Lognormal ($\sigma = 4.04$, $\mu = 0.57$)**
Area 9	DT	1	–	–	0.04	1	–	–	0.04	–
	ST	1	–	–	0.04					–
	SD	21	0.04	89.6	16.2					Lognormal ($\sigma = 2.77$, $\mu = 0.15$)*
	TK	4[d]	0.04	0.04	0.04					
Whole area	DT	34	0.04	12.6	0.71					Pareto ($\alpha = 1.21$, $\beta = 0.04$)**
	ST	46	0.04	2,330	61.7					Pareto ($\alpha = 0.64$, $\beta = 0.04$)**
	SD	115	0.04	19,400	386					Lognormal ($\sigma = 3.36$, $\mu = 1.36$)**
	TK	20	0.04	727	97.1					Log-Logistic ($\alpha = 0.39$, $\beta = 0.77$)**
Common in all areas	Pipe	6	0.04	0.16	0.06					Pareto ($\alpha = 4.33$, $\beta = 0.04$)**
	Jar	30	0.04	0.16	0.05					Pareto ($\alpha = 8.66$, $\beta = 0.04$)**

[a]DT = deep tube well; ST = shallow tube well; SD = shallow dug well; TK = tanker water.

DT: collected in 2014–2016, ST&SD in area 7, 9, whole: collected in 2014–2016, ST and SD in the other areas: collected in 2009–2016, TK: collected in 2016.

[b]Concentration of ST multiplied by ratio (DT/ST) in same area.

[c]Concentration of ST multiplied by ratio (DT/ST) in whole area.

[d]Included the complemented data collected from the nearest station(s) out of the correspondent area.

μ: location parameter; σ: scale parameter; α, β: shape parameter.

Goodness of fit test: * = Chi-squared ($p < 0.01$); ** = Anderson–Darling ($p < 0.01$).

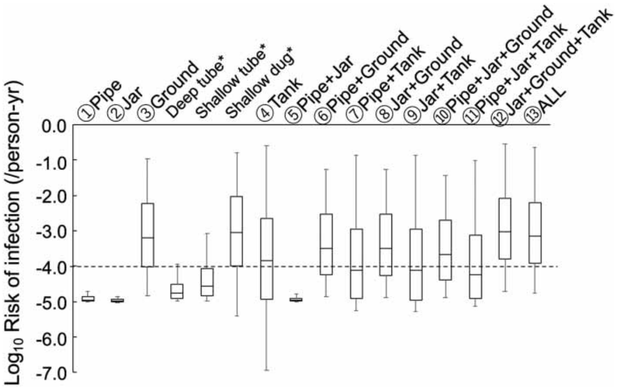

Figure 2 | Comparison of the estimated risk of each combination from the drinking pathway across the whole area before the earthquake. The upper and lower bars represent the 95th and 5th percentile values, respectively. The upper and lower lines of these boxes represent 75 and 25%, respectively, and the middle lines represent the median values. *The risk was estimated under an assumption that households drink groundwater only from the correspondent well.

hand, in supply area 9, where the estimated infection risk rose, less households had access to piped water, while those drinking jar water and groundwater increased.

DISCUSSION

This study estimated the annual infection risk of diarrhoea in the Kathmandu Valley of Nepal. Drinking and bathing were considered as the exposure pathways, and the volume of ingestion per day or event was determined based on previous reports. Residents of this area used multiple water sources to cope with water scarcity. Therefore, the current study focused on the calculation of the infection risk from multiple water sources with various EPEC concentrations in different supply areas. In addition, we investigated the impact of the Gorkha earthquake on the infection risk of diarrhoea.

Effect of water sources on the infection risk

The estimated infection risk of households drinking groundwater was the highest, followed by tanker water, while those of households drinking piped water and jar water were lower (Figure 2). Despite the high microbial concentrations in groundwater and tanker water, our study uncovered the use of these contaminated waters by some households as a drinking water source, thus causing deterioration to human health. Drinking groundwater from shallow dug wells increased the estimated infection risk compared with groundwater from the deep tube and shallow tube wells. In addition, it was proven that tanker water might be a water source that adversely affects human health.

In this study, EPEC concentrations in each source were calculated from the concentration of *E. coli* based on a previous report (Levine 1987) that EPEC constitutes 8% of *E. coli* in water. However, the report did not specify the water source or type and several papers have shown different values of the constitution ratio in different water sources. Although the presumable maximum risk was estimated in this study, further studies are necessary to evaluate if this assumption is realistic in the study area.

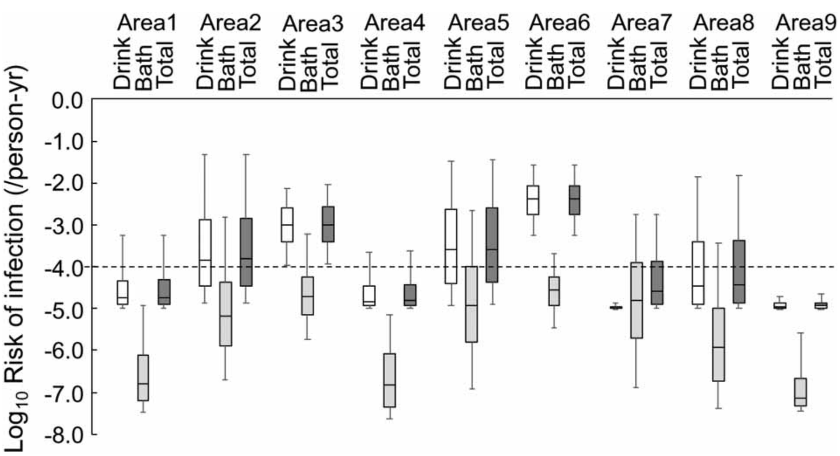

Figure 3 | Comparison of the estimated risk from each pathway before the earthquake. The upper and lower bars represent the 95th and 5th percentile values, respectively. The upper and lower lines of these boxes represent 75 and 25%, respectively, and the middle lines represent the median values.

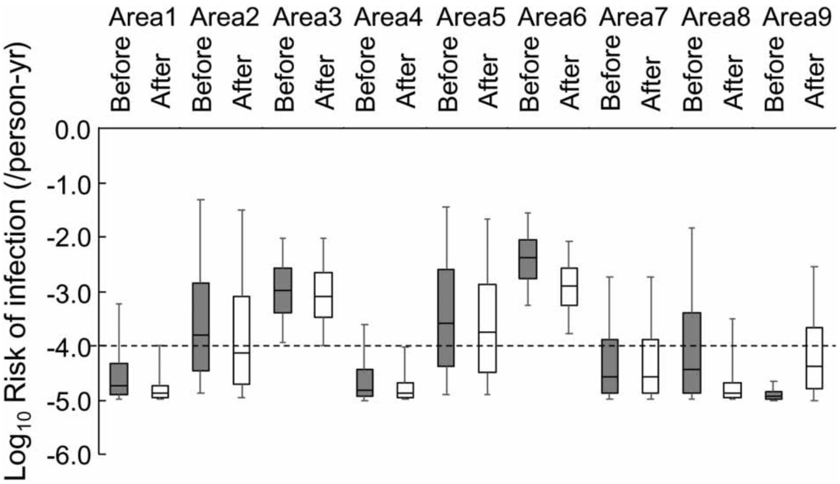

Figure 4 | Comparison of the estimated risk before and after the Gorkha earthquake. The upper and lower bars represent the 95th and 5th percentile values, respectively. The upper and lower lines of these boxes represent 75 and 25%, respectively, and the middle lines represent the median values.

Table 4 | The number of households drinking each water source

Supply area	Before/After the earthquake	No. of households: Pipe	Pipe only	Jar	Jar only	Tanker	Tanker only	Ground	Ground only	Total
Area 1	Before	87 (53)	62 (38)	93 (57)	49 (30)	0 (0)	0 (0)	29 (18)	6 (4)	163
	After	73 (45)	65 (40)	95 (58)	88 (54)	0 (0)	0 (0)	4 (2)	1 (1)	163
Area 2	Before	39 (71)	5 (9)	46 (84)	15 (27)	8 (15)	1 (2)	1 (2)	0 (0)	55
	After	18 (33)	2 (4)	50 (93)	33 (61)	4 (7)	1 (2)	0 (0)	0 (0)	54
Area 3	Before	61 (39)	34 (22)	108 (68)	79 (50)	22 (14)	12 (8)	1 (1)	1 (1)	158
	After	48 (30)	18 (11)	129 (80)	100 (62)	18 (11)	9 (6)	1 (1)	1 (1)	162
Area 4	Before	93 (38)	38 (15)	188 (76)	128 (52)	20 (8)	2 (1)	21 (9)	9 (4)	247
	After	97 (38)	55 (22)	194 (76)	151 (59)	1 (0)	0 (0)	6 (2)	4 (2)	254
Area 5	Before	44 (45)	10 (10)	82 (85)	47 (48)	12 (12)	1 (1)	1 (1)	0 (0)	97
	After	41 (43)	8 (8)	86 (90)	51 (53)	1 (1)	0 (0)	4 (4)	2 (2)	96
Area 6	Before	45 (52)	3 (3)	74 (86)	13 (15)	59 (69)	9 (10)	5 (6)	0 (0)	86
	After	41 (50)	5 (6)	71 (87)	34 (41)	13 (16)	5 (6)	1 (1)	0 (0)	82
Area 7	Before	0 (0)	0 (0)	28 (100)	28 (100)	0 (0)	0 (0)	0 (0)	0 (0)	28
	After	0 (0)	0 (0)	28 (100)	28 (100)	0 (0)	0 (0)	0 (0)	0 (0)	28
Area 8	Before	7 (28)	4 (16)	20 (80)	17 (68)	1 (4)	1 (4)	0 (0)	0 (0)	25
	After	13 (52)	8 (32)	17 (68)	12 (48)	0 (0)	0 (0)	0 (0)	0 (0)	25
Area 9	Before	23 (96)	21 (88)	3 (13)	1 (4)	0 (0)	0 (0)	0 (0)	0 (0)	24
	After	0 (0)	0 (0)	29 (85)	28 (82)	0 (0)	0 (0)	6 (18)	5 (15)	34
Whole area	Before	399 (45)	177 (20)	642 (73)	377 (43)	122 (14)	26 (3)	58 (7)	16 (2)	883
	After	331 (37)	161 (18)	699 (78)	525 (58)	37 (4)	15 (2)	22 (2)	13 (1)	898

Note: The values in parentheses represent the households' rates.

In the Kathmandu Valley, *Giardia* was frequently detected among the enteric protozoan parasites, followed by *Cryptosporidium* (Ono *et al.* 2001; Pandey *et al.* 2002). Shrestha *et al.* (2015) examined shallow groundwater and demonstrated that the infection risk from EPEC was 1,000 times lower than that from *Cryptosporidium* and 10,000 times lower than that from *Giardia*. When protozoa data are available for each water source in each supply area, the method proposed in this study can be applied and the estimation possibly become more accurate. Furthermore, Shrestha *et al.* (2016) indicated positive correlations between *E. coli* and protozoa concentrations in wastewater irrigation sources. Therefore, although the risk presented here is supposedly underestimated, it could show relatively the difference among areas or periods.

Regional disparity of the estimated risk

This study indicated that various water sources with different quality were used in households in the Valley and caused the regional disparity of infection risk in both periods, before and after the earthquake. In supply areas 1 and 4, although some households were drinking tanker water and groundwater, the estimated risk was relatively low compared to other areas, due to their lower EPEC concentration. In these areas, there was also a possibility that residents chose groundwater or tanker water for drinking purposes because they might have felt the water sources in their area are safe. The samples of the water quality survey were not collected from the same households targeted for the questionnaire survey. In addition, although Shrestha *et al.* (2014) reported that microbial concentrations were higher during the wet season, sufficient microbial data were unavailable for risk calculation in the dry season. Nevertheless, under this limited data condition, the proposed method for calculating health risk in each supply area is effective to relatively understand the difference among local areas.

Impact of the Gorkha earthquake on water use practice

After the Gorkha earthquake, changing the water sources used in households decreased the estimated risk in most of the areas, as shown in Table 4 and Figure 4. The number of households drinking only jar water increased after the earthquake. Moreover, drinking relatively contaminated water, such as tanker water and groundwater, tended to decrease. The number of households that used tanker water for drinking and bathing purposes decreased after the earthquake (Table 4 and Supplementary material Table A1). In the field surveys conducted after the earthquake, we observed that tanker water could not be distributed due to the collapse or blocking of the road. However, the number of households using groundwater for bathing purposes increased, while its use as a drinking water source decreased. In other words, the number of households that avoided drinking groundwater but used it for bathing increased after the earthquake, probably due to confidence loss regarding its quality. Jar water was the most expensive and the safest water among the sources used in this study. Before the earthquake, many households drank jar water, with some other sources, especially piped water. After the earthquake, the number of households drinking piped water slightly decreased, while that of drinking jar water increased in six among nine areas. This might be due to the pipeline being damaged by the earthquake. Mostafavi *et al.* (2018) reported a breakage in the main trunk across 100 m of a sub-system due to landslide-led disruption of water supply for 2 weeks, and the water supply connection to houses was also damaged. Thapa *et al.* (2016) reported a 40% decrease in water supply by KUKL after the earthquake. The greatest damage was observed in supply area 2, where the number of households drinking piped water significantly decreased (Thapa *et al.* 2016). Moreover, households that could not get enough piped water or households that received piped water of poor quality had to choose other sources, thus affecting the health risk estimation. Consequently, the earthquake and the subsequent damage to piped water and decrease of the tanker water availability changed the choice of water sources and forced people to drink jar water, thus enhancing the water market. However, households that could not afford it used either the relatively cheaper tanker water or the freely available groundwater.

CONCLUSIONS

In the Kathmandu Valley, locals used multiple water sources and in various combinations. Our study showed that the estimated diarrhoea infection risk significantly depends on the water source used for drinking and bathing purposes, while it is also affected by the water supply region. Moreover, it was demonstrated that powerful natural phenomena, like an earthquake, may have a strong impact on the locals' choices, thus altering the health risk assessment. This study also confirmed the vulnerability of piped water, making clear that the infrastructure of piped water supply in the Kathmandu Valley should be improved and strengthened against disasters. Our results could contribute to water supply management by suggesting the area to be prioritised. As a direct measure, we suggest that locals are encouraged to pay more attention to the quality of drinking water. Our proposal to calculate the health risk for each supply area contributes to the understanding of the local situation and the realisation of this initiative that could be adopted by similar regions.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/wh.2020.223.

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