Quality of Rainwater Runoff on Roofs and Its Relation to Uses and Rain Characteristics in the Villa Alexandra and Acacias Neighborhoods of Kennedy, Bogota, Colombia

Andrés Torres[1]; Sandra Méndez-Fajardo[2]; Ángela Patricia Gutiérrez Torres[3]; and Santiago Sandoval[4]

Abstract: In Colombia, several communities with limited or uncertain access to drinking water services collect rainwater for various domestic uses. This paper presents the results of a water quality analysis of the rainwater runoff from roofs in Kennedy (Bogota) to evaluate the suitability of adapting this water to satisfy domestic uses in this district. Based on the high values of turbidity and biochemical oxygen demand, and on the high concentrations of total suspended solids and heavy metals found in the studied rainwater, it is concluded that the water samples are not suitable for any of the domestic uses currently employed by the citizenry. Nevertheless, a high spatial and temporal variability was detected, in addition to variability as a function of the roof material. In particular cases, the runoff water from roofs may be adapted as an alternative source for domestic uses in the district. **DOI:** 10.1061/(ASCE)EE.1943-7870.0000746.

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Introduction

Successful experiences of rainwater harvesting have been reported in developing countries, both in Asia (Han and Ki 2010) and Latin America (Ghisi et al. 2009). However, urban runoff contains many pollutants that can affect human health and the quality of the surface water and groundwater (Göbel et al. 2007). The literature reports that the typical urban concentrations of metals that are present in the runoff as a result of the surface corrosion of roofs range from 0.1 to 32 $\mu g/L$ for cadmium (Cd), 3 to 247 $\mu g/L$ for copper (Cu), 16 to 2,764 $\mu g/L$ for lead (Pb), and 802 to 38,061 $\mu g/L$ for zinc (Zn) (Gromaire-Mertz et al. 1999; Göbel et al. 2007). These metals originate from dust particles that result from combustion processes, industries of ferrous and nonferrous metals, incineration plants, cement or glass industries, and vehicular traffic (Göbel et al. 2007). It has also been found that, in the runoff from roof surfaces, the concentrations of total suspended solids (TSSs) range between 3 and 304 mg/L, the biochemical oxygen demand after 5 days (BOD_5) is between 1 and 27 mg/L (Gromaire-Mertz et al. 1999), and the pH is low [between 4.7 and 6.8 according to Göbel et al. (2007)].

Several factors influence the corrosion of roofs, including the relative humidity and the pH of the rainwater (Gromaire-Mertz et al. 1999). Additionally, the concentration of pollutants in urban runoff depends on atmospheric deposition during dry and wet weather periods, surface characteristics, and type of urban area. Additionally, the runoff process is closely related to rainfall characteristics, such as the volume, intensity, flow, and periods of dry weather preceding the precipitation (Gromaire-Mertz et al. 1999; Göbel et al. 2007).

In Colombia, many communities collect rainwater for different domestic uses, such as toilets, washing floors and walls, irrigation, and animal and human consumption. This practice is common in communities with limited or poor access to drinking water or when the cost of the service is not commensurate with the income level of the residents. Specifically, according to direct observations in periurban areas of Bogota since 2002, several families currently use rainwater runoff from roofs to meet certain household uses without the prior assessment of its quality. There is, however, a health risk associated with this practice, particularly because of the quality of the rainwater and its adaptability to various community activities and methods of collection, storage, preservation, and distribution. Despite these risks, there have not yet been reports of detailed studies in Colombia on the quality of the rainwater runoff from roofs or its variability, to assess the adaptability of this source for different uses by the communities. The goal of this research was to characterize the rainwater runoff from rooftops for possible domestic use in periurban areas of Bogota. Specific case studies were used of the neighborhoods of Villa Alexandra and Acacias (district

[1]Associate Professor, Grupo de Investigación Ciencia e Ingeniería del Agua y el Ambiente, Departamento de Ingeniería Civil, Facultad de Ingeniería, Pontificia Universidad Javeriana, Carrera 7 No. 40–62, Bogota, Colombia, PBX. E-mail: andres.torres@javeriana.edu.co

[2]Professor, Grupo de Investigación Ciencia e Ingeniería del Agua y el Ambiente, Departamento de Ingeniería Civil, Facultad de Ingeniería, Pontificia Universidad Javeriana, Carrera 7 No. 40–62, Bogota, Colombia, PBX. E-mail: sandra.mendez@javeriana.edu.co

[3]Civil Engineer, Grupo de Investigación Ciencia e Ingeniería del Agua y el Ambiente, Departamento de Ingeniería Civil, Facultad de Ingeniería, Pontificia Universidad Javeriana, Carrera 7 No. 40–62, Bogota, Colombia. E-mail: gutierrez.angela@javeriana.edu.co

[4]Master's student, Grupo de Investigación Ciencia e Ingeniería del Agua y el Ambiente, Departamento de Ingeniería Civil, Facultad de Ingeniería, Pontificia Universidad Javeriana, Carrera 7 No. 40–62, Bogota, Colombia, PBX (corresponding author). E-mail: sandoval.s@javeriana.edu.co

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of Kennedy, Bogota), where the use of the rainwater runoff from rooftops is a common practice and where the impact may be high, considering that it is the most populous district of Bogota (Alcaldía Mayor de Bogota 2009).

Materials and Methods

The economic sectors with the largest number of local companies in Kennedy are trade (44%), industry (18%), real estate sales and rental of homes and business (8.1%), transport and communications (8%), and hotels and restaurants (7%) (Alcaldía Mayor de Bogota 2009). Informally, this list includes the recovery of vehicle tire wire through a burning process, the collection of charcoal, and the burning of solid waste from recycling processes, activities for which there is an absolute lack of technical and environmental controls. In particular, the neighborhood of Villa Alexandra has many warehouses that are used as garages for vehicle repair. Within this area, there are also businesses for recyclable materials and burning sites for household fuels, waste (generally tires, plastics, and solid waste), and charcoal. Although there are no specific measurements to estimate the magnitude, there is a certain level of atmospheric pollution in the area, primarily caused by vehicular traffic (the emanation of gases and the removal of dust from unpaved roads). It is a common practice by the inhabiting communities to use the rainwater collected from the roofs of buildings and houses.

For some rainfall events, samples were collected from different roofing materials of the selected periurban area and the values of pH, true color and turbidity, and concentrations of TSS, BOD_5, and heavy metals (Cd, Cu, Pb, and Zn) were determined in the laboratory for water quality of the Faculty of Engineering at Pontificia Universidad Javeriana in Bogota following the procedures in the standard methods [American Public Health Association (APHA)/American Water Works Association (AWWA)/ Water Environment Federation (WEF) 1998] (Table 1 includes more details). To facilitate the ANOVA for the obtained results, each quality parameter was analyzed in triplicate. To evaluate the possible use of the runoff water sampled for different domestic uses, such as toilet flushing, washing floors and walls, irrigation, and animal and human consumption, quality standards were checked from both national (Ministerio de Salud República de Colombia 1984; Ministerio de la Protección Social, Ministerio de Ambiente Vivienda y Desarrollo Territorial 2007) and international sources [98/83/EC 1998, 2006/7/EC 2006; USEPA 2004; World Health Organization (WHO) 2006]. The cited documents propose a minimum quality of the collected water for various uses by taking into account the microbiological and physicochemical parameters.

After homogeneity tests for variance (Bartlett test) and normality (Shapiro-Wilk test) of the water quality results, it was concluded that the Kruskal-Wallis test should be conducted in all cases because homogeneity of variance or normality (p-values <0.05) was not obtained in any case. Kruskal-Wallis and Bonferroni t-tests were performed for each quality parameter to identify the influence of the type of roof (zinc or cement tiles) and the variability of rainfall events on the sampled water quality from different houses located in the studied zone. The following correlation tests were undertaken for the pollutant concentrations and the characteristic values of rain events (from the Santa Lucia rain gauge close to the experimental site, discussed in Table 2): antecedent dry weather period (ADWP) in minutes; total height of rain event (H) in mm; duration of rain event (D) in minutes; mean intensity of rain event (I) in mm/h and mean intensity of antecedent rain event (I_a) in mm/h. These correlation tests were applied by using the Pearson and Spearman methods, considering the results of the Shapiro-Wilk normality tests with *R* software.

Table 1. Laboratory Method, Manufacturer, and Detection Limit for the Studied Pollutants

Pollutant	Method	Manufacturer	Detection limit
True color (TCU)	Visual comparison	Hach	NA
pH	Potentiometry	YSI	0
Turbidity (NTU)	Nephelometry	Orbeco-Hellige	2
TSS (mg/L)	Gravimetry	Scientech	4.5
BOD_5 (mg/L)	Winkler method	Wheaton	2
Cd (mg/L)	Atomic absorption spectroscopy	Termo	0.03
Cu (mg/L)	Atomic absorption spectroscopy	Termo	0.09
Pb (mg/L)	Atomic absorption spectroscopy	Termo	0.43
Zn (mg/L)	Atomic absorption spectroscopy	Termo	0.06

Results and Discussion

Between February and April and September and October of 2010, 53 samples (one sample from the March 22 event was not preserved appropriately and was removed) from Acacias and Villa Alexandra were collected from houses with zinc and cement roof tiles. Table 3 summarizes the average values of pollutants and standard deviations for each house, each rainfall event (February 15, February 16, April 12, September 7, September 21, September 27, October 5, and October 6, 2010), and each roofing material (fiber-cement tiles and zinc tiles).

From the Kruskal-Wallis test performed on the water quality results obtained, the following was concluded (Fig. 1): (1) the temporal variability (the factor labeled "event") has a significant influence on the results of all measured water quality parameters (true color, pH, turbidity, TSS, BOD_5, Cd, Cu, Pb, and Zn; p-values <0.05); (2) the spatial variability (the factor labeled "house") has a significant influence on the results of pH and Zn (p-values <0.05); and (3) the roofing materials (the factor labeled "roof") have significant influences on the results of pH, Cd, Cu, and Zn (p-values <0.05). A more detailed analysis of the results of the Kruskal-Wallis test indicates that the most influential factor on the quality is the temporal variability, because the corresponding percentage of variance on the total variance is greater for this factor than the other factors.

Table 2. Characteristics of Rainfall Events Registered by Santa Lucia Rain Gauge

Event	ADWP (min)	H (mm)	D (min)	I (mm/h)	I_a (mm/h)
February 15	5,660	1.2	20	3.6	43.8
February 16	4,360	5.9	20	17.7	3.6
April 12	1,720	28.8	480	3.6	1.3
September 7	4,520	10.6	1,340	0.5	1.4
September 21	420	0.3	20	0.9	1.2
September 27	1,800	1.7	120	0.9	0.1
October 5	3,760	16.2	900	1.1	0.9
October 6	420	0.5	900	0	0.1

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Table 3. Averages, Standard Deviations, Minimum, Maximum, Number of Observations, and Number of Missing Values of Pollutants for All Samples Collected during Rainfall Events from February 15 to April 30 and from September 7 to October 6 of 2010

Pollutant	Mean	Standard deviation	Minimum	Maximum	Observations	Missing values
True color (TCU)	29.66	13.42	8.33	65	30	23
pH[a]	7.55	0.52	6.62	8.53	53	0
PH, roof FC	7.74	0.53	6.76	8.53	27	0
PH, roof Zn	7.35	0.43	6.62	8.02	26	0
Turbidity (NTU)	10.64	15.59	0.53	60.17	53	0
TSS (mg/L)	75.99	101.48	5.33	461	52	1
BOD_5 (mg/L)	15.93	12.18	0	64	29	24
Cd (mg/L)[a]	0.31	0.45	0.01	2.25	40	13
Cd, roof FC	0.17	0.18	0.01	0.62	21	6
Cd, roof Zn	0.48	0.58	0.01	2.25	19	7
Cu (mg/L)[a]	0.05	0.06	0.01	0.32	53	0
Cu, roof FC	0.06	0.07	0.01	0.32	27	0
Cu, roof Zn	0.04	0.03	0.01	0.13	26	0
Pb (mg/L)	0.15	0.17	0	0.79	30	23
Zn (mg/L)[a]	1.73	1.78	0.01	5.4	53	0
Zn, roof FC	0.75	1.06	0.01	3.78	27	0
Zn, roof Zn	2.74	1.8	0.01	5.4	26	0

[a]Additional statistics for pollutants were significantly different between roofing material (Zn, FC).

Regarding true color, this parameter was only measured for the September 7 event and thereafter. Figs. 2–4(a) show that the samples from the first rainfall events present values of true color, pH, turbidity, TSS, and BOD_5 that are significantly higher (p-value <0.05; t-test with Bonferroni adjustment) than the values associated with the samples of the subsequent events. These differences (especially for turbidity, TSS, and BOD_5) may be the result of a long dry period preceding a rainfall: particulate matter accumulation (e.g., leaves and bird droppings) on the roof may be swept off later during the rainfall event.

Fig. 4(b) shows that the samples collected during the events of February 15 and 16 have values of Cd that are significantly lower (p-value <0.05; t-test with Bonferroni adjustment) than those obtained for the samples collected during the subsequent events.

Fig. 5(a) shows that samples collected during the event on October 6 have values of Cu that are significantly greater (p-value <0.05; t-test with Bonferroni adjustment) than those obtained for the samples collected during the previous events.

Fig. 5(b) shows that the samples collected during the events of September 21 and 27 show no detectable values of Pb (Table 1 shows Pb detection limit), whereas the Pb values for the previous rainfall events are high.

For the results of color, turbidity, TSS, BOD_5, and Cd, the variability of the replicates has a major influence on the results, because the maximum corresponding percentage of variance on the total variance reported in Fig. 1 is approximately 30%. This observation indicates the presence of problems in the experimental process of

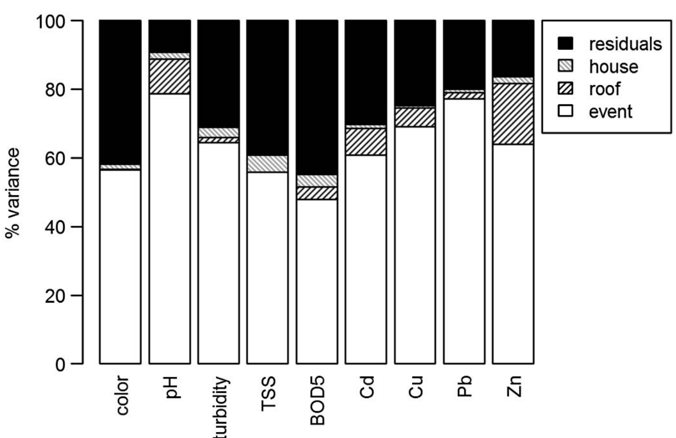

Fig. 1. Results of the Kruskal-Wallis variance analysis for each quality parameter measured in the study

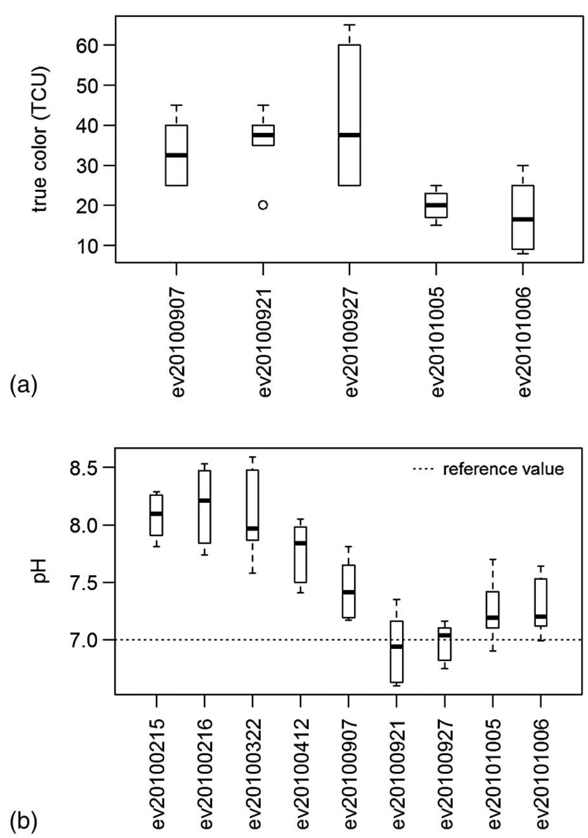

Fig. 2. Variability of the results for each rainfall event: (a) true color; (b) pH (reference value for irrigation: 7)

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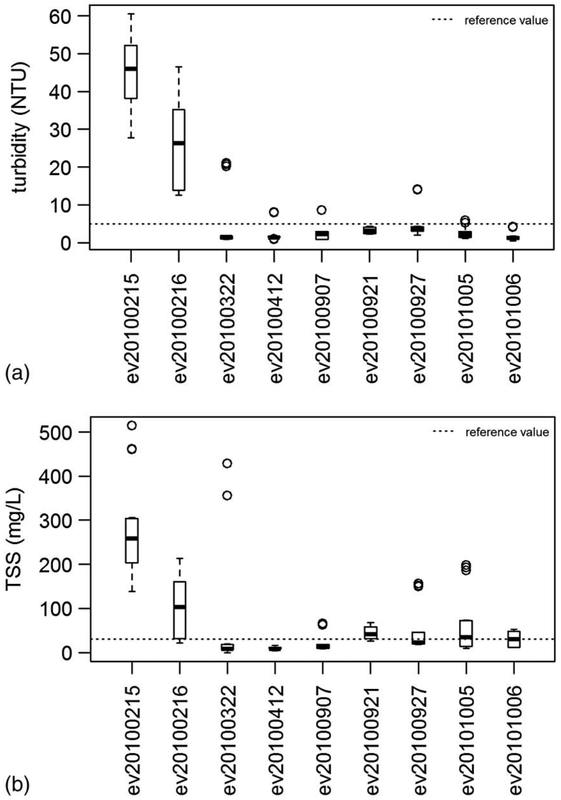

Fig. 3. Variability of the results for each rainfall event: (a) turbidity (reference value for agricultural irrigation: 5 NTU); (b) TSS (reference value for agricultural irrigation: 30 mg/L)

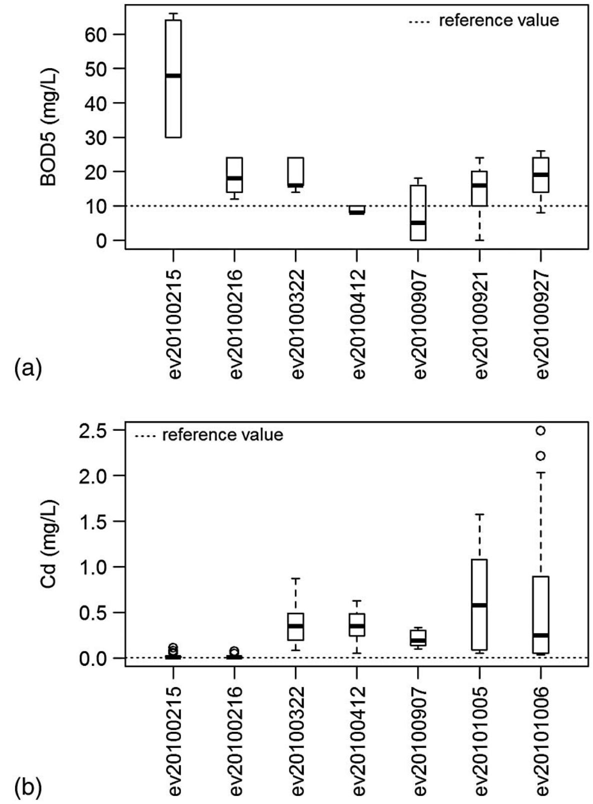

Fig. 4. Variability of the results for each rainfall event: (a) BOD_5 (reference value for flushing toilets and urinals, primary contact recreation uses, and irrigation: 10 mg/L); (b) Cd (reference value for human consumption: 0.003 mg/L)

sampling and/or laboratory tests and may, therefore, question the reliability of the results; this must be corrected in future studies.

Fig. 6(a) shows that the samples from the rainfall events of October have Zn concentrations below those associated with the previous events. Additionally, the samples of asbestos cement roofs (FC) have significantly lower Zn concentrations (p-value <0.05; t-test with Bonferroni adjustment) than those of the zinc roofs [Fig. 6(b)].

According to the results, the sampled water is not suitable for flushing toilets and urinals, irrigation, washing floors and walls, or animal and human consumption. First, high turbidity values [greater than 5 nephelometric turbidity units (NTU)] were reported for the first two rainfall events [particularly for the samples of February 15 and February 16, as shown in Fig. 3(a)], which is the limit recommended for less restrictive uses, such as nonagricultural irrigation (USEPA 2004). The concentrations of TSS for all rainfall events, except the April 12 event [Fig. 3(b)], were above 30 mg/L, a limit that is recommended for less restrictive uses, such as agricultural irrigation (USEPA 2004). Concentrations of BOD_5 for all rainfall events, except the events of April 12 and September 7 [Fig. 4(a)], showed values greater than 10 mg/L, which is the recommended limit for flushing toilets and urinals, primary contact recreation uses, and irrigation (USEPA 2004). High Cd concentrations were detected (with values higher than 0.003 mg/L) in all of the samples [Fig. 4(b)]. This limit value is recommended for human consumption (Ministry of Social Protection, Ministry of Environment, Housing and Territorial Development 2007). High Cu concentrations [Fig. 5(a)] were above 0.01 mg/L, which is a recommended limit for irrigation (Ministry of Health Republic of Colombia 1984; USEPA 2004), particularly for avoiding the blockage of irrigation components. Pb concentrations, particularly for the events of February 15 and 16 and September 7 [Fig. 5(b)], were reported above 0.01 mg/L, which is a recommended limit for human consumption (Ministry of Health Republic of Colombia 1984; Ministry of Social Protection, Ministry of Environment, Housing and Territorial Development 2007). Finally, Zn concentrations, especially in houses with zinc roofs, were registered above 2 mg/L (Table 1), which is a recommended limit for irrigation (Ministry of Health Republic of Colombia 1984; USEPA 2004). In addition to the preceding values, slightly elevated pH values (above 7) were detected, particularly for the first four rainfall events and for houses with cement roofs, restricting the use of this water for irrigation as a result of the possible blockage of the irrigation elements (Lazarova et al. 2004).

With the exception of the heavy metals (especially Cd and Cu), a more restrictive water quality was found in the samples for the first three rainfall events (February and March). These observations could be attributable to a change in the pattern (dry season/rainy season) or rainfall characteristics (height, intensity, duration of rainfall, and duration of dry weather before) in February and March compared to the other months or pollution in the first months of the year. If it is found that the improvement in the quality of the rainwater runoff from roofs, similar to that observed in April, is associated with a rainy season, it may be proposed that the rainwater collected during these times should be used to flush toilets and urinals and wash floors and walls.

Table 4 shows positive significant correlations between: (1) ADWP and pH, turbidity and Pb; (2) I and pH; and (3) I_a and pH, turbidity and Zn. Table 4 also shows negative significant correlations between: (1) ADWP and Cu; (2) D and turbidity, TSS, BOD_5, and Zn; and (3) I_a and Cd.

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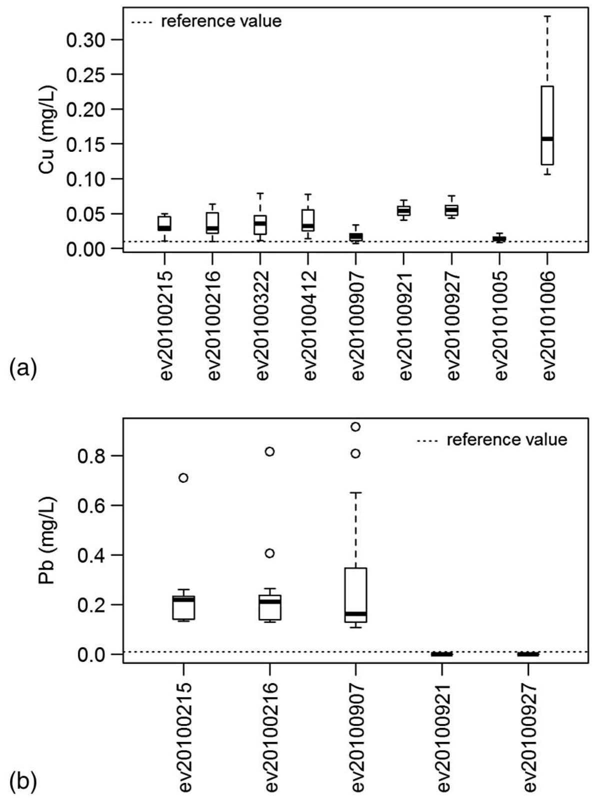

Fig. 5. Variability of the results for each rainfall event: (a) Cu (reference value for irrigation: 0.01 mg/L); (b) Pb (reference value for human consumption: 0.01 mg/L)

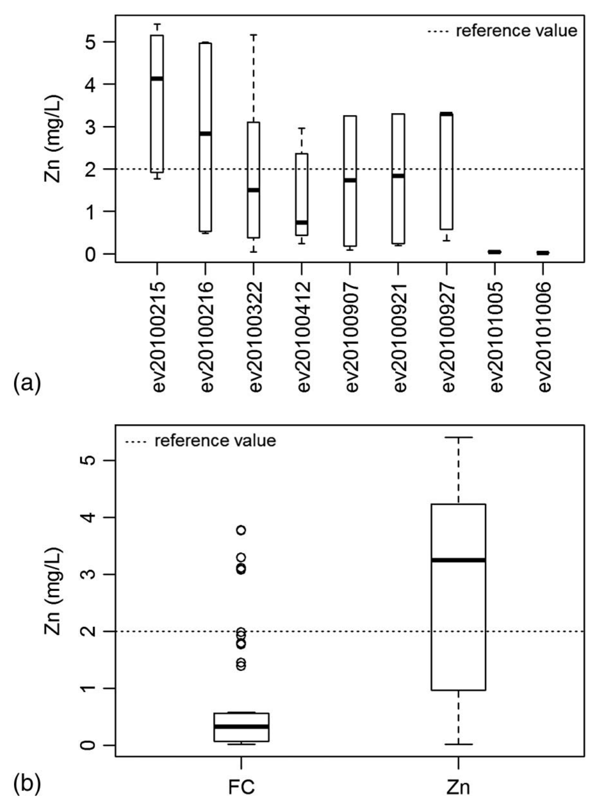

Fig. 6. Variability of the results for each rainfall event: (a) Cu; (b) Pb

Table 4. Results of Correlation Tests

Parameter	ADWP (min)	H (mm)	D (min)	I (mm/h)	I_a (mm/h)
Color	-0.01_p	-0.20_s	-0.56_s	0.30_s	0.30_s
pH	$0.69_p{}^a$	0.35_s	-0.33_s	$0.74_s{}^a$	$0.84_s{}^a$
Turbidity	$0.73_s{}^a$	-0.19_s	$-0.67_s{}^a$	0.55_s	$0.68_s{}^a$
TSS	0.63_s	-0.23_s	$-0.67_s{}^a$	0.60_s	0.55_s
BOD_5	0.58_s	-0.49_s	$-0.82_s{}^a$	0.65_s	0.63_s
Cd	-0.63_p	0.07_s	0.47_s	-0.54_s	$-0.82_s{}^a$
Cu	$-0.69_s{}^a$	-0.57_s	-0.15_s	-0.34_s	-0.55_s
Pb	$0.91_p{}^a$	0.82_s	0.34_s	-0.05_s	-0.56_s
Zn	0.52_p	-0.23_s	$-0.76_s{}^a$	0.55_s	$0.70_s{}^a$

Note: Pearson correlation test (p); Spearman correlation test (s).
[a] p-values less than 0.05.

Conclusions

The results obtained in this study clearly show that, despite its current use to satisfy certain household uses in periurban areas of Bogota, the rainwater runoff from roofs is not suitable for any of these uses, primarily because of high turbidity values and high concentrations of TSS, BOD_5, and heavy metals. With the exception of Cd, whose measured concentrations are almost 10 times higher than those reported as acceptable limits in the literature, the concentrations of TSS, BOD_5, and heavy metals and their variability are of the same magnitude as those reported in the literature for rainwater runoff from roofs (Gromaire-Mertz et al. 1999; Göbel et al. 2007; Schriewer et al. 2008).

There was a high temporal variability in the quality of the water runoff from roofs. Such variations suggest that, in some cases and under special conditions, rainwater runoff from rooftops may be adapted for use as an alternative source of water to meet certain household needs, such as flushing toilets and washing floors and walls. For example, it is proposed that the samples for which a better quality was detected may be associated with the rainy season; therefore, it may be argued that, at certain times of the year, a restricted use of runoff water from rooftops may be possible. However, a finer and prolonged characterization of the rainwater runoff from roofs for both periods of dry weather and during periods of heavy rain should be performed to suggest more specific recommendations about the operation of rainfall harvesting systems in association with the characteristics of rainfall, including the volume, intensity, flow, and periods of dry weather before the event.

The presented results highlight the need to account for the quality of rainwater runoff from rooftops in periurban areas of cities, and to develop policies and regulations aimed at protecting civil health, particularly with regard to urban agriculture. It was verified that the population of the study area is using rainwater as an alternative irrigation source in their homes. However, from the obtained results, the roofing material plays an important role in the concentrations of rainwater pollutants. Therefore, local environmental authorities should consider a more rigorous control over the distribution, use, and replacement of roofs, taking into account aging and expected water uses.

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