A PVC-pipe device as a sanitary barrier for improving rainwater quality for drinking purposes in the Brazilian semiarid region

José Roberto Santo de Carvalho, Julio Luz, Sylvana Melo Santos and Sávia Gavazza

ABSTRACT

We evaluate the behavior of a device designed to automatically divert and store the first flush of harvested rainwater in cisterns. The first phase (PI) was conducted with artificial precipitation in an experimental installation seeking to identify how many millimeters of rainwater should be diverted to preserve the rainwater quality. In the second phase (PII), we designed a PVC-pipe device to store the first millimeter of rainwater, and tested it in field (a rural area in Brazil) during two real rainfall events. In the third phase (PIII), the device and a hand pump were assayed for two years using eight cisterns in a rural area where people drink the rainwater. PI results indicated that the most significant pollution of the rainwater is flushed with the first millimeter of rain, and diversion promoted the removal of 98% and 100% of the total coliforms and *Escherichia coli*, respectively. The bacteriological behavior was maintained in the subsequent phases. The device was able to preserve the quality of the rainwater most of the time, satisfying drinking requirements for the parameters of turbidity and color. The satisfactory performance of the device was confirmed in the field, behaving as a sanitary barrier for rainwater quality protection.

Key words | coliforms, *E. coli*, first flush device, harvesting rainwater, sanitary barrier, water quality

José Roberto Santo de Carvalho
Julio Luz
Sylvana Melo Santos
Sávia Gavazza (corresponding author)
Department of Civil and Environmental Engineering,
Federal University of Pernambuco,
Av. Acadêmico Hélio Ramos, s/n. Cidade Universitária, Recife, PE CEP: 50740-530,
Brazil
E-mail: *savia@ufpe.br*

INTRODUCTION

Historically, water availability and the relationship between the quality of water and its uses have represented a major obstacle to human development. Water security is a central theme when seeking to protect the future of cities. The planning and development of cities require better efficiency in terms of the use of natural resources, including changing society and industrial habits, aiming to build sustainable productive chains based on the scarcity of resources. Rainwater is a natural resource that is unpolluted during the hydrologic cycle. The collection and storage of rainwater is an important solution when facing water scarcity. This practice is already common in arid and remote areas, where the implementation of conventional water supply systems is unprofitable or technically unviable (Sazakli *et al.* 2007). Water storage in tanks, usually known as cisterns, is common in areas that suffer long periods of drought, such as arid zones in northern China (Zhu *et al.* 2004), southern Syria (Braemer *et al.* 2015), and Palestine (Al-Salaymeh *et al.* 2011).

Between 2011 and 2017, the Brazilian social program known as '*Água para todos*' (Water for All, WA) assisted approximately 4.5 million people through the installation of 911,000 cisterns in the Brazilian semiarid region. The Brazilian semiarid region is characterized by long dry

doi: 10.2166/wh.2018.208

periods (eight to nine months per year) and a rainy period concentrated in three to four months of the year (Alves *et al.* 2014). The aim of the WA program is to complete 1.5 million cisterns (MI 2017), delivered to the population in the semiarid region where the conventional water supply is not viable. The program builds one 16,000-liter cistern (made of concrete or polyethylene) for every house. This volume should supply a family of five with drinking water, as well as water for cooking and brushing teeth, during the entire dry season (Fonseca *et al.* 2014). Rainwater is used for human consumption because it is free of pathogens and many other pollutants that are usually found in surface and groundwater. However, rainwater can be contaminated by a number of processes, including microbial contamination from animal feces, chemical contamination from the atmosphere and the dissolution of compounds from roof materials, and physical contamination from the deposition of solids (McBean *et al.* 2013). Additionally, water handling, the method of water retrieval from cisterns, and water storage methods may also affect the quality of water used for human consumption.

Zhu *et al.* (2004) recommended boiling water before drinking, while water chlorination was preferred by Dillaha & Zolan (1985). These recommendations are related to the public health risk of bacterial diarrhea (from *Salmonella* and *Campylobacter*), bacterial pneumonia (from *Legionella*), or botulism (from *Clostridium*) (Lye 2002). Additionally, poor management of water in cisterns can lead to a favorable environment for the multiplication of *Aedes aegypti*, which is the vector for several viruses, including *dengue, zika* and *chikungunya* (Petersen *et al.* 2016). Physical barriers, such as plastic screens (placed at the end of gutters), first flush devices, filters, and pumps can provide initial sanitary protection and reduce the chances of rainwater being contaminated during the collection process.

In general, there is a strong consensus that diverting the first flush of rainwater is a protective factor against the consumption of contaminated water. However, most of the first flush devices used are made of concrete, for which leakages are a common problem, often leading to the abandonment of their use (Souza *et al.* 2011). It is also common to manually divert the first flush (Gikas & Tsihrintzis 2012). It has even been recommended to disconnect the pipes that divert water containing suspended solids from gutters (Alves *et al.* 2014). The manual diversion of the first flush is extremely dependent on the attitude and availability of the user. Plastic-made devices are widely commercially available. However, scientific studies reporting the behavior and proper amount of rainwater to be diverted in the field are limited.

To improve the quality of rainwater stored in cisterns, the aim of the present study was to assess the performance of a device designed to store the first millimeter of rainfall collected in cisterns. The water is diverted automatically. The device is made of PVC for reducing leakages, and it was tested from demonstration scale to practical application in the field (rural site). Additionally, we tested a hand pump as a complementary protective device.

MATERIAL AND METHODS

Study area

The present study was conducted in the city of Caruaru in the state of Pernambuco in the northeast of Brazil (Figure 1). The Caruaru population projected for 2016 (IBGE 2010) was 351,686, distributed over an area of approximately 921,000 km^2. Pernambuco has 185 municipalities, with 122 of them located in the Brazilian semiarid region (Figure 1). This classification was made by the regional secretary for policies development of the Ministry of National Integration (MI 2005). The criteria used to award this classification include annual rainfall of less than 800 mm and a 60% or higher risk of drought.

The present research involved three phases: (1) identifying the amount of rainwater to be diverted; (2) defining the automatic diversion device (with no human interventions required); and (3) long-term monitoring of protective devices.

Phase 1: identifying the amount of rainwater to be diverted

In this phase, the experiments were conducted in a rainwater catchment experimental station (RCES) (Figure 2), which was built on the university campus in the city of Caruaru. The RCES is a ground-floor building with a roof of

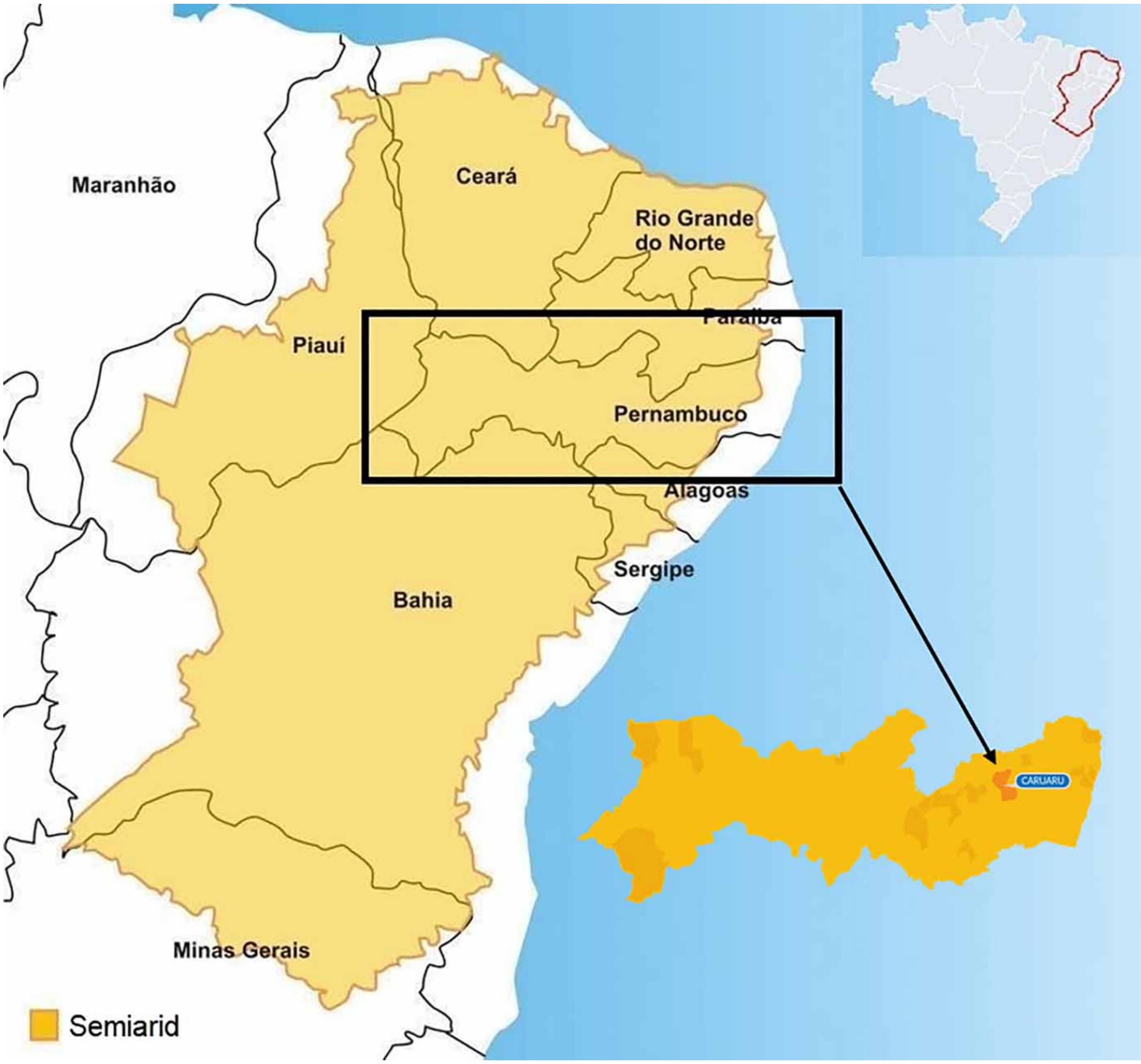

Figure 1 | Location of the city of Caruaru in the Brazilian semiarid region.

ceramic tiles. The roof of the RCES comprises two independent surfaces with areas of 50 m^2 and 59 m^2. It is possible to pump water from a polyethylene reservoir (1,000 L) to create artificial rainfall using nozzles, which are uniformly distributed on both sets of tiles. The nozzle system comprised 28 fixed nozzles, with a 0.5 m^3/h flow rate (Fabrimar® Sempre Verde, Brazil), radial range of 4 m and maximum pressure of 20 mca for each nozzle. The collection of rainwater (artificial or not) was performed using collecting gutters and PVC pipes. Two concrete cisterns (16,000 liters each) were built to store the rainwater. The pumping station is composed of a one-stage centrifugal pump, with the following characteristics: 0.8–5.9 m^3/h flow rate, manometric height of 9–30 m, and power of 1 HP (Schneider Motobombas® BC-92, Brazil). Two hydrometers were used to measure the amount of water pumped in the precipitation simulations, with accuracy rates of 0.015 m^3/h (Sappel Aquarius, Brazil). In addition, two analog gauges, with a maximal pressure of 20 mca, were used (Mecaltec, Brazil).

The RCES was installed in a rural area of the campus, close to a non-paved area used as a parking lot. Preliminary

Figure 2 | Photography of the rainwater catchment experimental station used in Phase 1.

tests with AP (artificial precipitation) indicated the absence of total coliforms and *Escherichia coli* (*E. coli*) on the roof tiles of the RCES. Therefore, prior to beginning the experiment, artificial bacteriological contamination was performed by spreading 400 mL of sewage sludge evenly over the tiles (40.2 g SSV/L). The sludge was collected in an anaerobic reactor from a local sewage treatment plant, of which the microbial diversity is known (Lucena *et al.* 2011).

Two AP experiments were carried out in the RCES in triplicate (total of six assays). The aim of these experiments was to find the first flush volume that should be diverted to improve the quality of rainwater stored in the cisterns. The water used in the AP experiments was provided by the local sanitation company. The two precipitation intensities used were the average for the study area (23 mm/h – performed in triplicate) and another that was twice as high (46 mm/h – also performed in triplicate).

Samples of the first, second, third, and fourth millimeters of rainfall were collected. For sampling each millimeter of AP, four graded plastic buckets (named A, B, C, and D), with a maximum capacity of 59 liters each, were used to collect ten sequential samples (Table 1). Immediately after each bucket was filled, the water was mixed to standardize the water and collect samples for the analysis.

Physical-chemical analyses were conducted in accordance with *Standard Methods for the Examination of Water and Wastewater* (APHA 2005). The following parameters were determined: true and apparent color (2120C), turbidity (2123B), pH (4500H + B), alkalinity (2320B), total suspended solids (2540D), total dissolved solids (2540C), total coliforms (9223B), *E. coli* (9223B), total hardness (2340C), conductivity (2510B), and chlorides (4500 Cl-B).

Phase 2: defining the automatic diversion device (with no human interventions required)

Based on the results from the first phase, we designed a device to automatically divert and store the first flush of rainwater. The device design is a variation of commercially available devices (Rain harvesting®, Waterplex®, etc.). It is made of PVC pipes and connections, arranged to store

Table 1 | Identification of the AP samples collected

Sample	Description
SW	Water used to perform the simulation
BD	Water collected in the gutter, before diversion
A1	Water collected after diverting 1 mm
A2	Water collected after diverting 2 mm
A3	Water collected after diverting 3 mm
A4	Water collected after diverting 4 mm

1 mm of rainwater. The device was named the DesviUFPE (Figure 3) and is characterized by its tightness, easy installation (like a puzzle), simple design, and low cost (approximately US$83.00 in 2017). The DesviUFPE differs from the commercially available ones, as it can be fitted to store the desired volume of diverted water according to the roof size. Additionally, the PVC pipes can be shaped to fit into the height of the house (usually the houses in rural areas are lower than houses in urban sites). It is a non-patented device.

The working principle is based on the communicating vessels. When the rain starts, the first flush is automatically stored in the device, and cleaner rainwater is forwarded to the cistern (Figure 3).

The water stored inside the device can be discarded or used for non-human consumption purposes. The DesviUFPE was installed in a house in the semiarid rural area of Caruaru-PE. Its efficiency was assessed through the analysis of water samples collected from five points along the rainwater course (Figure 4): rainwater (point A), water that had passed over the tiles and gutters (point B), water taken from inside of the DesviUFPE (point C), water sent to the cistern (point D), and water stored inside of the cistern (point E). These samples were collected during two rainfall events that occurred during the region's rainy season. The first collection occurred during the first rainfall event after the installation of the DesviUFPE (rainfall event I). The second collection occurred one year after the first (rainfall event II).

After the water samples had been collected in sterilized plastic receptacles, the same physicochemical parameters from Phase 1 were analyzed (with the exception of total suspended solids) using the methodology described in *Standard Methods for the Examination of Water and Wastewater* (APHA 2005).

Phase 3: long-term monitoring of protective devices

In this phase, we expanded the study of the DesviUFPE behavior in the field by adding the assessment of a hand pump, which is commonly used by the rural community. We collected water from eight cisterns (Table 2) installed in the rural area of Caruaru (Figure 1), 40 km distant from the urban center. The detail in Figure 3 illustrates a typical house found in the rural area of Caruaru. These typical houses have a ceramic tile roof and a wide variety of ceiling heights (in most cases). The DesviUFPE was installed successfully in every house, due to its advantage of being adjustable in many different layouts and roof areas.

Cisterns C2 and C3 (Table 2) were monitored for 24 months. Cisterns C1, C5, C6, C7, and C8 were monitored for 12 months. Four of the analyzed cisterns did not receive any protective device throughout the entire monitoring period (C3, C6, C7, and C8). Cistern C5 only had a hand

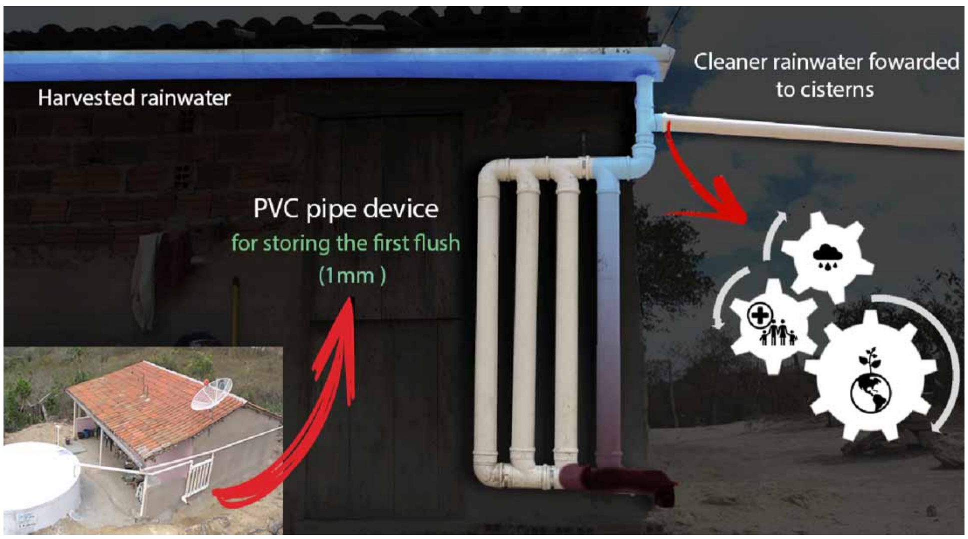

Figure 3 | Illustration of the DesviUFPE communicating vessels working principle. In detail, the DesviUFPE is installed in a rural area house, with low ceiling height.

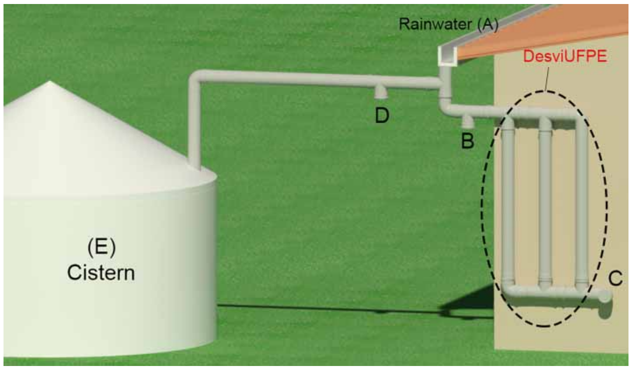

Figure 4 | Sampling points A, B, C, D, and E for assessing the DesviUFPE efficiency, installed in a house in a semiarid rural area of Caruaru-PE.

pump. Cisterns C1 and C2 had two protection devices (DesviUFPE and the hand pump). Cistern C4 was monitored for a total period of 24 months, with the two protection devices (DesviUFPE and the manual pump) installed in the 13th month of monitoring (Table 2). The samples were directly collected from the cistern monthly using the hand pump (when available) or by introducing a bucket into the cistern.

The hand pump utilized can extract 1 liter of water at each pump round. This device was made using PVC pipes and connections (50 mm and 40 mm), rubber rings, and two small marbles (Figure 5).

All obtained data (same parameters as Phase 2) were analyzed using descriptive statistics tools and a level of significance of 5%. The comparison of mean values (Student's *t*-test) and analysis of variance (ANOVA) were also applied. Tukey's test was used to make comparisons based on the minimum significant difference.

RESULTS AND DISCUSSION

Phase 1: identifying the amount of rainwater to be diverted

The first millimeter was responsible for the most substantial removal of color (87.52%) and turbidity (88.40%, Figure 6) from rainwater that could reach the cistern. The diversion of the second, third, and fourth millimeters resulted in low additional contributions of 4.55%, 6.73%, and 7.86%, respectively, for color, with corresponding values of 6.39%, 7.39%, and 9.32% for turbidity. Thus, no significant differences were found between the second, third, and fourth diverted millimeters (ANOVA: p-value = 0.160078 for $\alpha = 5\%$).

The only parameter affected by the change in the precipitation intensity (from 23 to 46 mm/h) was turbidity

Table 2 | Description of installed sanitary barriers, number of consumers, and the monitoring period of the cisterns used during Phase 3

Sampling points (description)	Coordinates	First flush device (DesviUFPE)	Hand pump	Number of consumers	Monitoring period
C1	08°12′32.9″ 36°5′34.4″	Installed	Installed	2	12 months
C2	08°12′25.9″ 36°4′32.5″	Installed	Installed	4	24 months
C3	08°12′32.9″ 36°5′33.7″	NI	NI	2	24 months
C4	08°12′.7″ 36°5′40.5″	Installed[a]	Installed[a]	1	24 months
C5	09°12′27.9″ 36°5′29.0″	NI	Installed	4	12 months
C6	08°13′36.1″ 36°02′52.9″	NI	NI	3	12 months
C7	08°13′.6″ 36°00′42.3″	NI	NI	8	12 months
C8	08°13′21.9″ 36°00′40.9″	NI	NI	6	12 months

NI, not installed.
[a]DesviUFPE and hand pump installed in the 13th month.

Figure 5 | Hand pump used in the experiment: (a) before and (b) after installation on the cistern.

(Figure 6). This influence was only relevant for the first millimeter (Student's *t*-test: p-value $= 0.0446$ for $\alpha = 5\%$), with 5% higher removal at the intensity of 46 mm/h when compared with the result found for the 23 mm/h intensity. The runoff velocity was higher for the higher intensity, which only affected suspended solids, measured as turbidity.

When we consider the removal of total coliforms, once more, the first millimeter was responsible for the most significant removal (98.5%). The concentration of total coliforms in the rainwater that passed over the roof and gutters was reduced from 536,433 (BD, Figure 7) to 7,876 MPN/100 mL (A1, Figure 7) after diverting the first millimeter. However, after the fourth millimeter, total coliforms dropped to 510 MPN/100 mL (99.7% of removal efficiency) (A4, Figure 7). At this point, it is necessary to consider the ratio between the additional volumes of water that were discharged after the first (59 liters) and the fourth (236 liters) millimeters and the benefit generated by these diversions. When we consider regions with annual precipitation of less than 800 mm, the importance of preserving water resources is more extreme. During the years 2012 and 2013, the mean monthly precipitation was 29 mm and 50 mm, respectively, in the region monitored herein (INPE 2015). If we consider, for example, a catchment surface of 100 m² (mean catchment surface area of the cisterns monitored), the maximum volume that one family could store monthly was 2,900 liters and 5,000 liters. Thus, the diversion of the first 4 millimeters (corresponding to 400 liters in this case) of rainfall could be reckless, in terms of water resource management, due to the large amount of water being discharged. The scenario is critical when more than one discharge is required in a month, due to dry deposition between rainy events.

The best performance of diverting the first flush millimeter was found for *E. coli*, with a 100% removal efficiency. The association of microbes with settleable organic and inorganic solid particles may be the key for explaining the removal efficiency of pathogens by sedimentation, given that the attached microbes settle down faster than microorganisms in a free phase. Bacterial indicator organisms exhibit a consistent sedimentation correlation with settleable solids in urban runoff water samples. According to Characklis *et al.* (2005), centrifuging fecal coliforms, *E. coli*, and *Enterococci* with suspended solids increased the removal of these microbes by 30 to 50% in comparison to raw samples without centrifugation. This helps explain the good behavior of the device in removing *E. coli* (100%) and total coliforms (98.5%) in association with total solids (86.3%).

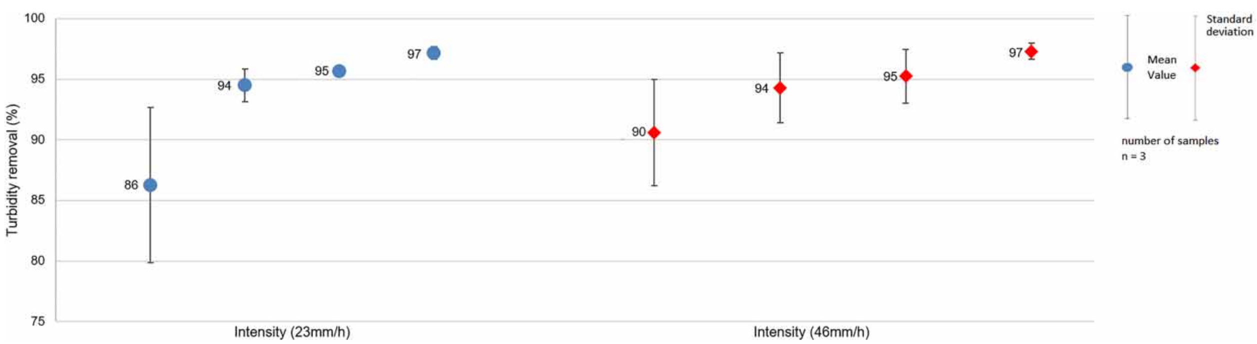

Figure 6 | Turbidity removal efficiency after each millimeter diversion for the precipitation intensities of 23 mm/h and 46 mm/h.

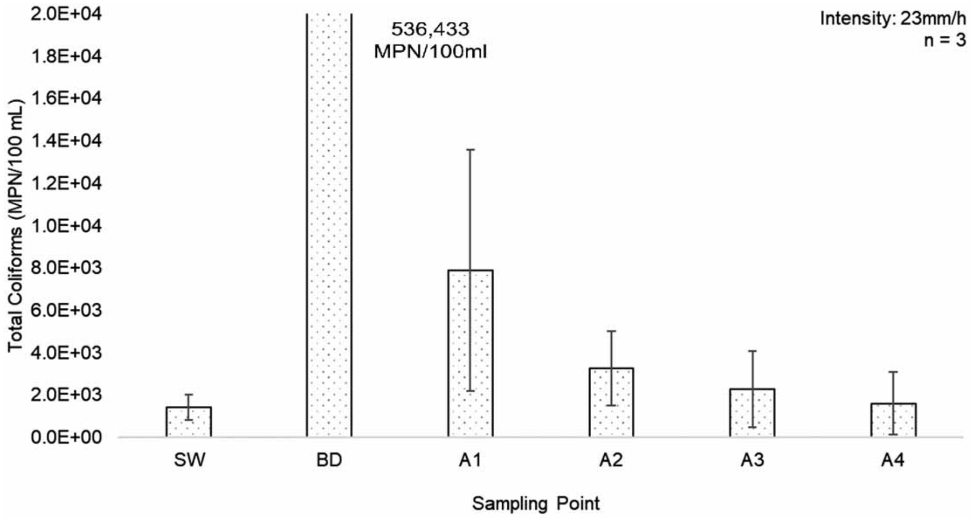

Figure 7 | Total coliforms for the water used in the experiment (SW), the water collected before diversion (BD), and for water collected after diverting the 1st (A1), 2nd (A2), 3rd (A3), and 4th (A4) millimeters of rainwater (precipitation intensity of 23 mm/h). The error bars represent the standard deviation.

Phase 2: defining the automatic diversion device (with no human interventions required)

Analysis of the physicochemical parameters confirmed that turbidity, true color and apparent color were removed in the greatest quantities from rainwater that passed over the roof and gutters (difference between the results found for points B and D, Figure 4); average removal efficiencies of 71%, 66%, and 69%, respectively, were found for these parameters (Table 3).

The best results, as in the first phase of this study, were found for the microbiological parameters. In the field, the

Table 3 | Results for the main physicochemical parameters evaluated during the rainfall events I and II

Parameters	Rainfall events	Sampling points A	B	C	D	E	MAV[a]
pH	I	6.79	6.43	6.22	6.53	7.82	7–9
	II	6.09	6.24	6.41	6.57	7.79	
Conductivity (µS/cm)	I	16.67	11.06	8.46	9.25	55.12	–
	II	6.5	10.2	9.5	6.3	79.9	
Turbidity (NTU)	I	0.69	6.60	2.17	0.44	1.05	5
	II	1.31	17.48	10.30	4.89	0.41	
Apparent color (Hu)	I	0.1	6	5	2	1	15
	II	0.1	7	5	2	1	
Salinity	I	0	0	0	0	0	–
	II	0	0	0	0	0	
Total alkalinity (mg/L of $CaCO_3$)	I	6.31	5.11	5.17	4.89	29.38	–
	II	7.12	5.56	5.91	7.53	40.50	
Hardness (mg/L of $CaCO_3$)	I	3.30	2.50	4.00	9.20	27.65	500
	II	1.99	3.97	5.96	1.99	34.25	
Chlorides (mg Cl^-/L)	I	0.69	0.69	0.35	0.35	4.84	250
	II	3.20	3.70	4.07	2.95	4.43	

[a]Maximum allowable value according to the Brazilian legislation for drinking water (number 2,914/2011– Ministry of Health).

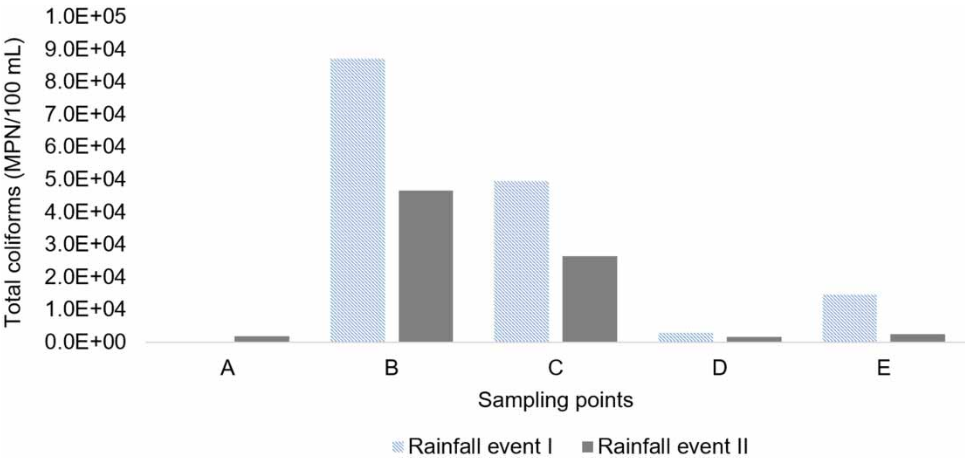

Figure 8 | Total coliforms found in sampling points A, B, C, D, and E during the two rainfall events.

DesviUFPE retained 96.2% and 96.5% of the total coliforms (difference between points B and D, Figure 8), respectively, for rainfall events I and II. This result is particularly important given that the population drinks the rainwater stored in cisterns.

Rainfall event I occurred immediately after the installation of the DesviUFPE in the field. It is interesting to note that the total coliform value found in the cistern (point E, Figure 8) in rainfall event I was 14,592 MPN/100 mL. A year after the DesviUFPE installation, this value was reduced to 2,490 MPN/100 mL (point E, rainfall event II, Figure 8). Thus, 82.9% of total coliform removal was found in the field after one year of diverting the first millimeter of the rainwater stored in the cistern. This is the consequence of diluting the water prior to device installation with better quality rainwater, which had passed through successive diversions of the first millimeter.

Phase 3: long-term monitoring of protective devices

Cistern C1 had both the DesviUFPE and a hand pump installed, while a hand pump was the only device in cistern C5 (Table 2). The other cisterns monitored (C6, C7, and C8) were not supplied with any protective devices. We used the parameter of turbidity to exemplify the significant differences found between the cisterns monitored (ANOVA: p-value $= 6.14 \times 10^{-25}$, para $\alpha = 5\%$). The results found for cistern C1 were the most significantly different from the others (Table 4). The mean value for turbidity in C1, with both protection devices (pump + device), was 34.4% lower than the mean value found for C5 (only pump) and 70.7% lower than C8, which had no protection devices and exhibited the worst water quality.

The best results found in C1 are mainly related to *E. coli* (0.75, Figure 9), considering that the water is used for drinking purposes. The *E. coli* value in C1 was 63.6% lower than C5 (only pump) and 78.5% lower than C8 (no protective devices installed). This reflected the great influence of both devices, with better results found for the combination of a hand pump and the first flush device (cistern C1). Cistern C1 also showed the lowest levels for other parameters such as apparent color (mean of 3.58 uH) and total coliforms (mean of 557 CFU/100 mL).

Lee *et al.* (2010) advised that when monitoring specific storage tanks for rainwater, it is important to guarantee that the monitoring interval is long enough to assess the variations caused by the changing of the seasons throughout

Table 4 | Turbidity results found during Phase 3 (Tukey's test)

Cistern	Mean	Min.	Max.	Groups
C1	0.799	0.39	1.00	a
C5	1.222	0.96	1.49	ab
C6	2.023	1.60	2.45	bc
C7	2.286	1.85	2.72	bc
C8	2.734	2.32	3.15	c
M.S.D.	1.25			
α	5%			

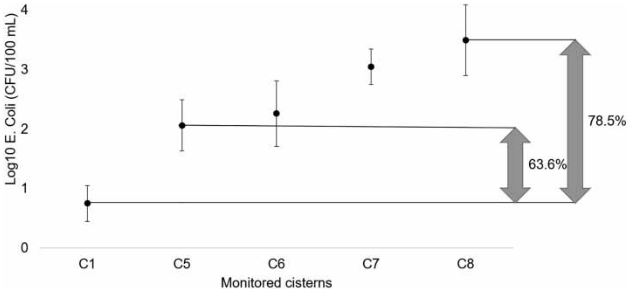

Figure 9 | Mean values found for *E. coli* in cisterns C1, C5, C6, C7, and C8 during the experimental period. The error bars represent the standard deviation.

the year. In our case, the first 12 months of this phase were affected by a severe drought, with accumulated precipitation of 450 mm. Consequently, C2 (with a hand pump and the DesviUFPE) and C3 (without protective devices) were then monitored for an additional 12 months (997 mm of accumulated precipitation in the period of 24 months). Cistern C2 performed better than C3, with apparent color, turbidity, and dissolved solid values 50%, 67%, and 45% lower than in C3, respectively. Concerning the microbiological parameters, a significant difference was also observed (Student's t test $= 3.85.10^{-5}$, $p < 0.05$) for total coliforms, for which content in C2 was 82% lower than in C3 (average value of 4,488 MPN/100 mL in C2, and 24,897 MPN/100 mL in C3), showing the sanitary barrier effect of the devices applied.

The last part of the experiment sought to determine the performance of the protective devices, comparing their influence in the same cistern. The water from cistern C4 was monitored for 12 months before the installation of the hand pump and the DesviUFPE (period named P1, Table 5) and 12 months after installation (period named P2, Table 5). The physicochemical parameters of apparent color, true color, turbidity, and dissolved solids were affected by the barriers installed, with removals of 43%, 35%, 70%, and 48%, respectively (Table 5).

For microbiological parameters, the corresponding removal was 18% and 60% for total coliforms and *E. coli*, respectively. During the rainfall harvesting process, the potential for microbiological contamination through sediments on roofs and gutters, as well as the direct depositions from birds, insects, and small mammals in the harvested water, has been widely discussed (Dillaha & Zolan 1985; Evans *et al.* 2006; Helmreich & Horn 2009). However, very few studies have discussed the management strategies that the cistern user should apply to avoid direct contamination of the reservoir. Factors such as the presence of animals in the vicinity of the reservoir, the use of dirty recipients to remove water, and the exposure of stored water (lack of a protective cover) can contribute to an increase in the microbiological pollutants found in stored water (Hoque *et al.* 2006). The low removal efficiency of total coliforms found in cistern C4 (18%) after one year of diverting the first millimeter may have been affected by this type of direct contamination in the reservoir. This efficiency tends to increase as the water storage procedures

Table 5 | Parameters investigated in cistern C4 during the 12 months before (P1) and the 12 months after (P2) the installation of the sanitary barriers (hand pump + DesviUFPE)

Parameter	Unit	Period	Mean	Min	Max	SD	MAV[a]	Reduction (%)
Apparent color	Hazen	P1	5.57	2	7	1.51	15	43
		P2	3.17	2	6	0.83		
True color	Hazen	P1	4.11	2	5	0.93	–	35
		P2	2.67	2	6	1.19		
TDS	mg/L	P1	181	105	233	42	1,000	48
		P2	94	75	178	28		
Turbidity	NTU	P1	2.84	0.9	5.86	1.45	5	70
		P2	0.85	0.6	1.36	0.23		
Total coliforms (mean = Log10)	CFU/100 mL	P1	3.664	750	14,150	4,321	Absence/100 mL	18
		P2	3.019	600	4,500	1,099		
E. coli (mean = Log10)	CFU/100 mL	P1	2.127	0	2,200	839	Absence/100 mL	60
		P2	0.842	0	1,200	393		

[a]Maximum allowable concentration according to Brazilian legislation (MS – 2,914/2011).

are improved, together with improved management of the reservoir on behalf of the users. The better behavior for removing *E. coli* (60%) in comparison with total coliforms (18%) reinforces the device relevance when harvested rainwater is used for drinking purposes.

CONCLUSIONS

The results of Phase 1, conducted with artificial rainwater in an experimental installation on the university campus, indicated that the greater load of pollutants is removed when the first millimeter of the harvested water is diverted. Discarding the first millimeter of rainwater reduced total coliforms and *E. coli* by 98% and 100%, respectively. In Phase 2, during which a PVC-pipe device named the DesviUFPE was used to accumulate 1 mm of precipitation, the results indicated a 96% removal efficiency of total coliforms for two monitored rainfall events in consecutive years. When the use of the device was extended to three houses in the rural site and a monthly monitoring program was conducted for 24 months (Phase 3), the previous behavior of working as a sanitary barrier was confirmed for the DesviUFPE. The cisterns equipped with the device and a manual pump exhibited lower concentrations of apparent color, turbidity, total dissolved solids, total coliforms, and *E. coli* (43%, 70%, 48%, 84%, and 72%, respectively) when compared with a cistern without any sanitary protection. The reduction found in the parameters investigated here ensures a lower health risk for drinking harvested rainwater when the 1 mm diverting device was used for the sanitary protection of the cistern.

ACKNOWLEDGEMENTS

The authors would like to thank the Brazilian funding agencies CNPq (process 556202/2009-0, granted to Savia Gavazza, and process 577035/2008-8, granted to Sylvana Melo dos Santos) and FACEPE (APQ 0966-3.07/15, granted to Savia Gavazza) for supporting this research project.

REFERENCES

Al-Salaymeh, A., Al-Khatib, I. A. & Arafat, H. A. 2011 Towards sustainable water quality: management of rainwater harvesting cisterns in southern Palestine. *Water Resources Management* **25** (6), 1721–1736. doi:10.1007/s11269-010-9771-0.

Alves, F., Kochling, T., Luz, J., Santos, S. M. & Gavazza, S. 2014 Water quality and microbial diversity in cisterns from semiarid areas in Brazil. *Journal of Water and Health* **12** (3), 513–525. doi:10.2166/wh.2014.139.

APHA 2005 *Standard Methods for the Examination of Water and Wastewater,* 20th edn. American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC, USA.

Braemer, F., Gazagne, D. & Davtian, G. 2015 Small-scale water systems in the Fertile Crescent. The role of cisterns-based water systems in an arid zone between rain-fed agriculture and stockbreeding during Roman times. *Water History* **7** (4), 455–471. doi:10.1007/s12685-015-0142-x.

Characklis, G. W., Dilts, M. J., Simmons, O. D., Likirdopulos, C. A., Krometis, L. A. H. & Sobsey, M. D. 2005 Microbial partitioning to settleable particles in stormwater. *Water Research* **39** (9), 1773–1782. doi:10.1016/j.watres.2005.03.004.

Dillaha, T. A. & Zolan, W. J. 1985 Rainwater catchment water quality in Micronesia. *Water Research* **19** (6), 741–746. doi:10.1016/0043-1354(85)90121-6.

Evans, C. A., Coombes, P. J. & Dunstan, R. H. 2006 Wind, rain and bacteria: the effect of weather on the microbial composition of roof-harvested rainwater. *Water Research* **40** (1), 37–44. doi:10.1016/j.watres.2005.10.034.

Fonseca, J. E., Carneiro, M., Pena, J. L., Colosimo, E. A., da Silva, N. B., da Costa, A. G. F. C., Moreira, L. E., Cairncross, S. & Heller, L. 2014 Reducing occurrence of Giardia duodenalis in children living in semiarid regions: impact of a large scale rainwater harvesting initiative. *PLoS Negleted Tropical Discease* **8**. doi:10.1371/journal.pntd.0002943.

Gikas, G. D. & Tsihrintzis, V. A. 2012 Assessment of water quality of first-flush roof runoff and harvested rainwater. *Journal of Hydrology* **466–467** (12), 115–126. doi:10.1016/j.jhydrol.2012.08.020.

Helmreich, B. & Horn, H. 2009 Opportunities in rainwater harvesting. *Desalination* **248** (1–3), 118–124. doi:10.1016/j.desal.2008.05.046.

Hoque, B. A., Hallman, K., Levy, J., Bouis, H., Ali, N., Khan, F., Khanam, S., Kabir, M., Hossain, S. & Shah Alam, M. 2006 Rural drinking water at supply and household levels: quality and management. *International Journal of Hygiene and Environmental Health* **209** (5), 451–460. doi:10.1016/j.ijheh.2006.04.008.

IBGE (Instituto Brasileiro de Geografia e Estatística/Brazilian Institute of Geography and Statistics) 2010 *Censo Demográfico 2010* (Demographic census of 2010).

http://www.ibge.gov.br/home/estatistica/populacao/censo2010/default.shtm (accessed 4 January 2017).

INPE (Instituto Nacional de Pesquisas Espaciais/National Institute of Climate Research) 2015 *Data Collection Platform*. http://sinda.crn2.inpe.br/PCD/SITE/novo/site/historico/passo2.php (accessed 10 January 2017).

Lee, J. Y., Yang, J. S., Han, M. & Choi, J. 2010 Comparison of the microbiological and chemical characterization of harvested rainwater and reservoir water as alternative water resources. *Science of the Total Environment* **408** (4), 896–905. doi:10.1016/j.scitotenv.2009.11.001.

Lucena, R. M., Gavazza, S., Florencio, L., Kato, M. T. & Morais Jr, M. 2011 Study of the microbial diversity in a fullscale UASB reactor treating domestic wastewater. *World Journal of Microbiology and Biotechnology* **27**, 2893–2902. doi:10.1007/s11274-011-0771-x.

Lye, D. J. 2002 Health risks associated with consumption of untreated water from household roof catchment systems. *Journal of the American Water Resources Association* **38** (5), 1301–1306. doi:10.1111/j.1752-1688.2002.tb04349.x.

McBean, E. A., Rajib, M. A. & Rahman, M. M. 2013 Improved sustainability of water supply options in areas with arsenic-impacted groundwater. *Water (Switzerland)* **5** (4), 1941–1951. doi:10.3390/w5041941.

MI (Ministry of National Integration) 2005 *The New Delimitation of Semiarid Brazil, Brasilia, Brazil* (in Portuguese). www.mi.gov.br/.../cartilha_delimitacao_semi_arido.pdf&nome_arquivo=cartilha_delimitacao_semi_arido.pdf (accessed 13 January 2015).

MI (Ministry of National Integration) 2017 *Water for All Governmental Program*. http://www.mi.gov.br/web/guest/agua-para-todos (acessed 21 March 2017).

Petersen, L., Jamieson, D. J., Powers, A. M. & Honein, M. A. 2016 Zika virus. *The New England Journal of Medicine* **374**, 1552–1563. doi:10.1056/NEJMra1602113.

Sazakli, E., Alexopoulos, A. & Leotsinidis, M. 2007 Rainwater harvesting, quality assessment and utilization in Kefalonia Island, Greece. *Water Research* **41** (9), 2039–2047. doi:10.1016/j.watres.2007.01.037.

Souza, S. H. B., Montenegro, S. G., Santos, S. M., Gavazza, S. & Nobrega, R. L. B. 2011 Evaluation of water quality and efficiency of sanitary barriers devices in systems to utilization of rainwater. *Brazilian Journal of Water Resources* **16**, 81–93 (in Portuguese).

Zhu, K., Zhang, L., Hart, W., Liu, M. & Chen, H. 2004 Quality issues in harvested rainwater in arid and semi-arid Loess Plateau of northern China. *Journal of Arid Environment* **57** (4), 487–505. doi:10.1016/S0140-1963(03)00118-6.

First received 9 August 2017; accepted in revised form 27 December 2017. Available online 12 February 2018