Urban rainwater runoff quantity and quality – A potential endogenous resource in cities?

Sara Angrill[1], Anna Petit-Boix*[1], Tito Morales-Pinzón[2], Alejandro Josa[3,4], Joan Rieradevall[1,5], Xavier Gabarrell[1,5]

[1] Sostenipra (ICTA-IRTA-Inèdit; 2014 SGR 1412) Institute of Environmental Science and Technology (ICTA; Unidad de excelencia «María de Maeztu» (MDM-2015-0552)), Universitat Autònoma de Barcelona (UAB), Edifici ICTA-ICP, Carrer de les Columnes, 08193 Bellaterra, Barcelona, Spain.

[2] Universidad Tecnológica de Pereira, Facultad de Ciencias Ambientales, AA 097 Pereira, Colombia.

[3]Department of Civil and Environmental Engineering, School of Civil Engineering, Universitat Politècnica de Catalunya (UPC-BarcelonaTech), Jordi Girona 1-3, Building D2, 08034 Barcelona, Spain

[4] Institute of Sustainability (IS.UPC), Universitat Politècnica de Catalunya (UPC-BarcelonaTech), Jordi Girona 31, 08034 Barcelona, Spain.

[5] Department of Chemical, Biological and Environmental Engineering, Xarxa de Referència en Biotecnologia (XRB), School of Engineering (ETSE), Universitat Autònoma de Barcelona (UAB), Campus of the UAB, Bellaterra (Cerdanyola del Vallès), 08193 Barcelona, Catalonia, Spain.

***Corresponding author:** Email: anna.petit@uab.cat; Postal address: Sostenipra (ICTA-IRTA-Inèdit; 2014 SGR 1412) Institute of Environmental Science and Technology (ICTA; Unidad de excelencia «María de Maeztu» (MDM-2015-0552)), Universitat Autònoma de Barcelona (UAB), Edifici ICTA-ICP, Carrer de les Columnes, 08193 Bellaterra, Barcelona, Spain.

Post-print of Angrill, Sara et al. «Urban rainwater runoff quantity and quality – A potential endogenous resource in cities?» in Journal of Environmental Management (Elsevier), Vol. 189 (March 2017), p. 14-21. The final version is available at DOI 10.1016/j.jenvman.2016.12.027

Abstract

Rainwater harvesting might help to achieve self-sufficiency, but it must comply with health standards. We studied the runoff quantity and quality harvested from seven urban surfaces in a university campus in Barcelona according to their use (pedestrian or motorized mobility) and materials (concrete, asphalt and slabs). An experimental rainwater harvesting system was used to collect the runoff resulting from a set of rainfall events. We estimated the runoff coefficient and initial abstraction of each surface and analyzed the physicochemical and microbiological properties, and hydrocarbon and metal content of the samples. Rainfall intensity, surface material and state of conservation were essential parameters. Because of low rainfall intensity and surface degradation, the runoff coefficient was variable, with a minimum of 0.41. Concrete had the best quality, whereas weathering and particulate matter deposition led to worse quality in asphalt areas. Physicochemical runoff quality was outstanding when compared to superficial and underground water. Microorganisms were identified in the samples (>1 CFU/100 mL) and treatment is required to meet human consumption standards. Motorized traffic mostly affects the presence of metals such as zinc (31.7 µg/L). In the future, sustainable mobility patterns might result in improved rainwater quality standards.

Keywords: runoff coefficient, urban artificial areas, rainwater harvesting, rainfall events, urban mobility

1. Introduction

Water supply is a major challenge in terms of quantity and quality. Water management is a priority in cities, where population is expected to rise up to 70% by 2050 (UN, 2012) and water must be accessible without compromising sustainability. In addition, urban growth fosters artificial land covers and hinders stormwater infiltration. Worldwide, there are more than 500,000 km^2 of impervious surfaces (e.g., roads, streets, parking lots and sidewalks), being larger than the area of Spain (Elvidge et al., 2007). In this context, artificial urban areas can provide alternative water sources through rainwater harvesting systems, which might help to reduce the transport and treatment of drinking water and wastewater and to control floods (Fletcher et al., 2008; van Roon, 2007; Zhu et al., 2004).

However, stormwater quality has become of great interest for sanitary institutions and a barrier to rainwater harvesting systems, mainly motivated by the microbial presence in runoff (Adeniyi and Olabanji, 2005; Simmons et al., 2001). As a result, the end use of the runoff (e.g., street cleaning, irrigation, etc.) might vary depending on the stormwater quality and quantity, which can be related to the features of the harvesting site. So far, roof covers were the main surfaces assessed to deal with the potential rainwater provision to households or services (Adeniyi and Olabanji, 2005; Angrill et al., 2016; Belmeziti et al., 2013; Farreny et al., 2011; Huang et al., 2015; Meera and Mansoor Ahammed, 2006; Melidis et al., 2007), probably because of the implementation of rainwater harvesting systems at a building scale. Nevertheless, superficial runoff might be equally valuable to reduce potable water consumption (Antunes et al., 2016). Further, urban patterns are evolving towards more sustainable cities. As a result, rainwater quality might improve because of an increasing implementation of electric and pedestrian mobility and a reduced fossil fuel consumption. Hence, it is interesting to assess the quality and quantity of harvested rainwater in different types of cities and urban surfaces.

Regarding quantity, the rainwater harvesting potential of a surface can be estimated by multiplying the annual rainfall, the catchment area and the runoff coefficient (McCuen, 2004; Viessman and Lewis, 2003). The runoff coefficient is the amount of water that becomes runoff with respect to the total incident rainfall volume. The difference is lost because of leakages, surface material retention and evaporation (Singh, 1992). Therefore, the runoff coefficient can be used to determine the rainwater harvesting potential of a certain surface. So far, reported values for roads, streets and other urban areas range from 0.5 to 0.95 (Butler and Davies, 2000; Liaw and Tsai, 2004; Ragab et al., 2003). However, surface materials and local features might affect these results and specific analyses are needed.

In the case of quality, the most influential factors are the surface geometry and material, location and maintenance of the catchment area, climatic features and pollutant concentration (Abbasi and Abbasi, 2011). For instance, seasonality might affect the concentration of suspended solids in the runoff, especially in areas with snowy winters and melt period (Westerlund et al., 2003). Surface material and land use might play an important role in the case of paved urban areas. In this context, Drapper et al. (2000) found no significant correlation between the traffic volume and the pollutant concentrations in road runoff. In contrast, Apul et al. (2010) detected a significant contribution of the daily traffic to the concentrations of certain heavy metals. This might also depend on the frequency and intensity of rainfall events.

In this context, we studied different artificial urban areas to find out whether these are significantly different in terms of runoff quality and quantity. To this end, our goal was to evaluate the rainwater runoff quantity and quality in pedestrian and motorized areas and to determine their suitability as rainwater harvesting sites that meet quality standards.

We based our assessment on an experimental case study in Barcelona (Spain) that is representative of the Mediterranean climate.

2. Materials and methods

2.1 Case study area

The campus of the Autonomous University of Barcelona (UAB), located in Cerdanyola del Vallès (Barcelona, Spain), was selected for the assessment. This area presents a semi-wet Mediterranean climate with an average annual rainfall and temperature of 514 mm and 15.5°C, respectively (SMC, 2013). The campus is located in a green environment near Collserola hills and less than 1 km away from a motorway with dense traffic. The area includes different types of pedestrian and motorized public spaces, seven of which were selected for the quantity and quality surface analysis. Catchment areas were selected according to two criteria: surface material and function. These seven surfaces were grouped into three functional types (**Table 1**): pedestrian areas, traffic roads and parking lots. At the same time, each functional type was divided into surface materials: asphalt, concrete and precast concrete slabs (the latter only apply to pedestrian areas). The characteristics of each surface are shown in **Supporting Information 1**.

<Table 1>

2.2 Experimental design

A rainwater harvesting conveyance and storage system was installed in each study surface. The storage tank was located at a lower elevation to obtain a gravity flow and avoid major civil works. The experimental design consisted of delimiting the catchment area and installing a gutter and downpipe that conducted water to one or two polypropylene tanks with a capacity of 1 m^3 (**Figure 1**). This tank volume was selected considering the expected amount of water that might be collected during a rainfall event, which depends on the catchment area, runoff coefficient and maximum rainfall. A common membrane filter (1.5 mm pore diameter) was located at the entrance of the storage tank to prevent leaves and other large objects from entering the tank. No first flush diversion was installed and there was no maintenance of the catchment surface during the experimental period. However, pipes and gutters were frequently cleaned out of sand, leaves and other pollutants, and the storage tanks were rinsed with pressurized water twice a year. After collecting two homogenized unitary samples for the analysis, the storage tank and rainfall gauge were emptied and cleaned. We took samples at three different tank levels after agitation.

The experimental campaign took place from June 2011 to April 2013 (22 months). Throughout this period, we collected quantity and quality data for 25 different rainfall events. Local rainfall was monitored with a rain gauge set near each catchment surface. Rainfall events of less than 2.4 mm were excluded because of insufficient runoff.

<Figure 1>

2.3 Runoff quantity assessment

2.3.1 Data collection

A set of variables was needed to perform the quantitative assessment. Rainfall height was locally monitored using rain gauges and contrasted with the measurements of a nearby weather station located in Cerdanyola del Vallès. We gathered data on the amount of harvested runoff, duration of the event, minimum and maximum temperatures, predominant wind orientation and speed, and antecedent dry weather period (ADWP). **Table 2** presents the number of valid events used in the calculations for each catchment surface and their main features. A maximum of 16 events could be assessed out of 25, as in these cases runoff was generated but did not exceed the tank capacity.

<Table 2>

2.3.2 Estimation of the runoff coefficient

Equation (1) was the linear regression model considered to estimate the runoff coefficient, although more complex models could be studied using a larger set of variables. A p-value lower than 0.05 indicated a significant correlation.

$$Harvested\ runoff\ (mm) = Runoff\ coefficient\ (mm^{-1}) \times Rainfall\ height (mm) + Initial\ abstraction\ (mm), \forall\ rainfall\ height > initial\ abstraction\ \geq\ 0$$

Equation (1)

The rainfall height was retrieved from the weather station of Cerdanyola del Vallès (SMC, 2013). The initial abstraction is the amount of rainfall that is evaporated, retained by the surface material or lost by infiltration and is therefore not present in the direct runoff, which is the amount of water collected by the tank (McCuen, 2004). Additional water losses might be associated with the features of the collection area, e.g., tank overflows resulting from heavy rainfall events, but these cases were excluded from the analysis. These coefficients are affected by the local climatic conditions, especially the rainfall profile. Thus, because this study was performed in a semi-wet Mediterranean area, results might differ in other climatic regions (Longobardi et al., 2003).

2.4 Runoff quality assessment

2.4.1 Sample collection, physicochemical and microbiological analysis

At the end of each rainfall event, we took two homogenized unitary samples (V=0.5 L each) from the tanks and kept them refrigerated. One sample was used to perform the physicochemical analysis and the other, to determine the microbiological, hydrocarbon and metal content. After that, the tank was emptied and cleaned. The composition of the sample represents the event mean concentration, which is the total amount of onsite pollutants divided by the amount of harvested runoff (Bertrand-Krajewski et al., 1998). **Table 2** shows data on the events.

The physicochemical parameters analyzed are pH and electrical conductivity (EC) at 20°C measured with a pH meter ORION 701A and a conductivity meter ORION 101; alkalinity (HCO_3^-), ammonia (NH_4^+) and phosphate (PO_4^{3-}) analyzed by segmented flow colorimetry (AutoAnalyzer3 Bran&Luebbe); chloride (Cl^-) and sulfate (SO_4^{2-}) measured with a conductivity detector (Waters 431), nitrite (NO_2^-) and nitrate (NO_3^-) determined by a UV-Visible detector (Waters 2487) at a wavelength of 214 nm (anionic column IC-Pack Anion 4.6 x 50 mm Waters); Total Suspended Solids (TSS) measured by membrane filtration (Whatman filters of 47 mm diameter and 1.2 micron pore); Total Organic Carbon (TOC) and Chemical Oxigen Demand (COD) analyzed by IR spectrometry (TOC Analyzer) and colorimetry (Spectroquant NOVA 60 Merck), respectively. The analyses were performed based on the APHA (1999) standard methods.

The total petroleum hydrocarbons (TPH) of the samples were determined by gravimetry (petroleum ether extraction with Soxhlet equipment, vacuum pump and filtration funnel). The metal content was measured through plasma emission spectrometry (ICP-OES) for chrome (Cr), nickel (Ni), copper (Cu), zinc (Zn), mercury (Hg), cadmium (Cd), lead (Pb), iron (Fe) and arsenic (As). Microbiological analyses were conducted by common seed and count in culture media for colonies at 22 and 37°C, total and fecal coliforms, *Pseudomonas aeruginosa*, *Clostridium perfringens*, *Enterococcus*, which correspond to the most common indicators in water analysis.

2.4.2 Data analysis

The data analysis was conducted using the software SPSS Statistics 20.0. Descriptive statistics were obtained for each parameter and type of surface expressed as maximum and minimum values, mean (with standard deviation) and median. The dataset was subjected to a variance and correlation analysis. When one-way ANOVA test conditions were not satisfied (i.e., data distribution did not follow a normal distribution), the Kruskal-Wallis test was performed, which is used for determining whether k independent samples come from different populations (Sawilowsky and Fahoome, 2014).

We conducted a correlation analysis to determine the degree of association between water quality parameters among themselves and with the characteristics of the event. This analysis was performed for the whole set of catchment surfaces by means of the Spearman Rho correlation (r_s) (Kornbrot, 2014).

3. Results and discussion

3.1 Runoff quantity assessment

Based on **Equation (1)**, **Table 3** shows the runoff coefficient and initial abstraction values obtained at each catchment surface. They were based on the experimental runoff and rainfall data provided by the weather station of Cerdanyola del Vallès (SMC, 2013). The regression models are presented in **Supporting Information 2**. The regression line was adjusted by excluding outliers above the upper inner fence and values that diverged from the requirements in **Equation (1)**.

<Table 3>

Some of our results are apparently low when compared with those reported by ASCE (1969) (0.70-0.95), and are inconclusive in terms of material selection. In general, asphalt has the lowest runoff coefficient (0.41) and is the best option among parking lot scenarios as opposed to the results reported by Gilbert and Clausen (2006). In contrast, the runoff coefficient of concrete roads (0.67) is lower than that of asphalt (0.89). In the case of pedestrian areas, both materials result in the same values. The degradation state of the pavement might be affecting these variable results, as water can infiltrate through joints and cracks. Another parameter that might result in low runoff coefficients is the rainfall intensity (**Supporting Information 3**). 95% of the events had a rainfall intensity lower than 3 mm/h. In this context, stormwater might be lost due to evapotranspiration or seepage, and the runoff quantity is not high. The same experimental design should be assessed during intense rainfall events.

However, it is interesting to assess these low intensity events because (i) they are usually associated with high uncertainty and (ii) the runoff coefficient and initial abstraction are more relevant when related to the accumulated rainfall. During the experimental process, the average accumulated rainfall was 20 mm per event, but around 65% of the events were below this value. **Table 4** illustrates the effect of accumulated rainfall on the initial abstraction. In the case of an average rainfall (20 mm), initial abstraction might represent up to 20% of the runoff, i.e., the water collected by the tank. This is especially notable in asphalt pedestrian areas and parking lots. Again, the degradation of the pavement might be responsible for the infiltration of rainwater. Note that some of the initial abstraction results are zero. These were surfaces with low data availability due to tank overflows and we forced the intersection between the regression line and the Y axis at zero to comply with **Equation (1)**.

<Table 4>

We also compared our results with on-campus roof runoff coefficients reported by Farreny et al. (2011), who applied the same experimental design. In the aforementioned study, metal and plastic roof covers with a smooth surface gave runoff coefficients over 0.9. Besides, ceramic tiles that consist of a more porous material with a higher interception capacity showed a lower runoff coefficient (0.84). Finally, flat gravel roofs presented a runoff coefficient of 0.62, much lower than the others because of the lack of slope and high initial retention capacity. Our results are generally lower. Here, the state of degradation and the material texture play an important role. In the case of urban surfaces, the superficial and sub-superficial materials may have different retention capacities and they are used more frequently, which results in higher degradation.

3.2 Runoff quality assessment

There is a wide variety of pollutant sources in urban environments that directly or indirectly affect runoff water quality, such as atmospheric pollution, animal waste, road traffic, pavement weathering and erosion, drain gates corrosion, public works and debris and others (Sazakli et al., 2007; Simmons et al., 2001; Villarreal and Dixon, 2005). **Section 3.2.1** compares the quality results in different urban surfaces. In **Section 3.2.2**, the urban runoff quality is compared with previous studies, the quality thresholds established by the European regulation Drinking Water Directive (DWG) 98/83/EC that set the water quality guidelines for human consumption (EC, 1998), and the values extracted from regional superficial and groundwater sources. The quality values correspond to the location where water is extracted and transferred for water purification to the treatment plant (ACA, 2012).

3.2.1 Rainwater quality comparison among urban surfaces

Figure 2 presents the water quality results obtained during the experimental period for each urban surface (for additional data, see **Supporting Information 4**). After conducting the Kruskall-Wallis test for independent samples significant differences were found among catchment surfaces and the following analyzed parameters: pH, EC, COD, NO_3^-, Cl^-, NO_2^-, HCO_3^-, SO_4^{2-}, PO_4^{3-}, NH^{4+}, SST, *Clostridium Perfringens*, Zn and Fe.

<Figure 2>

SPA presents the highest runoff quality. In this case, the slab's surface was smooth and might prevent particle accumulation and pollutant retention. In contrast, asphalt surfaces show the worst water quality results. In particular, APA presents the highest values for COD (55.7 mg O_2/L), NO_3^- (5.52 mg/L), HCO_3^- (80.8 mg/L), PO_4^{3-} (0.52 mg/L) and SO_4^{2-} (21.3 mg/L). This surface belongs to a crowded campus square with significant material weathering. In this surface, deposition of particulate matter is associated with flora, sand, seeds and other anthropogenic waste, together with the material roughness and lack of slope. The asphalt parking lot (AP) also shows the worst results for NO_2^-, probably related to the traffic emissions and particle deposition. The presence of cracks, joints and soil weathering might also influence these results and might have similar effects on other types of materials.

Finally, concrete-built urban areas present a good runoff water quality for most physicochemical indicators. However, CPA shows extremely high chlorine records (103 mg/L) due to the addition of salt during a snowfall event. On this surface, high SST results were associated with the use frequency, as it is located near the entrance to a building. Furthermore, CPA presents the worst Fe mean value (284 µg/L), which can be related to the corrosion of the metal drain gate installed for the runoff collection.

The only correlation associated with the surface use was found for CR, CP and AR, which correspond with trafficked surfaces and present high concentrations of Zn. This metal is commonly found in roads as an organometallic compound that results from tire wear (Ball et al., 1998; Davis et al., 2001; Helmreich et al., 2010). For this reason, other studies propose porous pavements as a solution for reducing runoff pollutants resulting from vehicles (Shutes et al., 1999; Yu and Zhao, 2012), as well as for safety reasons and flood prevention.

In the light of these results, we can state that runoff water quality is highly determined by the catchment surface material and its state of conservation. The type of activity developed on the surface was relevant in high-polluting surface uses such as traffic areas. Further studies should extend the analysis of both materials and surface uses in order to validate these results.

3.2.2 General assessment of the runoff quality

Supporting Information 5 presents the descriptive statistics extracted from the dataset analysis of the water samples. The minimum and maximum values, the mean and standard deviation together with the median are given for the whole set of urban surfaces. In addition, the percentages of samples below the detection limit are presented for each parameter. Spearman Rho correlation coefficients (r_s) are provided in **Supporting Information 6**.

The pH range varies from 6.9 to 8.6, with a slight alkalinity tendency that might be due to the predominance of winds that come from the North of Africa and the related dry atmospheric deposition (Farreny et al., 2011; Göbel et al., 2007). In this pH range, undesired chemical reactions that occur during the storage period are generally avoided (Zhu et al., 2004). The correlation analysis shows that ADWP and pH are inversely proportional ($|r_s|$ = -0.311), which can be related to an acidification process that occurs due to the accumulation of compounds such as sulfates and nitrates in the atmosphere and the soil surface during the dry period. In terms of conductivity, rainwater has a low dissolved ion content (Göbel et al., 2007), which is common in Mediterranean watersheds. The worst-case result was related to a snowfall event (27,150 µS/cm), when there was an external addition of salt on CPA. This sample was excluded from the analysis.

The conveyance of rainwater from ground-level surfaces implies a higher concentration of organic matter and other pollutants accumulated on the ground that are later diluted into the harvested runoff. Proof of it were significant correlations between ADWP and most physicochemical parameters (**Supporting Information 6**). SST median values are low (8 mg/L) when compared with similar studies (Kayhanian et al., 2007). Although nowadays no legislation regulates this parameter, in the DWG a value under 25 mg/L is considered excellent. Similarly, there is no threshold for TOC in water for human consumption but concentrations below 20 mg/L correspond to good water quality. Results are higher than the ones found in the other natural water sources, but better than the roof runoff quality (Farreny et al., 2011). The same trend was shown in COD (median value 16 mg O_2/L), which was three 3 times higher than that of the DWG legislation. Furthermore, TOC and COD results were better than those reported in similar studies (Göbel et al., 2007; Kayhanian et al., 2007; Nolde, 2007).

Sulfates, NO_x and other organic compounds can be related to motorized mobility, as they are common combustion emissions or fuel additives. Inorganic nitrogen was mainly found in the form of nitrates (median value 2.4 mg/L), although this concentration was far below the DWG threshold and the amounts found on the other water sources. In this case, this compound might come from animal feces, fuel combustion, soil, and dry deposition. Ammonia and nitrites are also low according to the legislation. Ammonia results were 2.2 times higher in roof runoff (Farreny et al., 2011). In this sense, the concentrations of ammonia and hydrocarbons were proportional ($|r_s| = 0.754$), as ammonia can be used as antistatic additive in polymers. Parallel to these results, sulfate concentrations were also low, which implies low interferences with pollution originated by industrial facilities and traffic emissions.

Microbial results are less positive because the legislation does not allow fecal bacteria to be present in drinking water. Microbial and pathogen registers were found in all of the samples (> 1 CFU/100 mL). However, the average results are similar to those of superficial and underground sources (ACA, 2012). The presence of coliforms was expected because, besides feces, they might come from outdoors vegetation; as a result, this might not only be an indicator of fecal contamination (Ahmed et al., 2011). These results are in concordance with the microbial quality review performed by De Kwaadsteniet et al. (2013). Besides, a great number of individual studies reported the poor microbiological quality of urban runoff due to high levels of bacterial contamination (Nolde, 2007; Sazakli et al., 2007; Zhu et al., 2004), although results vary depending on the environment and surface maintenance. Unexpectedly, inverse correlations were found between enterococcus and hydrocarbons ($|r_s| = -0.728$), which could be due to a toxic effect of hydrocarbons on microorganisms (Heipieper and Martínez, 2010).

Therefore, efforts should focus on the installation of a water treatment technique that removes pathogens from rainwater, which should be adapted to the end use of rainwater. A membrane or granular-activated carbon filter together with chemical disinfection with chlorine is highly recommended (Sazakli et al., 2007). In addition, solar UV water treatment, slow sand filtration and heat treatment (if water is intended for hot water uses) could significantly improve microbiological water quality (De Kwaadsteniet et al., 2013).

TPH include a big family of compounds that originate from crude oil and some derivatives, while PAH (Polycyclic Aromatic Hydrocarbons) correspond to a group of polycyclic hydrocarbons included in the TPH family. PAH compounds are emitted due to inefficiencies in engine combustion and stand out for their effects on human and animal health. Therefore, their concentration in water is expected to be more restrictive than TPH.

In general, hydrocarbons were not problematic in the samples tested as they were found at very low doses (median value 2 mg/L). The same analytical limitation was found for Cu, with a detection limit of 10 µg/L that is above the DWG threshold. Zn values also appeared to be high, although no legislation was found. Together with Pb, it is mostly related to areas with motorized mobility (Nolde, 2007). The other metals analyzed in this study were consistent with the DWG directive. Ni, Hg, Cd and Pb were not detected in any of the samples. Similar results were found for TPH and Pb in previous pavement assessments (Brattebo and Booth, 2003).

For a more complete and precise interpretation of these results, some factors should be considered, such as the storage time until the sample was taken, the ADWP and seasonal fluctuations. These may have a significant influence on microbiological - as well as physicochemical - results, since most microorganisms present a logarithmical growth in a convenient environment (Kayhanian et al., 2007; Zhu et al., 2004). Moreover, runoff quality is directly influenced by the first flush phenomena, as the first few milliliters that contain the main concentration of pollutants were not diverted. In practice, a simple first flush diverter would increase runoff quality significantly (Villarreal and Dixon, 2005).

4. Conclusions

In the light of the results obtained, different parameters should be considered in urban design and water management. In terms of quantity, the runoff coefficient was often lower than previous reports, with a minimum of 0.41 in asphalt parking lots. One of the reasons was the rainfall intensity, which is low – or very high during specific events - in the Mediterranean and evapotranspiration might be more relevant than infiltration. Further, the initial abstraction results support this finding, as they can represent up to 20% of the runoff in low intensity rainfall. The pavement degradation should also be considered, as it might enable water infiltration through cracks and joints. In general, pavement runoff was lower than roof runoff.

Regarding quality, results indicated that asphalted urban spaces are more likely to foster particulate matter deposition and accumulation, which may become diluted in the runoff and is responsible for the decrease in rainwater quality. On the contrary, precast concrete slabs present a smoother surface that allows all deposited particles to be washed away leaving a cleaner surface behind and therefore a better quality runoff. In practice, first flush diverters should be installed to increase water quality and the effects of periodic maintenance of the public urban surfaces should be assessed. Besides, the runoff from concrete urban surfaces presents an in-between quality.

Physicochemical runoff quality is outstanding when compared to superficial and underground water sources, although rainwater is not meant to be a potable water source. For most parameters except COD, runoff harvested from urban spaces accomplishes the DWG directive thresholds for human consumption, although rainwater harvesting is mostly related to non-potable uses. Hydrocarbon and metal concentrations were below the detection limit. However, treatment efforts should focus on microbial disinfection, as all samples have microbial traces that are considered a risk for most water applications. First flush diverters, together with simple disinfection techniques applied during the conveyance and storage stages, would improve runoff quality significantly.

Motorized mobility did affect the concentration of certain metals, such as Zn, in both concrete and asphalted surfaces. The surface material and its maintenance play a crucial role in conferring runoff water a higher or lower quality, although activities performed on the catchment surface also affect rainwater quality, especially traffic surfaces. However, in the framework of sustainable cities, urban patterns are adapting to electric and pedestrian mobility. As a result, the runoff quality might be even better in the future and this type of study should confirm this in the future. Quantity issues might become more important than qualitative properties. In this sense, this paper aims to promote rainwater harvesting in paved areas, which could be combined with roofs in order to provide cities with water. Therefore, taking advantage of public areas can increase the water self-sufficiency potential.

5. Acknowledgements

The authors would like to thank the Laboratori de Medi Ambient linked to the Environmental Assessment and Management Technical Office belonging to Diputació de Barcelona for the technical aid. The authors are also grateful to the Spanish Ministry of Science and Innovation (MICINN) for funding the PLUVISOST project (Ref. CTM2010-17365) and wish to thank the Catalan and Spanish governments for the scholarships enjoyed by S. Angrill and A. Petit-Boix (FPU13/01273), respectively.

6. References

Abbasi, T., Abbasi, S.A., 2011. Sources of Pollution in Rooftop Rainwater Harvesting Systems and Their Control. Crit. Rev. Environ. Sci. Technol. doi:10.1080/10643389.2010.497438

Adeniyi, I.F., Olabanji, I.O., 2005. The physico-chemical and bacteriological quality of rainwater collected over different roofing materials in Ile-Ife, southwestern Nigeria. Chem. Ecol. doi:10.1080/02757540500117318

Ahmed, W., Gardner, T., Toze, S., 2011. Microbiological quality of roof-harvested rainwater and health risks: a review. J. Environ. Qual. 40, 13–21.

Angrill, S., Segura-Castillo, L., Petit-Boix, A., Rieradevall, J., Gabarrell, X., Josa, A., 2016. Environmental performance of rainwater harvesting strategies in Mediterranean buildings. Int. J. Life Cycle Assess. in press, 1–12. doi:10.1007/s11367-016-1174-x

Antunes, L., Thives, L., Ghisi, E., 2016. Potential for Potable Water Savings in Buildings by Using Stormwater Harvested from Porous Pavements. Water 8, 110. doi:10.3390/w8040110

APHA. American Public Health Association, 1999. Standard Methods for the Examination of Water and Wastewater.

Apul, D.S., Miller, E., Jain, V., 2010. Road-runoff metal concentrations in Toledo, Ohio, and their relation to average daily traffic and age of pavement overlay. Water Sci. Technol. 61, 1723–1731. doi:10.2166/wst.2010.067

ASCE. American Society of Civil Engineers, 1969. Design and construction of sanitary and storm sewers. ASCE Manual of Practice No 37, WPCF Manual of Practice No 9. New York.

Ball, J.E., Jenks, R., Aubourg, D., 1998. An assessment of the availability of pollutant constituents on road surfaces. Sci. Total Environ. 209, 243–254. doi:10.1016/S0048-9697(97)00319-7

Belmeziti, A., Coutard, O., de Gouvello, B., 2013. A New Methodology for Evaluating Potential for Potable Water Savings (PPWS) by Using Rainwater Harvesting at the Urban Level: The Case of the Municipality of Colombes (Paris Region). Water 5, 312–326. doi:10.3390/w5010312

Bertrand-Krajewski, J.-L.L., Chebbo, G., Saget, A., 1998. Distribution of pollutant mass vs volume in stormwater discharges and the first flush phenomenon. Water Res. 32, 2341–2356. doi:10.1016/S0043-1354(97)00420-X

Brattebo, B.O., Booth, D.B., 2003. Long-term stormwater quantity and quality performance of permeable pavement systems. Water Res. 37, 4369–4376. doi:10.1016/S0043-1354(03)00410-X

Butler, D., Davies, J.W., 2000. Urban Drainage, 3rd Ed. ed. Spon Press, an imprint of Taylor &

Francis. London and New York.

Catalan Water Agency, 2012. Control networks [WWW Document]. URL Retrieved on May 2013 from http://aca-web.gencat.cat/aca.

Davis, A.P., Shokouhian, M., Ni, S., 2001. Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources. Chemosphere 44, 997–1009. doi:10.1016/S0045-6535(00)00561-0

De Kwaadsteniet, M., Dobrowsky, P.H., Van Deventer, A., Khan, W., Cloete, T.E., 2013. Domestic rainwater harvesting: Microbial and chemical water quality and point-of-use treatment systems. Water. Air. Soil Pollut. 224. doi:10.1007/s11270-013-1629-7

Drapper, D., Tomlinson, R., Williams, P., 2000. Pollutant Concentrations in Road Runoff: Southeast Queensland Case Study. J. Environ. Eng. doi:10.1061/(ASCE)0733-9372(2000)126:4(313)

EC. European Commission, 1998. Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption. Retrieved on September 2010 from http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31998L0083:EN:NOT.

Elvidge, C.D., Tuttle, B.T., Sutton, P.S., Baugh, K.E., Howard, A.T., Milesi, C., Bhaduri, B.L., Nemani, R., 2007. Global Distribution and Density of Constructed Impervious Surfaces. Sensors (Basel).

Farreny, R., Morales-Pinzón, T., Guisasola, A., Tayà, C., Rieradevall, J., Gabarrell, X., 2011. Roof selection for rainwater harvesting: Quantity and quality assessments in Spain. Water Res. 45, 3245–3254. doi:10.1016/j.watres.2011.03.036

Fletcher, T.D., Deletic, A., Mitchell, V.G., Hatt, B.E., 2008. Reuse of urban runoff in Australia: a review of recent advances and remaining challenges. J. Environ. Qual. 37, S116-27. doi:10.2134/jeq2007.0411

Gilbert, J.K., Clausen, J.C., 2006. Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut. Water Res. 40, 826–832. doi:10.1016/j.watres.2005.12.006

Göbel, P., Dierkes, C., Coldewey, W.G., 2007. Storm water runoff concentration matrix for urban areas. J. Contam. Hydrol. 91, 26–42. doi:10.1016/j.jconhyd.2006.08.008

Heipieper, H.J., Martínez, P.M., 2010. Toxicity of Hydrocarbons to Microorganisms, in: Handbook of Hydrocarbon and Lipid Microbiology. pp. 1563–1573.

Helmreich, B., Hilliges, R., Schriewer, A., Horn, H., 2010. Runoff pollutants of a highly trafficked urban road - Correlation analysis and seasonal influences. Chemosphere 80, 991–997. doi:10.1016/j.chemosphere.2010.05.037

Huang, C.-L., Hsu, N.-S., Wei, C.-C., Luo, W.-J., 2015. Optimal Spatial Design of Capacity and Quantity of Rainwater Harvesting Systems for Urban Flood Mitigation. Water 7, 5173–5202. doi:10.3390/w7095173

Kayhanian, M., Suverkropp, C., Ruby, A., Tsay, K., 2007. Characterization and prediction of highway runoff constituent event mean concentration. J. Environ. Manage. 85, 279–295. doi:10.1016/j.jenvman.2006.09.024

Kornbrot, D., 2014. Spearman’s Rho. Wiley StatsRef Stat. Ref. Online.

Liaw, C.-H., Tsai, Y.-L., 2004. Optimum storage volume of rooftop rain water harvesting systems for domestic use. J. Am. Water Resour. Assoc. 40, 901–912. doi:10.1111/j.1752-1688.2004.tb01054.x

Longobardi, A., Villani, P., Grayson, R., Western, A., 2003. On The Relationship Between Runoff Coefficient And Catchment Initial Conditions, in: Proceedings of MODSIM. pp. 867–872.

McCuen, R., 2004. Hydrologic analysis and design. 3rd ed. Upper Saddle River, NJ: Pearson

Education Inc.

Meera, V., Mansoor Ahammed, M., 2006. Water quality of rooftop rainwater harvesting systems: A review. J. Water Supply Res. Technol. - AQUA. doi:10.2166/aqua.2006.008

Melidis, P., Akratos, C.S., Tsihrintzis, V.A., Trikilidou, E., 2007. Characterization of rain and roof drainage water quality in Xanthi, Greece. Environ. Monit. Assess. 127, 15–27. doi:10.1007/s10661-006-9254-1

Nolde, E., 2007. Possibilities of rainwater utilisation in densely populated areas including precipitation runoffs from traffic surfaces. Desalination 215, 1–11. doi:10.1016/j.desal.2006.10.033

Ragab, R., Rosier, P., Dixon, A., Bromley, J., Cooper, J.D., 2003. Experimental study of water fluxes in a residential area: 2. Road infiltration, runoff and evaporation. Hydrol. Process. 17, 2423–2437. doi:10.1002/hyp.1251

Sawilowsky, S., Fahoome, G., 2014. Kruskal-Wallis Test: Basic. Wiley StatsRef Stat. Ref. Online.

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

Shutes, R.B.., Revitt, D.., Lagerberg, I.., Barraud, V.C.., 1999. The design of vegetative constructed wetlands for the treatment of highway runoff. Sci. Total Environ. 235, 189–197. doi:10.1016/S0048-9697(99)00212-0

Simmons, G., Hope, V., Lewis, G., Whitmore, J., Gao, W., 2001. Contamination of potable roof-collected rainwater in Auckland, New Zealand. Water Res. 35, 1518–1524. doi:10.1016/S0043-1354(00)00420-6

Singh, V.P., 1992. Elementary Hydrology. Prentice Hall.

SMC. Servei Meteorològic de Catalunya, 2013. Weather station of Cerdanyola del Vallès [WWW Document]. URL http://www.meteo.cat

UN. United Nations. Department of Economic and Social Affairs. Population Division, 2012. World Urbanization Prospects: The 2011 Revision, CD-ROM Edition.

van Roon, M., 2007. Water localisation and reclamation: Steps towards low impact urban design and development. J. Environ. Manage. 83, 437–447. doi:10.1016/j.jenvman.2006.04.008

Viessman, W., Lewis, G., 2003. Introduction to hydrology. 5th ed. ed. New Jersey: Prentice Hall.

Villarreal, E.L., Dixon, A., 2005. Analysis of a rainwater collection system for domestic water supply in Ringdansen, Norrköping, Sweden. Build. Environ. 40, 1174–1184. doi:10.1016/j.buildenv.2004.10.018

Westerlund, C., Viklander, M., Bckstrm, M., 2003. Seasonal variations in road runoff quality in Luleå, Sweden. Water Sci. Technol. 48, 93–101.

Yu, A.H., Zhao, C., 2012. Evaluation on the highway asphalt pavement runoff with the gray correlation model. Procedia Environ. Sci. 13, 1827–1835. doi:10.1016/j.proenv.2012.01.176

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. J. Arid Environ. 57, 487–505. doi:10.1016/S0140-1963(03)00118-6

Table 1 Characteristics of the catchment surfaces under analysis

Surface	Material	Function	Slope (^{0})	Roughness	Catchment area (m^2)	Environment description
APA	Asphalt	**Pedestrian area**	3^0	Rough	15.7	Urban environment (some trees nearby)
SPA	Precast concrete tile		6^0	Smooth	15.7	Urban environment (one side bounded by a building facade)
CPA	Concrete		5^0	Rather rough	19.8	Urban environment (no trees but a building nearby)
AR	Asphalt	**Road**	2^0	Rough	40.2	Urban environment (small trees and some buildings nearby)
CR	Concrete		45^0	Rather smooth	142.7	Urban environment (one side bounded by a building facade)
AP	Asphalt	**Parking lot**	3^0	Rough	21.2	Urban environment (small trees and a building nearby)
CP	Concrete		9^0	Rather smooth	9.3	Urban environment (no trees but some buildings nearby)

Table 2 Rainfall events considered for sample collection in the determination of the quantity and quality analysis

	QUANTITY ASSESSMENT			**QUALITY ASSESSMENT**					
				Physicochemical			**Microbiological, hydrocarbons and metals**		
Surface	**# events**	**ADWP (days)**	**Rainfall (mm)**	**# events**	**ADWP (days)**	**Rainfall (mm)**	**# events**	**ADWP (days)**	**Rainfall (mm)**
APA	16	3 - 45	2.4 - 37.6	16	3 - 45	2.4 - 66.8	6	5 – 45	2.4 - 34.5
SPA	15	3 - 45	2.4 - 37.6	14	3 - 45	2.4 - 66.8	7	5 – 45	13.2-34.5
CPA	5	3 - 30	2.4 - 15.8	13	0 - 30	2.4 - 66.8	4	3 – 19	2.4 - 24.6
AR	9	3 - 30	2.4 - 37.6	13	0 - 30	2.4 - 66.8	4	3 – 19	2.4 - 24.6
CR	8	3 - 29	2.4 - 24.6	16	3 - 45	2.4 - 66.8	6	5 – 45	2.4 - 34.5
AP	15	3 - 45	2.4 - 37.6	13	3 - 45	2.4 - 66.8	6	5 – 45	13.2-34.5
CP	15	3 - 45	2.4 - 37.6	14	3 - 45	2.4 - 66.8	6	5 – 45	13.2-34.5

Table 3 Runoff coefficient values, initial abstraction and correlation coefficient (R^2) for each catchment surface

Urban surfaces	Acronym	Runoff coefficient	Initial abstraction	R^2
Asphalted pedestrian area	APA	0.54	1.8	0.78
Concrete slabs in pedestrian area	SPA	0.77	1.2	0.80
Concrete pedestrian area	CPA	0.53	0	0.80
Asphalted road	AR	0.89	0	0.72
Concrete road	CR	0.67	0	0.64
Asphalted parking lot	AP	0.41	1.4	0.62
Concrete parking lot	CP	0.89	2.4	0.75

Table 4 Behavior of the initial abstraction and runoff under average (20 mm) and maximum rainfall (70 mm) conditions.

Urban surfaces	Acronym	Rainfall height (mm)	Harvested runoff (mm)	Harvested runoff / Rainfall height	Initial abstraction / Harvested runoff
Asphalt pedestrian area	APA	20	9.0	45%	20%
		70	36.0	51%	5%
Concrete slabs in pedestrian area	SPA	20	14.2	71%	8%
		70	52.7	75%	2%
Concrete pedestrian area	CPA	20	10.6	53%	0%
		70	37.1	53%	0%
Asphalt road	AR	20	17.8	89%	0%
		70	62.3	89%	0%
Concrete road	CR	20	13.4	67%	0%
		70	46.9	67%	0%
Asphalt parking lot	AP	20	6.8	34%	21%
		70	27.3	39%	5%
Concrete parking lot	CP	20	15.4	77%	16%
		70	59.9	86%	4%

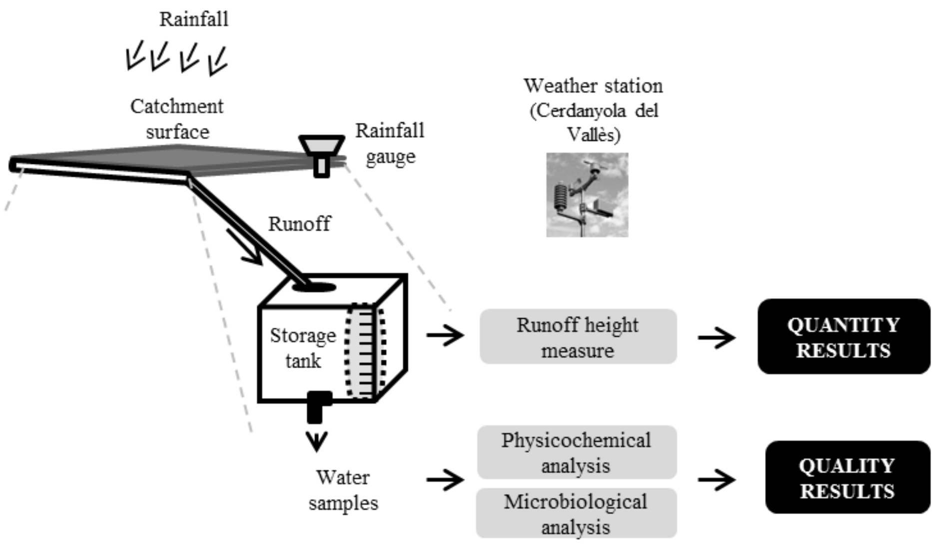

Figure 1 Rainwater harvesting system installation and experimental design diagram

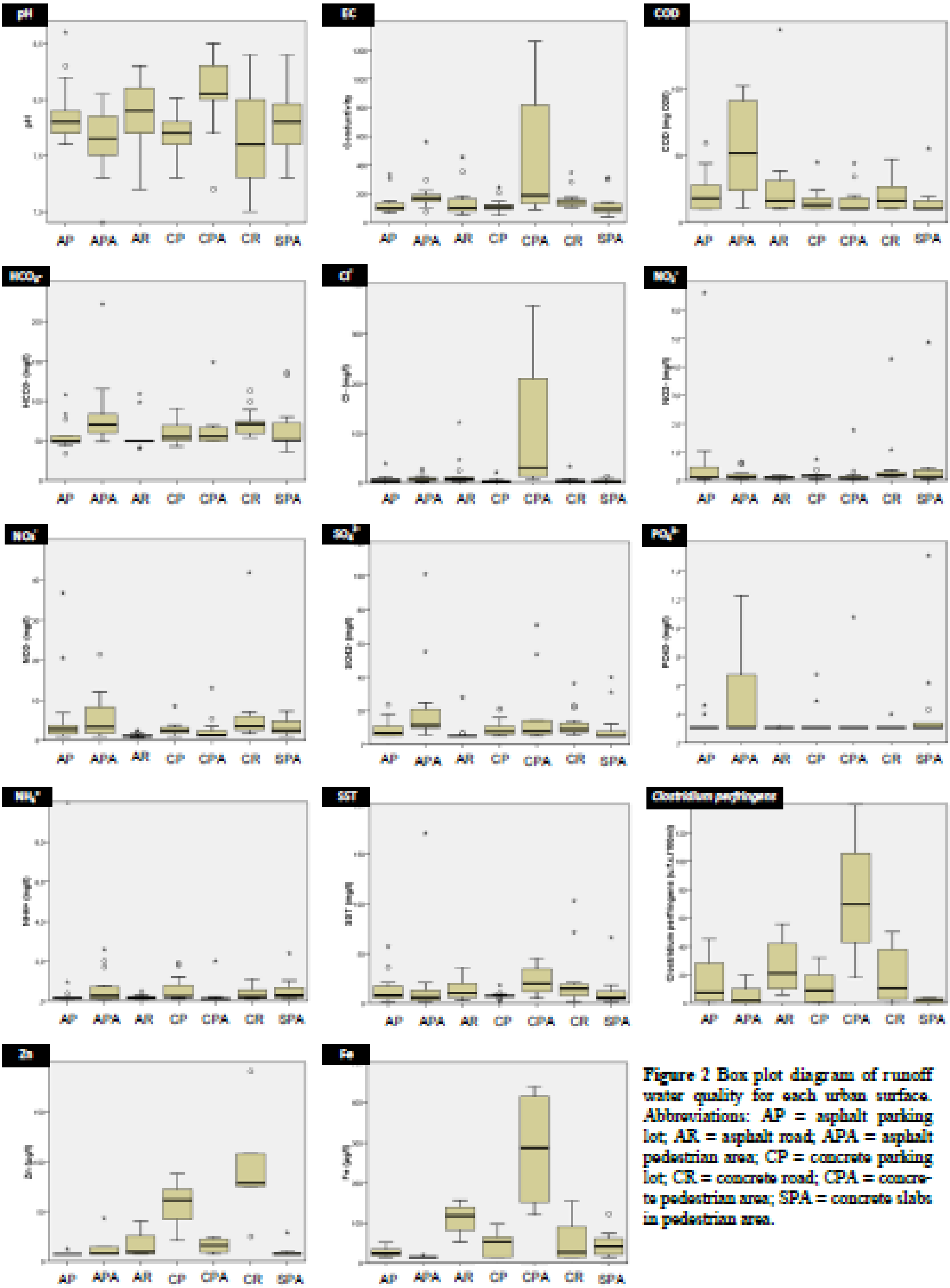

Figure 2 Box plot diagram of runoff water quality for each urban surface. Abbreviations: AP = asphalt parking lot; AR = asphalt road; APA = asphalt pedestrian area; CP = concrete parking lot; CR = concrete road; CPA = concrete pedestrian area; SPA = concrete slabs in pedestrian area.