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Roof selection for rainwater harvesting: Quantity and quality assessments in Spain

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ABSTRACT

Roofs are the first candidates for rainwater harvesting in urban areas. This research integrates quantitative and qualitative data of rooftop stormwater runoff in an urban Mediterranean-weather environment. The objective of this paper is to provide criteria for the roof selection in order to maximise the availability and quality of rainwater. Four roofs have been selected and monitored over a period of 2 years (2008–2010): three sloping roofs – clay tiles, metal sheet and polycarbonate plastic – and one flat gravel roof. The authors offer a model for the estimation of the runoff volume and the initial abstraction of each roof, and assess the physicochemical contamination of roof runoff. Great differences in the runoff coefficient (RC) are observed, depending mostly on the slope and the roughness of the roof. Thus, sloping smooth roofs (RC > 0.90) may harvest up to about 50% more rainwater than flat rough roofs (RC = 0.62). Physicochemical runoff quality appears to be generally better than the average quality found in the literature review (conductivity: 85.0 ± 10.0 μS/cm, total suspended solids: 5.98 ± 0.95 mg/L, total organic carbon: 11.6 ± 1.7 mg/L, pH: 7.59 ± 0.07 upH). However, statistically significant differences are found between sloping and flat rough roofs for some parameters (conductivity, total organic carbon, total carbonates system and ammonium), with the former presenting better quality in all parameters (except for ammonium). The results have an important significance for local governments and urban planners in the (re)design of buildings and cities from the perspective of sustainable rainwater management. The inclusion of criteria related to the roof's slope and roughness in city planning may be useful to promote rainwater as an alternative water supply while preventing flooding and water scarcity.

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1. Introduction

Rainwater harvesting (RWH) in urban areas is a strategy that brings many benefits and may serve to cope with current water shortages, urban stream degradation and flooding (Fletcher et al., 2008; van Roon, 2007; Zhu et al., 2004). In this context, the assessment of the quantitative potential of RWH and the quality of stormwater runoff from several types of roofs is essential in order to set up criteria for the (re)design of cities from the perspective of sustainable rainwater management. Both aspects (quantity and quality) are necessary in order to select the most adequate roof for RWH. Since roofs represent approximately half of the total sealed surface in cities they contribute to the most important urban stormwater runoff flow. As a consequence, they offer a significant possibility for RWH (Villarreal and Dixon, 2005), which makes it relevant to have criteria for roof selection at one's disposal.

The RWH potential (in L/year) of a roof can be estimated based on the local precipitations (*P*, in mm/year), the catchment area (*A*, in m^2) and the runoff coefficient (RC, nondimensional), as shown in Eq. (1):

$$\text{RWH potential} = P \cdot A \cdot \text{RC} \quad (1)$$

Eq. (1) draws inspiration from the rational method, which has traditionally been used in order to estimate the peak runoff rate of any watershed (McCuen, 2004; Viessman and Lewis, 2003). The RC is a dimensionless value that estimates the portion of rainfall that becomes runoff, taking into account losses due to spillage, leakage, catchment surface wetting and evaporation (Singh, 1992). Thus, the RC is useful for predicting the potential water running off a surface, which can be conveyed to a rainwater storage system. Since water shortage is recognised as an emerging problem which is becoming the number one problem in the world today (Sazakli et al., 2007), and many cities are facing water restrictions due to an increasing pressure on water resources (Fletcher et al., 2008), it is essential to consider the RC in the selection of roofs in order to maximise their RWH potential.

The value of the RC has usually been selected from generic lists based on the degree of imperviousness and infiltration capacity of the drainage surface. Estimates so far consider that roof RCs are within the range of 0.7–0.95 for relatively frequent storms (see Table 1 for details). This broad range is the result of the interaction of many factors, both climatic (size and intensity of the rain event, antecedent moisture, prevailing winds) and architectural (slope, roof material, surface depressions, leaks/infiltration, roughness). For this reason, it seems urgent to solve the lack of specific RC for different roof types under diverse environmental climatic conditions in the context of RWH.

On the other hand, an increased interest in the monitoring of roof runoff quality has been observed recently (Skaryska et al., 2007). Roofs are the first candidates for RWH systems because their runoff is often regarded to be unpolluted (Förster, 1999) or, at least, it presents relatively good quality standards compared to the rainwater from surface catchment areas (Göbel et al., 2007). Despite this, there is still some disagreement about the quality of roof runoff water: the assessment or rooftop runoff quality ranges from good or acceptable (for example, Adeniyi and Olabanji, 2005; Melidis et al., 2007; Uba and Aghogho, 2000) to severely polluted (for example, Chang et al., 2004; Gromaire et al., 2001; Simmons et al., 2001).

Table 1 – Review of runoff coefficient (RC) estimates.

Roof	RC	Reference
Roofs (in general)	0.7–0.9	Pacey and Cullis (1989)
	0.75–0.95	ASCE (1969), McCuen (2004), Singh (1992), TxDOT (2009), Viessman and Lewis (2003)
	0.85	McCuen (2004), Rahman et al. (2010)
	0.8–0.9	Fewkes (2000)
	0.8	Ghisi et al. (2009)
	0.8–0.95	Lancaster (2006)
Sloping roofs		
Concrete/asphalt	0.9	Lancaster (2006)
Metal	0.95	Lancaster (2006)
	0.81–0.84	Liaw and Tsai (2004))
Aluminium	0.7	Ward et al. (2010)
Flat roofs		
Bituminous	0.7	Ward et al. (2010)
Gravel	0.8–0.85	Lancaster (2006)
Level cement	0.81	Liaw and Tsai (2004))

Rooftop runoff quality is dependent on both the roof type and the environmental conditions (not only the local climate but also the atmosphere pollution). Most research on the quality of rainwater roof runoff has been carried out in East Asia (for example: Appan, 2000; Kim et al., 2005a; Kim et al., 2005b), in Central, Eastern and Northern Europe (for example: Albrechtsen, 2002; Förster, 1996, 1999; Gromaire et al., 2001; Moilleron et al., 2002; Polkowska et al., 2002; Ward et al., 2010; Zobrist et al., 2000), in the United States (for example: Chang et al., 2004; Van Metre and Mahler, 2003) and in Oceania (for example: Evans et al., 2006; Kus et al., 2010; Magyar et al., 2007; Simmons et al., 2001). However, there is scarce data from Southern Europe, in particular from Spain.

This research integrates quantitative and qualitative data of rooftop stormwater runoff in an urban Mediterranean-weather environment in order to select the best roof type for RWH. The eventual purpose of this is to maximise the rainwater harvesting potential as a measure of adaptation to water scarcity and of climate change effects mitigation.

The main objective of this paper is to provide criteria for roof selection in order to maximise the availability and quality of rainwater harvesting supplies. The specific objectives are to (1) develop a model for the estimation of the runoff and the initial abstraction of each roof; (2) estimate the global RC for the different roofs in Mediterranean-weather conditions; (3) estimate the physicochemical contamination of the roofs; (4) determine the degree of association between water quality parameters and storm characteristics and between water quality parameters themselves; and, (5) assess the differences in water quality between the different roofs.

2. Materials and methods

2.1. Study area

Four different roofs have been selected in the UAB University Campus, in Cerdanyola del Vallès (metropolitan region of

Barcelona, NE Spain). The climate in the area can be characterised as semi-wet Mediterranean and the average annual temperature and rainfall are 15.5 oC and 568 mm, respectively.

The selection of roofs, the main characteristics of which are shown in Table 2, includes: clay tiles (CT), metal sheet (M), polycarbonate plastic (P) and flat gravel (FG). CT roof is a well-known trademark of the constructed Mediterranean landscape, whereas M and P roofs are increasing in presence in the region. Flat roofs are the most common type of roofs in the driest regions within traditional Mediterranean architecture, being FG roofs increasingly popular in large buildings.

This set of roofs presents two extreme positions regarding slope and roughness: the M and P roofs present high slope (30°) and smooth surfaces, whereas the FG roof is flat and presents a rough surface. The CT roof, presents characteristics similar to the M and P roofs but with a slightly rougher surface. Our research hypothesis is that these two parameters (slope and roughness) are fundamental for the assessment of the quantity and quality of roof runoff.

All roofs are located between 0.5 and 1 km from a motorway with dense traffic, and at less than 4 km from some industrial states (light industry), both of which are located to the E, NE or SE of the campus. Predominant winds in this area come from westerly directions.

2.2. Experimental design

A one-way design with 4 levels – where the factor was the type of roof and the levels were CT, M, P and FG – was applied. The assessed variables were the runoff and the physical–chemical parameters; and rainfall height, predominant wind orientation and antecedent dry weather period (ADWP) were included as covariates.

A rainwater conveyance and storage system was installed in each roof. The experimental design consisted of connecting the building's gutters and downpipes to one or more polyethylene rainwater tanks with a capacity of 1 m^3 (Fig. 1), without first flush diversion system. No special maintenance of the roofs was carried out.

Data for the calculation of RC and/or water samples for the quality analysis were collected after several rainfall events during the experimental campaign between June 2008 and September 2010. A rain event was defined as a rainfall of a total height of at least 1 mm and separated one from another by an ADWP of at least 2 h. The amounts of rainfall were monitored using a rainwater gauge on each roof.

2.3. Quantity assessment

2.3.1. Data collection

After the rain events, the rainfall height and the amount of water collected were registered and the tank was emptied (rain events that did not generate runoff were not included). Several precipitation events were selected, the rainfall and ADWP range of which is shown in Table 3. The prevailing wind direction during the rain event was also recorded. Rainfall events that exceeded rainwater tank capacity were excluded.

2.3.2. Data analysis. Determination of RC

In order to develop a model to estimate the runoff of each roof, a statistical analysis has been conducted with the aid of PASW Statistics 17, from the Statistical Package for the Social Sciences (SPSS) software. This analysis included a correlation analysis followed by lineal regression model, considering the amount of runoff depending on several independent variables (rainfall, ADWP and wind direction). In all cases the assumptions were verified.

The technique of cross-validation (Snee, 1977) is used to assess how the results of the regression models will generalise to an independent dataset. Therefore, it is used to estimate how accurately the predictive model will perform in practice. The sample of data is divided into two complementary subsets (half and half at random division): the calibration and the validation sets. If the reduction in the cross-validation gives numbers smaller than 0.1, it is assumed that the model will accurately predict the runoff.

Then, the regression model is used in order to estimate the initial abstraction, defined as the amount of rainfall that occurs prior to the start of direct runoff (McCuen, 2004).

Table 2 – Characteristics of the roof catchments.

Roof	Roof type (slope)	Roughness	Orientation	Roof footprint (m^2)	Environment	UTM
Clay tiles	Hip sloping roof (30°)	Rather smooth	None prevailing	120.0	Surrounded by forest. A few trees overhanging the roof	424482.6 E 4594896.6 N
Metal sheet	Single pitch sloping roof (30°)	Smooth	50° NE	40.6	Urban environment (no trees nearby)	425349.6 E 4594851.4 N
Polycarbonate plastic	Single pitch sloping roof (30°)	Smooth	230° SW	40.6	Urban environment (no trees nearby)	425347.1 E 4594848.6 N
Flat gravel (particle diameter: ~5 mm, gravel depth 15–20 mm)	Flat roof (1°)	Rough	None prevailing	56.6	Urban environment (some trees nearby)	425476.6 E 4594733.4 N

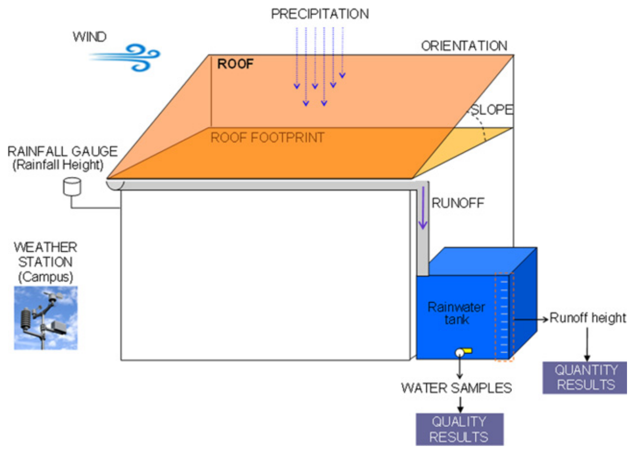

Fig. 1 – Diagram of the experimental design.

The global RC for the different roofs is estimated by means of the obtained runoff model, taking into account the local rainfall profile. Data from the weather station of Cerdanyola del Vallès (provided by the Meteorological Service of Catalonia, unpublished), where the roofs are located, has been used for the period 1999–2009. The calculation consists of, first, estimating the runoff of each rain event, and second, dividing the total runoff per year by the annual rainfall, according to Eq. (2):

$$RC = R/P \tag{2}$$

where R is the total height of runoff (L) and P is the total height of precipitations (L) in a yearly basis for each roof.

2.4. *Quality assessment*

2.4.1. *Sample collection and physical–chemical analysis*

A composite sample ($V = 0.6$ L) of the content of the rainwater tank was taken after each monitored rain event ($n = 55$). Several precipitation events were selected, with a rainfall which varied depending on the roof (Table 3) and an ADWP between 0.1 and 37.9 days for all roofs. The concentration of the composite sample represents the Event Mean Concentration (EMC) of that event. The EMC can be defined as the total mass load of a pollutant from a site during a storm divided by the total runoff water volume discharged during the storm (Bertrand-Krajewski et al., 1998).

After obtaining the composite sample, the tank was emptied. Then, samples were immediately prepared for analyses and taken to the laboratory. Electrical conductivity (EC) and pH were measured using a Crison probe (mod. 401/L K1 and 5202, respectively). Phosphate (PO_4^{3-}), sulphate (SO_4^{2-}), chloride (Cl^-), nitrate (NO_3^-) and nitrite (NO_2^-) in filtered samples were measured with ionic chromatography (DIONEX ICS-2000 Integrated Reagent-Free IC System with an auto-sampler AS40). Mixed liquor total suspended solids (TSS) were analysed according to standard procedures (APHA, 1995). Total ammonium nitrogen (TAN) was analysed using Lange LCK302, LCK303 and LCK304 ammonium kits. Finally, Total inorganic carbon (TIC) and total organic carbon (TOC) were measured using a 1020A O-I-Analytical TOC analyser. Bicarbonates (HCO_3^-), carbonates (CO_3^{2-}) and carbon acid (H_2CO_3) were calculated based on TIC and pH results. Heavy metals were not measured due to a lack of laboratory equipment and economic constraints. Base cations (Na^+, K^+, Mg^{2+}, Ca^{2+}) were not measured since previous quality assessments indicated that their concentration was in the low range and no precipitates were observed in water samples.

2.4.2. *Data analysis*

Descriptive statistics were obtained with the aid of PASW Statistics 17, from the SPSS software. Average values were expressed both in means (with standard error) and in medians, since some parameters do not have a lognormal distribution (Göbel et al., 2007).

The data generated was subjected to appropriate statistical analyses including variance and correlation analyses. Variance analyses were used to determine if the differences in the mean/median concentration of the roofs were statistically significant. Whenever possible, the one-way ANOVA test was the preferred option. For this reason, data about water quality were transformed with the aid of the power estimation procedure in order to meet the requirements of the ANOVA test (in particular, the normal distribution and the assumption of homogeneity of variance). When this was not possible, the Kruskal–Wallis test was used. Pairwise comparisons were carried out by means of either the Bonferroni method or the Mann–Whitney *U* test using Bonferroni correction method, respectively.

Correlation analyses were used to determine the degree of association between water quality parameters and storm characteristics (total rainfall height and ADWP) and between water quality parameters themselves, for the whole set of roofs and also for each particular roof (Spearman Rho correlation coefficient).

Table 3 – Rain events considered in the determination of the runoff coefficient (RC) and the samples for quality analysis. Abbreviations: ADWP: antecedent dry weather period.

Roof	Quantity assessment			Quality assessment	
	# Monitored events	ADWP range (days)	Rainfall range (mm)	# Monitored events (samples)	Rainfall range (mm)
Clay tiles	25	0.1–37.9	1–14	14	1.2–68
Metal	22	0.5–28	1–49	14	1–62
Plastic	23	0.5–28	1–49	15	2.5–31.2
Flat gravel	22	0.2–37.9	2–21	12	1–62

3. Results and discussion

3.1. Quantity assessment

The correlation between runoff and rainfall is high (Pearson coefficient > 0.95 and $p < 0.05$ for all roofs). The regression model ($R = mP + n$) between roof runoff (R) and precipitation height (P) for each roof is presented in Fig. 2. All the regression parameters are statistically significant ($p < 0.05$), except for the y-intercept (n) in the equations for M and P roofs. The regression model has been successfully cross-validated, with reductions in the cross-validation in the range of 0.005 and 0.039. Therefore, it can be assumed that the inferences of these regression models to the whole population are valid.

3.1.1. Initial abstraction

The texture of different roof materials causes different retention, different runoff behaviour and different weathering processes (Göbel et al., 2007). Therefore, each roof has its own characteristic initial abstraction volume, mostly explained by its slope and materials (roughness). The most important abstraction is interception, which can be defined as the rainfall that wets and sticks to aboveground objects until it is returned to the atmosphere through evaporation (Corbitt, 1998).

The initial abstraction is estimated as the value of the x-intercept ($-n/m$) from the regression model (see Fig. 2). Thus, the estimates of the initial abstraction are 0.8 and 3.8 mm for CT and FG, respectively. Since the estimation of the y-intercept (n) is not significant ($p > 0.05$) for M and P roofs, which means that it cannot be asserted that $n \neq 0$, it is assumed that their initial abstraction is also zero. Although it may be argued that there must be a certain amount of initial abstraction, it is so close to zero that it has not been possible to estimate it with the available data (despite us having included small rain events in the analysis).

The highest initial abstraction of the FG roof is explained by the fact that the more porous or rough the roof surface, the more likely it will retain or absorb rainwater (Lancaster, 2006). Therefore, the gravel intercepts the first litres of water due to its high water retention capacity (greater interstitial pore space) together with the lack of slope in the roof. The results for the FG roof coincide with the predictions from Wright–McLaughlin Engineers (Corbitt, 1998) who affirm that typical depression and detention values for flat roofs are between 2.5 and 7.5 mm. However, the results for the sloping roofs differ from their predictions since Wright–McLaughlin Engineers assume that the initial abstraction for sloping roofs is between 1.3 and 2.5 mm.

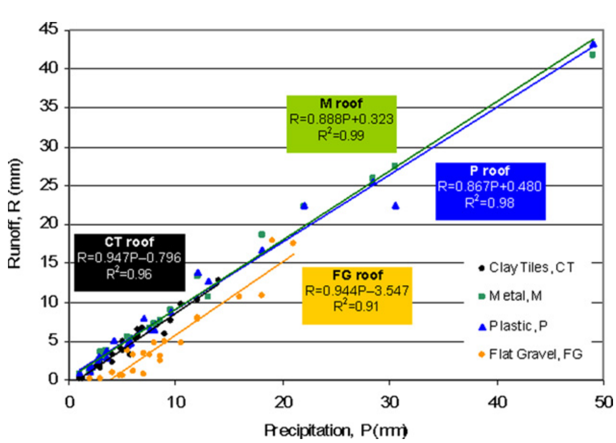

Fig. 2 – Regression model for roof runoff and rainfall height. Regression equations and corrected R^2 are also shown. Each point represents a rain event.

3.1.2. Global RC

Regression models are used to calculate the runoff for those rain events that exceed the initial abstraction. In the case of M and P roofs, it is considered that runoff never exceeds the event rainfall height (which would happen according to the runoff-rain function for the smaller rain events due to the positive y-intercept). Then, Eq. (2) is used to calculate the global RC. Depending on the local rainfall profile (either predominance of small or large rain events), the total annual losses related to initial abstraction will vary.

The average global RC (period 1999–2009) for CT, M, P and FG roofs is 0.84 ± 0.01, 0.92 ± 0.00, 0.91 ± 0.01 and 0.62 ± 0.04, respectively. The lowest RC for FG roof is explained because of its high initial abstraction. This is relevant for stormwater management and, particularly, for flood prevention. Many cities are facing problems with the management of combined sewer overflows during and after rain events. As a solution to this problem, combined sewer overflow tanks are being constructed to reduce the runoff peak flows, which might be alternatively attained by having roofs with low RC instead. In contrast, higher RC values (corresponding to sloping smooth roofs) would be preferable in order to maximise the amount of rainwater harvested. In this context, it worth mentioning what RWH has a great potential in the case study area, despite its rather limited rainfall. Previous research (Fragkou, 2007) has shown that rainwater falling on the urbanised areas within the administrative region compiled of 27 coastal municipalities of the Barcelona metropolitan region (with a population density of more than 5000 inhabitants per km^2) is about 1.4 times higher than its water consumption (including related losses due to leakage from piping). Therefore, rainwater management may have a substantial role in urban water supply schemes in Spain, for which the selection of the right roof is desirable. In addition, the selection of the most appropriate scale for its infrastructures (i.e. building vs. neighbourhood level) should be explored in order to implement the most cost-efficient strategy (Farreny et al., 2011).

Since the rainfall profile affects the RC, the application of the model to other climatic characteristics would lead to different results. The greatest differences in roof RC between the set of roofs are found when the size of rain events is small (i.e. if all rain events were of 5 mm, the RC would be 0.79, 0.95, 0.96 and 0.23 for CT, M, P and FG roofs, respectively). However, if the size of rain events were greater, differences would be much smaller (i.e. if all rain events were of 15 mm, the RC would be of 0.89, 0.91, 0.90 and 0.71 for CT, M, P and FG roofs, respectively).

3.1.3. The effect of ADWP and wind direction in the regression model

Since the effective collection area of each roof depends on factors such as the direction of prevailing winds and orientation (Villarreal and Dixon, 2005), particularly for sloping roofs, it is suggested that wind direction could affect the runoff from M and P roofs (the only single pitch sloping roofs). However, statistical analyses show that there is no significant ($p > 0.05$) relationship between runoff and wind direction for any of the roofs. However, we suggest that the effect of wind could partially explain the lack of significance of the y-intercept for M and P.

Another variable that could affect runoff is the ADWP. Although there is no significant ($p > 0.05$) correlation between runoff and ADWP for any roof, its incorporation in the regression model provides a more adjusted regression model in the case of FG roofs (corrected $R^2 = 0.92$):

$$R = 0.937\,P - 0.083\,\text{ADWP} - 2.901$$

The negative coefficient that accompanies the variable ADWP indicates that the longer the ADWP, the smaller the roof runoff. This is explained by the accumulation of water over longer periods in FG roofs, which is linked to their higher initial abstraction.

3.2. Quality assessment

Descriptive statistics including minimum, maximum, mean and median concentration of the water quality variables for the whole set of roofs are presented in Table 4. Nitrites and phosphates were not detected at all in most samples (35 and 41 out of 55, respectively), for which a concentration of 0 mg/L was considered for further statistical analyses. Table 4 also compares the water quality results to the values from a review of rooftop runoff quality of data expressed in EMCs (Chang et al., 2004; Evans et al., 2006; Göbel et al., 2007; Melidis et al., 2007). The variety and quantity of individual pollutants present in roof runoff are affected by a number of factors (Chang et al., 2004; Sazakli et al., 2007; Simmons et al., 2001; Skaryska et al., 2007; Villarreal and Dixon, 2005), namely, characteristics of the surface, atmosphere conditions and properties of pollutants.

In order to allow for comparisons, the water guidelines from the Drinking Water Directive 98/83/EC on the quality of water intended for human consumption (European Commission, 1998) are shown for the legislated parameters. Furthermore, the pollution levels of the currently used raw water sources for drinking purposes in the region – either surface or groundwater – previous to water purification are shown.

3.2.1. *General assessment of the runoff quality for the whole set of roofs*

EC, which represents the samples' total ion content, can be identified as a leading parameter (Göbel et al., 2007) and may be regarded, to a certain extent, as a measure of the concentration of dissolved matter (Deletic, 1998). All roofs are within a low range of EC (Table 4), particularly compared to current surface and groundwater sources.

Generally, the pH of rainwater ranges from 4.5 to 6.5 but increases slightly after falling on the roof and during storage in tanks (Göbel et al., 2007; Meera and Ahammed, 2006). However, our results indicate higher pH values, in the range of 6.54 and 8.25. These results are consistent with those obtained by Melidis et al. (2007) in several roofs in Greece (among which there were CT and M roofs). This pH can be explained as a result of the neutralisation which takes place mainly because of high values of alkalinity and base cations in African rains, which are common in the region, compared to the rains of European origin (Avila and Alarcón, 1999). The limited amounts of nitrates and sulphates also explain these high pH values.

The measurement of the TSS contents in urban runoff is of major concern with respect to the transport of anthropogenic

Table 4 – Rooftop runoff quality results and review of literature results.

Parameter	Units	Case study roofs				Roof review			DWG[b]	Surface and groundwater sources[c]		
										1	2	3
		Min	Max	Mean ± S.E.	Med	Min	Max	Med[a]	Limit	Mean	Mean	Mean
Physical–chemical parameters												
Conductivity	μS/cm	15.4	456	85.0 ± 10.0	59.3	2.2	269	141	2500	1439	481	3169
pH	upH	6.54	8.85	7.59 ± 0.07	7.61	3.3	8.25	5.7	6.5–9.5	8.11	7.91	7.52
Sum parameters												
TSS	mg/L	0	38.5	5.98 ± 0.95	3.63	13	120	43	–	n.a.	n.a.	n.a.
TOC	mg/L	0.65	53.6	11.6 ± 1.7	6.4	n.a.	n.a.	n.a.	–	4.04	1.76	4.04
TIC	mg/L	1.36	19.0	7.37 ± 0.66	5.78	n.a.	n.a.	n.a.	–	n.a.	n.a.	n.a.
Nutrients												
PO_4^{3-}	mg/L	0.00	6.60	0.32 ± 0.14	0.00	n.a.	n.a.	n.a.	–	0.51	0.11	
NH_4^+	mg N/L	0.04	2.42	0.50 ± 0.07	0.42	0.1	6.2	3.39	0.5	0.91	0.15	0.18
NO_3^-	mg/L	0.01	9.34	1.75 ± 0.26	1.16	0.1	5.73	2.78	50	9.23	7.84	4.89
NO_2^-	mg/L	0.00	3.45	0.13 ± 0.05	0.00	n.a.	n.a.	n.a.	0.1	0.55	0.13	0.05
Main ions												
SO_4^{2-}	mg/L	0	11.5	3.54 ± 0.39	2.59	0.01	19.7	46.7	250	173.5	58.8	244.2
Cl^-	mg/L	0.15	119	8.86 ± 2.38	3.38	5.73	40.5	7.74	250	292.2	47.1	977.7
Total carbonates	mmol/L	0.12	1.62	0.63 ± 0.06	0.49	n.a.	n.a.	n.a.	–	n.a.	n.a.	n.a.

a Medians are based on the review made by Göbel et al. (2007).
b Drinking water guidelines (European Commission, 1998).
c Sources 1, 2 and 3 correspond to quality data from Llobregat river, Ter river and Llobregat Delta Aquifer, respectively, (ACA, 2010).

pollutants, since pollutants are dominantly bound to particles (Moilleron et al., 2002). The amount of TSS is small in all roofs (median TSS <5 mg/L), particularly compared to the review. There is no guideline for TSS for drinking purposes. However, a content below 25 mg TSS/L is associated with excellent water quality (Davis and McCuen, 2005).

The TOC content, which is not legislated for drinking purposes, is slightly higher than that in surface and groundwater (Table 4). However, it is considered that concentrations below 20 mg/L correspond to good water quality (Davis and McCuen, 2005).

Inorganic nitrogen occurred mainly as NO_3^- and ammonium (NH_4^+) while NO_2^- occurred in smaller proportions (Table 4). Because NO_3^- is a transformation product, it shows a reversed behaviour and increases in concentration as the NH_4^+ concentration decreases (Göbel et al., 2007).

Sulphates and nitrates together represent the major ionic derivatives of industrial and traffic emissions (Evans et al., 2006), as a result of fossil fuels combustion (Mouli et al., 2005). Despite the proximity to a motorway, the concentrations of these pollutants are in the low range, compared to the review of roofs (Table 4). This can be partly explained by the relative position of the predominant direction of winds in the area and the motorway. Predominant winds come from westerly directions and the motorway is located to the east, which prevents its pollution from reaching the roofs. Ammonium concentrations are normally of natural origin – fermentation of nitrogenised products such as bird faeces – in areas with low industrial activity (Melidis et al., 2007). Therefore, bird excrements together with moss and lichens on the roofs can cause an increase in ammonium as well as phosphorus levels (Göbel et al., 2007).

The runoff quality data is affected by the first flush phenomena (see Kus et al., 2010; Zhang et al., 2010), since the experimental design does not consider first flush diversion. However, a practical implementation of a RWH strategy would divert the very dirty runoff from the first few millimetres of rainfall away from the tanks to avoid contamination (Villarreal and Dixon, 2005), which is a practice followed globally (Sazakli et al., 2007). Thus, the water quality of the RW collected in the tank would be significantly improved (Kus et al., 2010)

Comparing the quality (expressed in medians) of runoff from the case study roofs to the review made by Göbel et al. (2007) (Table 4), who reviews more than 300 references providing about 1300 pieces of data for different pollutants, the quality in the case study area is, in general, better for the parameters under study and with available data.

The violations in water quality standards were most severe for NO_2^- and NH_4^+ (18% and 24% of samples exceeded the European drinking water standards (Table 4), respectively). However, the nitrite concentration should not be considered a concern since American and Australian legislations establish a limit of 1 and 3 mg/L, respectively (Australian Government, 2004; US EPA, 2009). On the other hand, median NH_4^+ concentration was within the guidelines.

On the other hand, it can be stated that the physicochemical quality of the collected roof runoff is, in general, superior to the sources of surface and groundwater in the region. This can be partly explained by the degradation of current water sources in the region. This is consistent with van Roon (2007), who stated that the physical and chemical properties of rainwater are usually superior to sources of groundwater that may have been subjected to contamination.

3.2.2. *The effect of rainfall height and ADWP on runoff quality*

The wide distribution of EMCs depends on total rainfall because of the dilution effect during a storm (Kim et al., 2007). Our results show that, in general (for the whole set of roofs), the higher the rainfall height, the smaller the pollution loads in the samples. The correlation is significant ($p < 0.05$) and negative between rainfall height and the following parameters: EC, TIC, TOC, TC, total carbonates system, Cl^-, NO_3^- and SO_4^{2-} (Spearman

Table 5 – Spearman Rho correlation coefficients between the water quality parameters for the whole set of roofs.

	pH	EC	TIC	TOC	TC	Carb[a]	Cl^-	NO_2^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	NH_4^+	TSS
pH		,290*	,346**	,223	,302*	,368**	,260	,009	,156	,506**	-,202	-,453**	,547**
EC			,830**	,755**	,833**	,825**	,599**	,237	,424**	,656**	,057	-,346**	,119
TIC				,818**	,938**	,999**	,526**	,303*	,336*	,588**	,098	-,465**	,224
TOC					,954**	,818**	,440**	,275*	,321*	,501**	,121	-,500**	,180
TC						,939**	,524**	,311*	,376**	,576**	,091	-,491**	,226
Carb[a]							,520**	,297*	,340*	,593**	,087	-,477**	,247
Cl^-								,416**	,469**	,546**	-,011	-,101	,283*
NO_2^-									,226	,080	,287*	-,120	,121
NO_3^-										,639**	-,252	-,032	,137
SO_4^-											-,266*	-,377**	,190
PO_4^{3-}												-,093	,043
NH_4^+													-,158
TSS													

[a]Carb stands for total carbonates

*p<0.05; **p<0.01. The colour-shaded cells indicate the degree of correlation (light grey : |r| <0.5, dark grey: 0.5< |r| <0.9 and black: |r| >0.9)

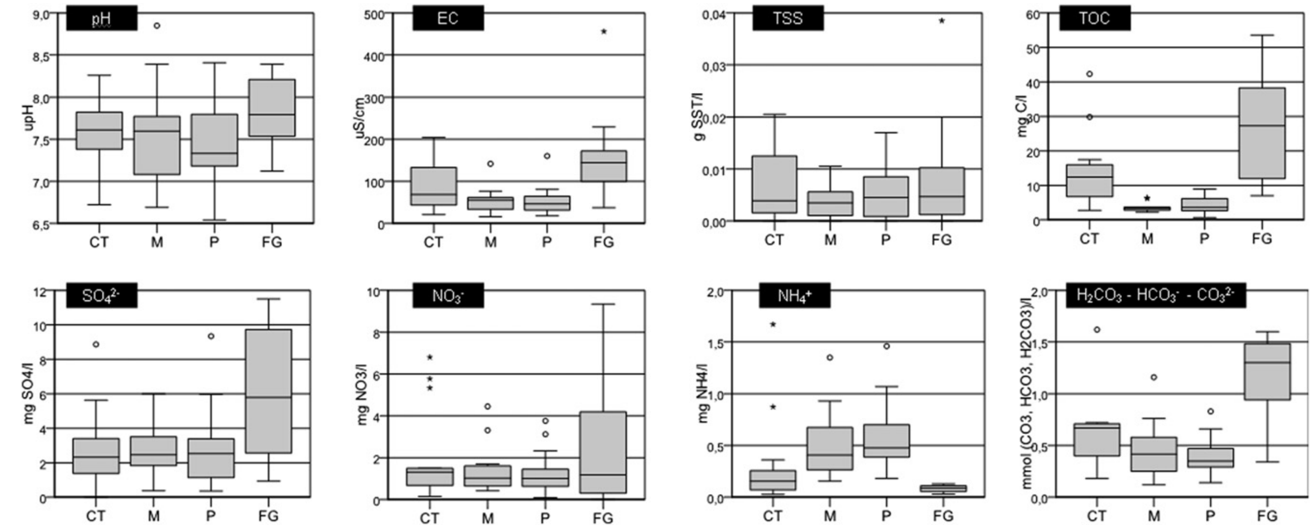

Fig. 3 – Box plot diagram of rooftop runoff water quality for each roof. Abbreviations: CT = clay tiles; M = metal; P = plastic; FG = flat gravel.

correlation coefficient between −0.301 and −0.642). If the correlation analysis distinguishes between roofs, the highest significant correlation is found between rain and EC (coefficient between −0.843 and −0.940 among the several roofs), TC (between −0.564 and −0.814 among the several roofs), total carbonates system (−0.723 for M roof), NO_3^- (−0.591, −0.771 and −0.789 for CT, M and P roofs, respectively) and SO_4^{2-} (−0.618, −0.656 and −0.629 for CT, M and P roofs, respectively).

On the other hand, it has been previously observed that ADWP can markedly affect the quality of runoff water (Fewtrell and Kay, 2007). However, no significant ($p > 0.05$) correlations are found between ADWP and the quality parameters, except for NO_2^- (Spearman correlation coefficient = 0.439). These results are consistent with those obtained by Kim et al. (2005c) who were disappointed because of a lack of correlation between water quality (from highways) and storm characteristics (such as ADWP).

Correlation analyses between the water quality parameters (Table 5) show that the highest correlations are found between any combinations of the following parameters: TIC, TOC, TC and total carbonates system. The negative significant ($p < 0.01$) correlation between NH_4^+ and some parameters (i.e. pH and TIC) can be explained by the fact that alkaline mediums foster ammonia (NH_3) volatilisation and also because aerobic conditions encourage oxidation processes – which result in CO_2, measured indirectly by means of TIC – and nitrification, both of which result in less amounts of NH_4^+.

3.2.3. *Differences in water quality between roofs*

The water quality results for the runoff collected during the study period in each roof are shown in Fig. 3 for the following parameters: pH, EC, TSS, TOC, SO_4^{2-}, NO_3^-, NH_4^+ and total carbonates system (HCO_3^-, CO_3^{2-} and H_2CO_3).

Statistical analyses of variances indicate that the differences in water quality within the whole roof set are not significant ($p > 0.05$) for the following parameters: pH, Cl^-, NO_3^-, SO_4^{2-} and TSS. However, significant differences were found ($p < 0.05$) between the quality in FG roof and the three pitched roofs for EC, TIC, TOC, TC, total carbonates system and NH_4^+, presenting higher pollution levels for all parameters except for NH_4^+.

The higher pollution load in FG roof can be explained by the weathering of the roof materials (gravels) and the accumulated deposits of particulates and associated flora on them. FG roofs are more predisposed to being colonised by a wide range of plants, notably mosses, algal crust and lichens. Besides this, the lack of slope aids the development of these processes. In contrast, lower levels of NH_4^+ in FG roof may be explained by the higher alkalinity and the greater oxidation processes (indirectly measured by means of TIC). Nevertheless, it is believed that other flat roofs with different materials other than gravel (such as concrete, asphalt, hot tar or tiles) would present different pollution results.

On the other hand, M and P roofs do not show significant differences ($p > 0.05$) for any of the parameters. This can be explained by the similarity of the hydraulic behaviour of both catchments (sloping smooth materials). The two studied roofs are actually the opposite sides of the same roof (although made of different material) but there are no differences in concentrations since neither side receives a distinctly higher net precipitation than the other. These results agree with those obtained by Chang et al. (2004) for similar roof materials (painted aluminium, galvanised iron and composite shingles), in which the orientation of the roof had no effect on the runoff water quality.

In contrast, M and P roofs present differences with the CT roof for TOC, TC and NH_4^+. The higher amount of TOC in CT roofs can be explained by the relatively high porosity of clay tiles, for which the material is exposed to greater physical, chemical and biological degradation. Besides this, the lichen's presence and growth can cause several additional deterioration problems (Kiurski et al., 2005).

From these results, one can affirm that runoff from M and P roofs is of the same or better quality than the other roofs for all parameters, except for NH_4^+. On the other hand, runoff from FG roofs presents the best quality in terms of NH_4^+ but the worst in terms of EC, TOC and the system of carbonates. The runoff from CT roofs presents an in-between quality.

4. Conclusions

- The linear regression model developed for each roof (clay tiles – CT, metal sheet – M, plastic sheet – P and flat gravel – FG) shows that runoff depends greatly on the rainfall height. The initial abstraction, which depends on the roof's slope and roughness, is highest in flat rough roofs (i.e. 3.8 mm for FG) while sloping roofs present much smaller abstractions ($\leq$0.8 mm).
- The selection of sloping smooth roofs (i.e. M and P roofs, with a RC > 0.9) implies a global RWH potential approximately 50% greater than flat rough roofs (i.e. FG roof, with RC = 0.62). The promotion of roofs with low RC may be advisable in order to reduce the peak flow and minimise the problem of combined sewer overflows.
- Quality analyses indicate that rainwater runoff samples are in the low range for EC (85.0 ± 10.0 μS/cm), TSS (5.98 ± 0.95 mg/L) and TOC (11.6 ± 1.7 mg/L); and their pH is basic (7.59 ± 0.07 upH). Thus, the quality of rainwater runoff in the case study area (north-eastern Spain) appears to be generally better than the average quality found for roof runoff in the literature review.
- Differences in runoff water quality are relevant between sloping smooth and flat rough roofs. The FG roof presents higher levels of all pollutants (except for NH_4^+) because of the processes of particle deposition, roof weathering and plant colonisation. In contrast, sloping roofs (such as CT, M and P roofs) present better quality.
- These results have an important significance for local governments and urban planners in the design and planning of cities. With city planning policies that could establish guidelines regarding the slope and roughness of roofs (both for the existing city and for new developments), stormwater roof runoff could be promoted both in terms of resource availability and quality. Thus, sloping smooth roofs, which have proved to perform best, may be preferable in order to foster RWH.

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