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Influence of rainfall intensity and pollution build-up levels on water quality and quantity response of permeable pavements

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Abstract

Permeable pavements are part of stormwater management practices known as sustainable urban drainage systems (SUDS). This study describes the influence of several environmental variables, such as the rainfall regime or the pollution build-up level, on the hydraulic and water quality performance of permeable pavements. Four infiltrometers with different configurations of pavement layers were used to study the influence of two rainfall regimes (Atlantic and Mediterranean) and two rainfall intensities (0.5 and 2.2 mm/min). The influence of the progressive pollution build-up level was studied by dry sprinkling of road deposited sediments collected with a mechanical street sweeper with a dose of 5 g/m^2/d. The results show that permeable pavements retained a significant rainwater volume and improved the infiltrated water quality in terms of suspended solids, organic matter and nutrients when compared to the corresponding surface runoff potentially generated from an impervious pavement. The volume of rainwater retained inside them varied between 16 and 66% depending on the variables studied. The water infiltrated from permeable pavements subjected to a Mediterranean rainfall regime contained, in general, higher concentrations of organic matter (22 to 89 mg Chemical Oxygen Demand/l) and nutrients (0.6 to 2.1 mg Total Nitrogen/l and 0.05 to 0.45 mg Total Phosphorus/l) than those under Atlantic regime. However, the latter infiltrated higher loadings in terms of mass. Nitrogen was the substance that infiltrated the most, reaching a 25% of the total mass of nitrogen deposited on the pavements surface. The concentration and mass loading in infiltrated water increased as the pollution build-up level did. The leachability of nutrients and organic matter was greater for high rainfall intensities. The results suggest that it is essential to carry out an adequate cleaning in dry conditions, especially when high intensity rainfall events are foreseen, because of its greater capacity to mobilize pollutants.

INTRODUCTION

About 46% of pollution discharged to surface water bodies is associated with urban runoff, according to Kamali et al. (2017). The proper management of urban runoff is therefore a key issue in the maintenance of good status of surface water bodies. Sustainable urban drainage systems (SUDS) aim to manage rainwater at source and they employ natural processes, thus renaturing the urban water cycle. According to their definition (Woods et al. 2015), SUDS provide four key benefits to the urban environment: improved water quality (1), reduced volume or speed water quantity (2), amenity (3) and biodiversity (4). Water infiltration into the ground is a key aspect of their operation. However, given that the accumulation of pollutants on urban surfaces is a clear hazard source, it is necessary to study the potential effects of stormwater on the surrounding environment even after this enhanced infiltration, especially when water passes into the groundwater.

Permeable pavements are one of the infrastructure features that can be included in SUDS design and provide a wide range of benefits, including: reduction of surface urban runoff and peak flow attenuation, reduction of combined sewer overflows, groundwater recharge (Tedoldi et al. 2016), noise reduction and avoidance of aquaplaning (Stotz and Krauth, 1994) or mitigation of urban heat island effect (Liu et al. 2018), among others. Therefore, they provide the first three key benefits of SUDS and the fourth, indirectly, via improved quality of water released to the water environment. There is an extensive list of studies on the hydraulic performance of these types of systems as well as how they contribute to reduce runoff at source. However, there are few investigations into how they affect the quality of the infiltrated water although the number has been growing in recent years (Drake et al. 2014; Brown and Borst, 2015 and Kamali et al. 2017 among others). Several aspects that remain to be studied are the influence of the rainfall regime, the rainfall intensity, and the level of pollution build-up prior to rain on the hydraulic behaviour and the quality of infiltrated water. Thus, studying the response of permeable pavements to high rainfall intensity events is crucial to demonstrating their ability to face future challenges associated with climate change, as the Intergovernmental Panel on Climate Change expects that extreme precipitation events will become more intense and frequent in many regions (IPCC, 2018).

The type of sediments (real dust and dirt or artificially provided) used to evaluate the decrease in permeability or the influence on the quality of infiltrated water varies between studies (Andrés-Valeri et al. 2016; Kamali et al. 2017). When changes in water quality are evaluated, it seems more appropriate to use actual dust and dirt in order to simulate more realistic conditions. Kamali et al. (2017) support the idea that applying the contaminant load through surface runoff is a more realistic experimental setup because pavements are frequently cleaned and the majority of pollutants are thus introduced through surface runoff. In this sense, one must be aware that real-scale installations will not behave in exactly the same way as experimental laboratory-scale sets. Pezzaniti et al. (2009) found that a real permeable pavement became clogged at a faster rate than those evaluated under laboratory conditions, whereas Razzaghmanesh and Borst (2019) did not observed surface clogging issues after an eight-year period of operation in a real parking lot.

Studies dealing with the quality of infiltrated water show that the conditions occurring within pavements, i.e. aerobic conditions and adequate pH, are suitable for the growth of nitrifying bacteria, thus nitrification is the dominant process affecting the nitrogen composition in the effluent (Brown and Borst 2015; Drake et al. 2014; Kamali et al. 2017; Razzaghmanesh and Borst, 2019). In addition, if the outflow is regulated using underdrains or valves, it is possible to create anoxic zones that favour the elimination of nitrogen through denitrification (Drake et al., 2014). In cases where denitrification does not take place, infiltration of nitrates into the groundwater increases, implying a negative impact. However, nitrate concentrations usually found in urban runoff are far from the established limits needed to declare nitrates vulnerable zones (Brown and Borst, 2015; Andrés-Doménech et al. 2018). Another important process that affects the quality of the infiltrated water is filtration: particulate substances can be retained in the pavement, thus improving the quality of the filtered water, although particles retained can decompose over time, slowly releasing the substances they are composed of (organic matter, nutrients, metals, etc).

The washing of the materials that compose the different layers of the permeable pavements also affects the quality of the infiltrated water. For example, Brown and Borst (2015) saw that porous asphalt leached nitrogen, i.e. the total nitrogen in the effluent was higher than in runoff, while permeable interlocking concrete pavement or continuous pervious concrete exported phosphates and the porous asphalt reduced it.

The present study considers the following hypotheses: the rainfall regime and rainfall intensity can significantly influence the hydraulic behaviour and the mobilization of pollutants through the pavement; the degree of pollutant build-up significantly reduces the infiltration rate, having consequences on the mobilization of pollutants. Knowing the influence of these factors will allow us to suggest recommendations for maintenance in order to lengthen as much as possible the lifespan of the permeable pavements as well as their positive impact on the receiving water bodies. Results are also important for establishing several technical specifications for their design and manufacturing processes. Therefore, the aim of this study is to gain knowledge about the changes in water quality of runoff produced by permeable pavements and their impact in both groundwater and surface water.

MATERIALS AND METHODS

Materials

The experimental setup designed to achieve the objectives of the study consists of a four infiltrometers battery. Two configurations of pavement layers were tested: the composition of configuration C1 is illustrated in Figure 1; configuration C2 has the same layers except the bottom layer of washed limestone aggregate 4-40 mm size. According to the information provided by the manufacturer, the components used in the concrete blocks production are the following: siliceous arid, white and grey cement, plasticizer and water-repellent additives and pigments (iron oxides). The rainfall simulator is based on Rodríguez-Hernández et al. (2016) and is composed of a water storage tank, a pump (Multi-1300 SICCE) and a grid of drip irrigation pipes consisting of 7 rows with 13 drippers per row evenly distributed and placed 50 cm above the pavement surface (see Figure 1). A rain gauge is positioned below each permeable pavement to measure the infiltrated water flow, which is then collected and kept in a refrigerator until chemical analysis is performed.

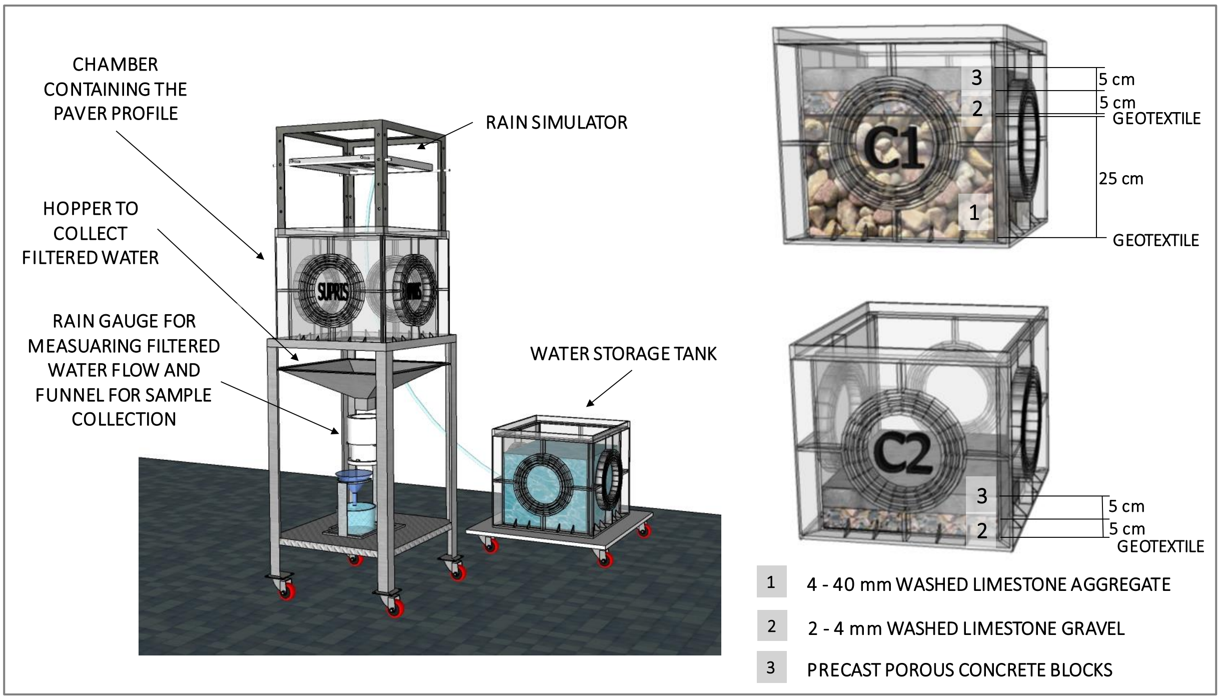

Figure 1. Scheme of the experimental setup.

Deionized water was used (Electrical Conductivity: 21 µS/cm, pH: 6.9) to simulate rainwater. The material used to simulate the different degrees of pollution build-up was collected by the road cleaning services of the university, thus being real dust and dirt deposited on urban roads. It was collected by a mechanical sweeper in dry conditions.

Methods

Two rainfall regimes, Atlantic and Mediterranean, were tested. The simulated rainfall reproduces the average rainfall regime of Valencia (Mediterranean) and Santander (Atlantic), both in Spain: events with a rainfall volume of 16 mm and 30 minutes duration (0.5 mm/min), with a weekly frequency for the Atlantic climate and biweekly in the Mediterranean climate (Andrés-Doménech et al., 2010). After each rainfall event, the infiltrated water was analysed. Each rainfall regime was tested in two infiltrometers (configurations C1 and C2). The experiments were planned to be long-term tests, starting in January 2017. After the first year, the infiltrometers with configuration C1 continued under the same conditions in order to have a longer-term experiment and those with configuration C2 were cleaned with a domestic vacuum cleaner and a brush and were then used to test the performance of the permeable pavements under more intense rainfall events, in particular 22 mm in 10 min (2.2 mm/min), which has a return period of once in 25 years in Valencia (Spain). For this test, a plastic mesh was installed according to Naves et al. (2017) to break rainfall drops. If surface runoff was generated it was collected and analysed.

The influence of progressive pollution build-up was studied by dry sprinkling sediments (real dust and dirt) on the pavement surface. The applied deposition rate (5 g/m^2/d) was selected according to the information provided by the cleaning services (mass collected, surface swept and cleaning frequency) and checked against scientific references (Table 1). The deposition rate used is the same for all the tests. The deposition rate was kept constant throughout the study period in order to evaluate the response of permeable pavements to a surface overload of pollutants.

Table 1. Deposition rates or build-up levels after different numbers of dry days measured by other authors.

Deposition rate or Build-up level	Collection method	Reference
15 – 18 g/m^2 after 3 dry days* 15 – 20 g/m^2 after 2 dry days*	Vacuuming: free load. Fibre brush + vacuuming: fixed load	Vaze and Chiew, 2002 *Total load (fixed + free)
0.1133 - 0.6525 g/m^2/d	Drain runoff with a corrugated pipe	Kim et al., 2006
2 – 2.43 g/m^2 for 1st dry day 2.85 – 5.29 g/m^2 for 21st dry day	Vacuuming (water filtration system + small circular foot with a brush)	Egodawatta and Goonetilleke, 2006
0.016 – 0.058 g/m^2/d	Capture runoff with slot drains, which drained to weir boxes	Winston et al., 2012
Particles < 0.150 mm: 1.50 – 2.45 g/m^2 for 1st dry day 1.10 – 1.50 g/m^2 for 21st dry day Particles > 0.150 mm: 0.25 – 0.30 g/m^2 for 1st dry day 1.10 – 3.50 g/m^2 for 21st dry day	Vacuuming (water filtration system + small circular foot with a brush)	Wijesiri et al., 2015
g/m^2 after 1st dry day: 0.13 – 0.45 < 44 µm 1.25 – 1.55 44 - 62 µm 1.75 – 2.38 62 - 105 µm 0.45 – 0.50 105 - 149 µm 1.00 – 1.25 149 - 250 µm 1.25 – 2.25 250 - 450 µm 0.95 – 2.13 450 - 1000 µm	Vacuuming with a domestic vacuum cleaner (Philips FC8264), with an air filtration system and cyclonic dustbin that effectively captures microscopic particulates.	Zhao et al., 2016

Note: Maximum values usually coincide with highly populated areas. Data from literature extracted from graphs, so there is a possibility of some slight imprecision from graph reading. Free load is collected only by vacuuming and fixed load is collected by brushing plus vacuuming after the collection of the free load.

In a complementary and independently way to the infiltrometer experiments, physicochemical analysis of an artificial mixture of dust in deionized water was made. The objective was to know the chemical composition of the potential runoff from an impervious urban area assuming that the entire volume of rainfall became runoff, and that almost all the mass of pollutant deposited on the surface was washed-off. This mixture was made with the same proportions of sediments and deionized water as in the infiltrometer tests (2.2 g/l for 1-week build-up level) and the same variables of water quality were analysed.

Physicochemical analyses of sedimentary material were performed according to the following standardized methods: particle size distribution (ISO 77314); organic matter as loss on ignition (LOI) (550ºC for 1 h) and as organic carbon (Walkley-Black method as described in Schumacher, 2002); moisture (105ºC for 24 h); total nitrogen (ISO 11261), total phosphorus (EN 14672) and electrical conductivity ($EC_{1:5}$) and pH of sediment suspension in water in proportion 1:5 (V:V) (ISO 11265). For metal analyses, material was milled and digested in a microwave with HNO_3 and H_2O_2 at 200ºC for 15 minutes except for Hg, which was measured in a mercury analyser (DMA-80).

The total volume of infiltrated water was collected and kept in the refrigerator until analysis within 24 hours. The water samples were analysed for the following parameters: Total Nitrogen (TN) (Spectroquant® test: ISO 11905-1 + photometry), Ammonium (Spectroquant® test: ISO 7150/1), Nitrites (Spectroquant® test: EPA354.1), Nitrates (Spectroquant® test), phosphate (test Spectroquant®: ISO 6878/1) and total phosphorus (test Spectroquant®: digestion + ISO 6878/1), Biological Oxygen Demand - BOD (respirometry test through OxiTop® control system), Chemical Oxygen Demand - COD (test Spectroquant®: ISO 15705), Total and Volatile Suspended Solids (UNE-EN 872 y UNE 77034 respectively) and turbidity with a TN100 Eutech turbidity-meter. WTW-Multi 340i probes were used to measure: temperature, dissolved oxygen (CellOx® 325), conductivity (TetraCon®) and pH (SenTix® 41).

Statistical analyses were performed using SPSS 16.0 software (SPSS® software). The influence of the pavement configuration and the rainfall regime was analysed by comparing the temporary data series. The statistical tests used were parametric if normality was satisfied (T-Student for related variables) and nonparametric otherwise (Friedman's test for several related variables and Wilcoxon's test for pairwise comparisons). Statistical significance was indicated by a probability of type I error of 5% or less ($p \leq 0.05$).

RESULTS AND DISCUSSION

Characteristics of the sediments used in the experiments

The sediments used to simulate a progressive pollutant build-up over the pavement surface were actual dust and dirt taken from the University roadways, as stated in the previous section. The particle size distribution presents a high proportion of sands and is quite similar to the material used by

Sañudo-Fontaneda et al. (2014). It is also comparable to other road deposited sediments, being located between the free and fixed fraction described by other reference studies (Vaze and Chiew, 2002), as shown in Figure 2. The particle size distribution described by Vaze and Chiew for free load (collected only by vacuuming) and fixed load (collected by brushing plus vacuuming after the collection of the free load) encompasses the data reported in many other studies (Zafra et al. 2008; Andrés-Valeri et al. 2016). The thicker particles obtained in the present study deviate a little from data on free material collected by Vaze and Chiew (2002), but if we project the particle distribution size described by Adachi and Tainosho (2005) upwards it can be supposed that these larger particles fall within this gradation.

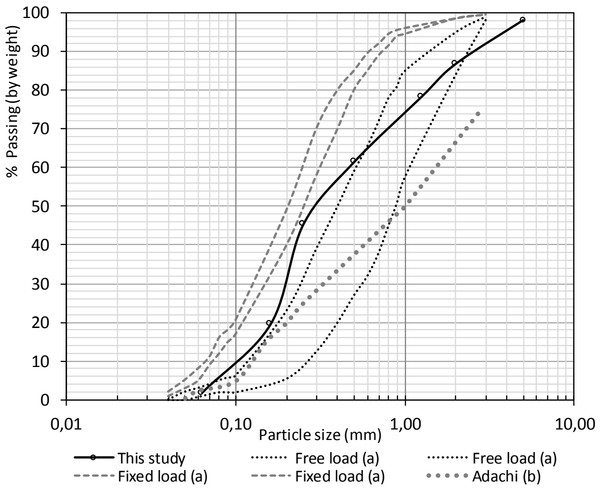

Figure 2. Particle size distribution in this study and ranges described by (a) Vaze and Chiew (2002) for fixed and free loads and (b) coarser distribution found by Adachi and Tainosho (2005). Data from literature is extracted from graphs, so there is a possibility of some slight imprecision from graph reading.

As reported in Table 2, the sediments collected in this study have a moderate content of organic matter (8.23 % dry weigh-dw) compared to natural and contaminated soils or sediments (Hernandez-Crespo et al. 2012; 2017) and low moisture content (2.02 % dw). The results obtained are within the range of variation of other studies analysing street dust and dirt (see Tables 2 and 3). The nutrient concentration can also be classified as moderate compared to natural soils or sediments (Hernández-Crespo et al. 2017), so the results indicate that the urban runoff could have a potentially negative impact on the receiving waters. The electrical conductivity of the aqueous extract is 890 µS/cm indicating that the dust and dirt material is saline according to the general classification of soils (Shrivastava and Kumar, 2015) and it has a moderately basic pH (8.0). In contrast to the organic and nutrient content, the concentration of some metals (Cr, Pb and Zn) should be considered very high as they far exceed the background concentrations of sediments from the nearest watershed, i.e. the concentrations that can be found naturally in soil and sediments (Hernández-Crespo and Martin, 2015).

Table 2. Physical-chemical characteristics of the dust and dirt used in the tests. Average and standard deviation of replicas are shown; n is the number of replica. Results are expressed on a dry weight (dw) basis.

Physico-chemical variable	Average ± Stnd.Dev. (n)	Metal	Average ± Stnd.Dev. (n)
Moisture (% dw)	2.02 ±0.00 (2)	Cd (mg/kg)	0.32 ±0.20 (4)
LOI (% dw)	8.23 ±0.15 (2)	Cr (mg/kg)	306 ±159 (4)
Organic carbon (% dw)	1.83 ±0.11 (4)	Cu (mg/kg)	36 ±11 (4)
COD (mg/g)	48.9 ±3.1	Pb (mg/kg)	132 ±45 (4)
Total nitrogen (mg/kg dw)	1351 ±197 (3)	Mn (mg/kg)	230.0 ±48.5 (4)
Total phosphorus (mg/kg dw)	302.5 ±18.5 (2)	Ni (mg/kg)	38.2 ±15.0 (4)
Electrical conductivity ($EC_{1:5}$) (µS/cm)	890 ±103 (3)	Zn (mg/kg)	238 ±43 (4)
$pH_{1:5}$	8.0 ±0.1 (3)	As (mg/kg)	4.79 ±0.70 (3)
Particle size distribution (% dw):		Hg (mg/kg)	0.0149 ±0.0024 (4)
Gravel (> 2mm)	13.2 ±0.6 (2)	Al (mg/kg)	3450 ±140 (3)
Sand (0.063-2 mm)	85.0 ±0.5 (2)	Fe (mg/kg)	8000 ±1000 (3)
Silt and clay (<0.063 mm)	1.8 ± 0.0 (2)		

Table 3. Review of dust and dirt quality in different cities around the world.

OM (%)	COD (mg/g)	pH	TP (mg/kg)	TN (mg/kg)	Comments on methods:
2.8-18.8[g]	107.7-253.7[b]	6.8-12.0[g]	529.4-1940.3[b]	3190.5-6268.7[b]	[a]Fraction <2mm; sweeping. [b]Fraction <2mm; sweeping. [g]Fraction <2mm; vacuum cleaner. [c]Fraction <1mm; sweeping. [h]Fraction <0.147mm; sweeping. [i]Fraction <0.050mm; sweeping. [j]Sweeping. [d]Fraction <2mm; vacuum sweeper.
2.5-13.6[d]		7.0-8.0[d]	346-933[d]		
			349.7-381.2[f]	429.6-832.4[f]	
Cd (mg/kg)	**Cu (mg/kg)**	**Ni (mg/kg)**	**Pb (mg/kg)**	**Zn (mg/kg)**	
3.77 ±2.25[a]	173 ±190[a]		181 ±92.9[a]	1450 ±869[a]	
0.0-13.1[c]	16.4-6688.4[c]	0.0-636.2[c]	0.0-199.4[c]	81.3-164.8[c]	
1.17-3.77[e]	94.98-196.8[e]	23-86.26[e]	53.33-408.41[e]	294.47-1450[e]	
1.3-3.4[g]	89.8-181.8[g]	13.4-33.0[g]	82.0-153.1[g]	1290-324.7[g]	
4.00-139[h]	102-966[h]	15.0-69.3[h]	157-1482[h]	813-45675[h]	
0-2.4[i]	19-1394[i]	10-2058[i]	12-2388[i]	70-9223[i]	
0.4-3.1[j]		12.7-151.3[j]	20.1-96.2[j]		
0.4-1.5[d]	67-151[d]	15-28[d]	96-222[d]	249-547[d]	
Al (mg/kg)	**As (mg/kg)**	**Hg (mg/kg)**	**Cr (mg/kg)**	**Fe (mg/kg)**	**Mn (mg/kg)**
4600-11200[h]	10.9-110.1[h]	0.18-10.8[h]	29.0-214[h]	14700-65600[h]	604-4761[h]
	7.1-16.3[j]	0.005-1.358[j]	51.29-167.28[e]	4883-54576[i]	149-999[i]
			19-3134[i]		
			33-70[d]		

References: [a]Li et al. (2001); [b]Burton and Pitt (2002); [c]Charlesworth et al. (2003); [d]Durand et al. (2003); [e]Wei and Yang (2010); [f]Berretta et al. (2011); [g]Duong and Lee (2011); [h]Ordóñez et al. (2015); [i]Marín Sanleandro et al. (2018); [j]Wu and Lu (2018).

The literature shows a very wide range of variation in terms of nutrients and heavy metals content in street dust (Table 3). The maximum values of metals corresponds to areas near metallurgical industries or heavy industrial cities (Ordóñez et al. 2015; Wei and Yang, 2010). Charlesworth et al. (2003) identified a spatial pattern in the variability of metals concentrations: the more traffic with many stops and starts and the higher the population, the higher concentrations. Marín Sanleandro et al. (2018) also identified traffic as a classification variable; they found a high accumulation of Pb and Zn in ledges of narrow city centre streets with moderate traffic; they also stated that the colour of samples can be considered as a proxy for rapid diagnosis, as dark samples were the most contaminated. The values obtained in the present study were in the lower limit of their range of variation, maybe because all parts of the sediment were analysed together, rather than analysing only the finest fraction. This was done because the entirety of the sediment was exposed to the rainfall, so we were interested to know the contaminant concentration of the whole sediment sample. Another potential reason could be that the sampled area is inside the university campus and the main contaminant activity is road traffic, but characterized by relatively few stops and starts.

Influence of pollution build-up level and rainfall intensity on infiltrated water quantity

The hydrographs of infiltrated water obtained in the different tests performed are shown in Figure 3. The maximum flow rates reached during high intensity rainfall events (around 1.7 mm/min, Fig. 3 E and F), were notably higher than those simulated at low intensity (between 0.3 and 0.5 mm/min, Fig. 3 A to D). The duration of the peaks were lower, in accordance with the lower duration of the simulated storms in the high intensity scenarios. Related to this, peak flows reached in the high intensity tests were clearly below the applied rainfall intensity, whereas they were closer to the rainfall intensity in the low intensity tests, due to their longer duration.

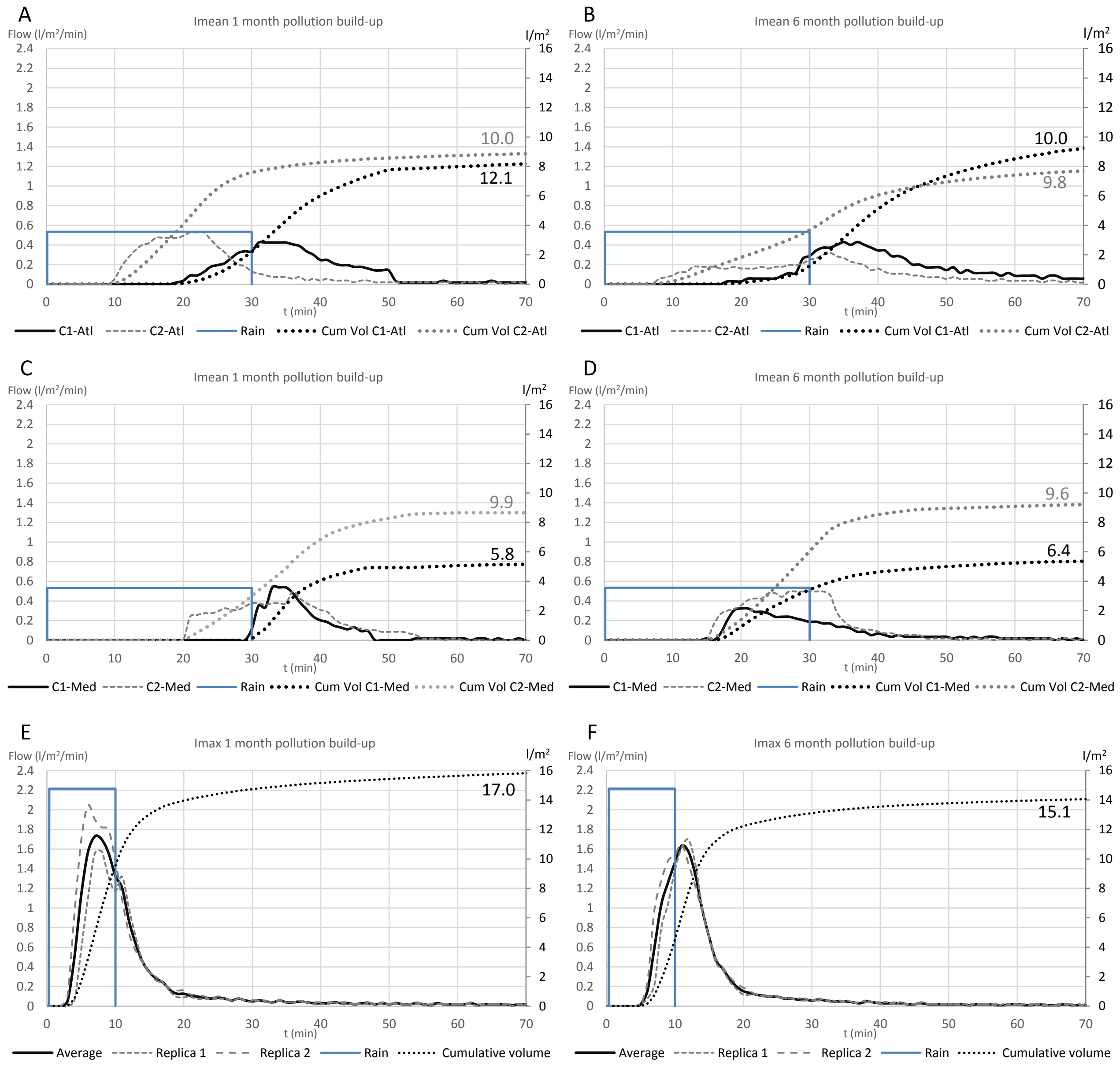

Figure 3. Hydrographs of infiltrated water of mean intensity (16 mm/30 min) under different rainfall regimes: Atlantic (A, B) and Mediterranean (C, D) and different pollution build-up levels: one month (A, C) and six month (B, D). C1: complete configuration; C2: simple configuration. Hydrographs of high intensity events (22 mm/10 min) under different pollution build-up levels: one month (140 g/m^2) (E) and six month (840 g/m^2) (F). Cumulative volume curves are displayed on the secondary axis and numerical data indicate the total drained volume. .

Regarding the influence of the pollution build-up level, it can be clearly observed in the intense rainfall simulations that the flow rate reached in the events simulated with a pollution build-up level of 6 months (Fig. 3 F) was lower and was reached later than in the simulation of 1 month of build-up level (Fig. 3 E). The larger quantity of dust and dirt accumulated on the pavement surface absorbed part of the rain, thus smoothing the peak flow of filtered water. Moreover, this might also have allowed for a better distribution of rainwater on the pavement surface, thus improving the distribution of flow through the entire pavement pore structure. A slight decrease in the infiltration rate was also observed in pavements subjected to low rainfall intensity regimes (Fig. 3 A and C versus B and D), which could be due to the absorption of water by the accumulated dust and to progressive pavement clogging.

For simulations performed at low rainfall intensity, reasonable differences were observed between the rainfall regimes when the build-up level reached one month (Fig. 3 A and C). The flow of filtered water under the Atlantic regime started earlier than it did under the Mediterranean regime, because the pavements under Mediterranean regime were drier due to the lower frequency of rainfall. There was also an observable difference between the pavement configurations: water began to drain earlier in pavements of simple configuration (C2), showing a lower capacity for water retention, and related to the shorter path of this configuration. However, for the rainfall events simulated when the build-up level reached six months (Fig. 3 B and D) the difference between drained water flows was not as clear. Water began to filter more quickly in the pavements under Mediterranean climate and the pavements with simple configuration started to drain earlier, but it did not look as clear as in the 1-month build-up scenarios. This finding could be related to the capacity of the accumulated dirt to attenuate the flow, as it absorbs part of water, and also associated with the increasing clogging.

Differences in the total drained volume can be seen in Figure 3 through the cumulative volume curves. The permeable pavements were always able to retain a significant part of the total rainfall volume applied (16 and 22 l/m^2 for the low and high rainfall intensities respectively), at least 16%. When rainfall events are frequent (Atlantic climate, Fig. 3 A and B), the complete configuration (C1) does not represent a great advantage in terms of water retention. In this case, the pavement with complete configuration retained a lower volume fraction (16 and 24% for one and six-month build-up levels respectively) than those with simple configuration (37 and 39% respectively). In contrast, in the Mediterranean climate tests, the benefit of having a thicker pavement layer is very evident, since the retained volume is much higher (62% of total rainfall volume applied on average) than when the pavement configuration is simple (39% on average) (Fig. 3 C and D). In the case of intense rainfall events, the volume retained varied between 23 and 31% for 1 and 6-month build-up levels respectively. In relation to the retained volume, and applicable to all configurations, regulating the permeable pavements outflow, by means of discharge underdrains or valves, would allow for a greater retention of volume inside them. Temporary storage of water would favour infiltration and evaporation processes and so increasing the hydraulic and environmental efficiency of the infrastructure. Figure 4 shows the complete data series of the total drained volume in each event for the average rainfall regime tests. For infiltrometers with C1 configuration, the total volume drained in the infiltrometers subjected to Atlantic regime is significantly higher than that from the infiltrometers under Mediterranean regime ($p < 0.05$). On average, there was not a significant difference between C1 and C2 in the Atlantic regime ($p > 0.05$), but for the Mediterranean regime ($p < 0.05$), which is in line with the aforementioned.

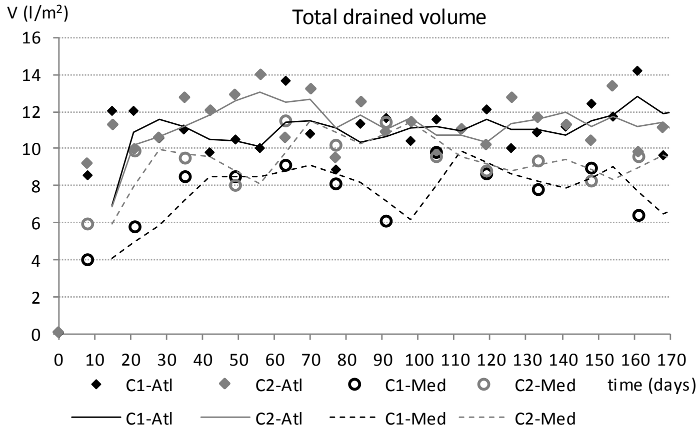

Figure 4. Temporal evolution of total drained volume in the average rainfall regimes (C1: configuration type 1; C2: configuration type 2; Atl: Atlantic rainfall regime; Med: Mediterranean rainfall regime). Dots represent the data and lines the moving average with a period of three data.

Overall, a very important result is that, after six months of pollution build-up, permeable pavements still maintain a high permeability, being able to infiltrate the total volume of water applied at low rainfall intensity and almost the entire volume in the high rainfall intensity tests. Surface runoff was only generated for the simulation made at high intensity of rain and six-month build-up level, the volume was 167 ml (3% of the total applied volume).

Water quality results

This section presents the water quality results for the permeable pavements, complete and simple configurations, under both rainfall regimes (Atlantic and Mediterranean) and high rainfall intensity. The water infiltrated through the permeable pavements initially presented very high values of electrical conductivity and pH, which decreased as the material received more and more rainfall, from values of about 3000 to 1000 μS/cm and from 12 to 10 for pH after six months. These high values of pH could negatively affect soil properties and microbiology, so it is advisable to analyse the manufacturing process of the pavement to see how such an increase in pH could be avoided. Several authors have also found increases in pH related to pavement components, particularly for pervious concrete and porous asphalt (Drake et al. 2014; Brown and Borst, 2015). In relation to a potential use for irrigation, guideline recommendations typically suggest pH values between 6.5 and 8.5. Although higher pH levels may not be harmful for plants, there might be a potential risk of fouling in irrigation systems especially if water also has a high alkalinity (Kazemi and Hill, 2015). In relation to these high values of pH it is worth noting that this increase can be considered as a positive point in locations that receive substantial amounts of acidic rainfall (Kazemi and Hill, 2015), because it contributes to neutralize the acidic rainfall.

The influence of pollution build-up levels and rainfall intensity on infiltrated water quality can be examined in Figures 5 to 8. For COD concentrations in infiltrated water, the rainfall regime and build-up level seemed to be of greater influence than rainfall intensity (Fig. 5). In the rainfall events simulated for one month of pollution build-up, the results were quite similar for both configurations and rainfall regimes, varying between 22 and 32 mg/l. When build-up corresponded to six months, the COD concentrations reached under Mediterranean climate were much higher, between 67 and 89 mg/l, than those for Atlantic climate (about 20 mg/l), and so is clearly associated with the lower rainfall frequency. For high rainfall intensity events, the COD is also noticeably higher for the six-month build-up level (68 mg/l) than for one month (28 mg/l). It is noteworthy that the concentration reached by the surface runoff was much higher, reaching a value of 111 mg/l. In this case, the volume of surface runoff generated was very small (168 ml) due to the zero slopes of the pavement and its high permeability, but in an impervious pavement it would have been considerably greater. Surface runoff was only generated in the test performed at high rainfall intensity and 6 month of build-up level, in which the filtration rate was slowed and the accumulation of water on the surface led to the generation of surface runoff. The results of BOD_5 test indicated that the organic matter present in the infiltrated water was slowly biodegradable, with a BOD_5/COD relationship of 0.2 on average, value similar to that found by Andrés-Doménech et al. (2018).

Regarding TSS, it should be noted that a first washing of the gravel that composes the pavement layers occurred, even though it was washed before the experimental set up. For this reason, the concentrations measured when the pollution build-up level reached one month were higher (17 to 63 mg/l) than those for six month of dust accumulation (5 to 32 mg/l). Having a low concentration of suspended solids in infiltrated water is very important if the permeable pavement can be used as a rainwater harvesting tank for irrigation purposes, since high TSS concentrations could obstruct irrigation systems.

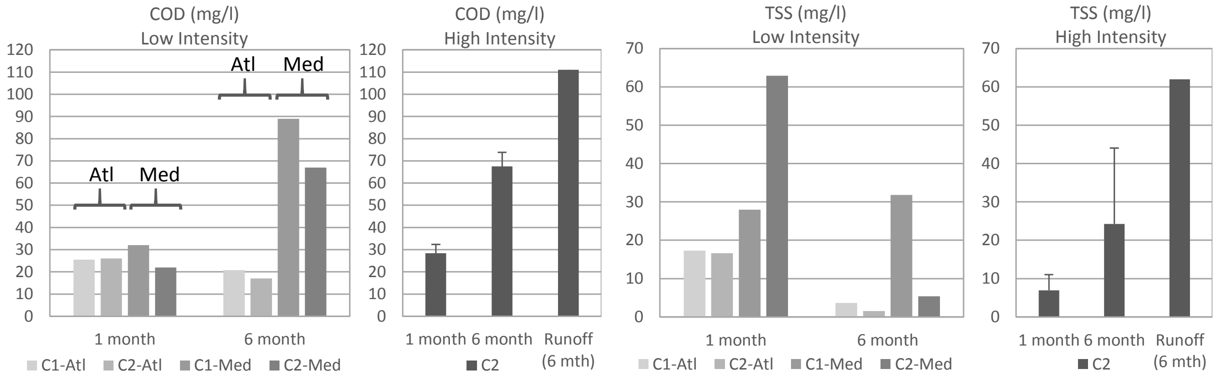

Figure 5. Chemical oxygen demand (COD) and total suspended solids (TSS) in the different assays performed (C1: configuration type 1; C2: configuration type 2; Atl: Atlantic rainfall regime; Med: Mediterranean rainfall regime; Low intensity: 16 mm/30 min; High intensity: 22 mm/10 min). All values refer to infiltrated water except when the x-axis indicates runoff, which refers to surface runoff.

Regarding the infiltrated nitrogen, the behaviour depends on its form (Figure 6). In general, the infiltrated water in the six-month build-up level events presented a higher concentration, especially in the pavements under Mediterranean climate. Rainfall intensity did not influence in a very remarkable way the concentrations reached under one-month build-up levels, but did at the six-month build up levels, where greater nitrate and total nitrogen concentrations were recorded. Nevertheless, the measured concentrations, with maximum of 1.55 mg NO_3-N/l, were well below the value established to declare vulnerability to nitrate contamination (11.3 mg NO_3-N/l according to the European Directive 91/676/EEC). The risk of contamination by nitrates was also categorized as low or moderate by Burton and Pitt (2002). Other authors have also found nitrates as the main nitrogen form in water drained from permeable pavements, and values similar to those obtained in this study (Drake et al. 2014; Brown and Borst, 2015). Drake et al. (2014) showed a reduction of nitrate concentrations in one of the permeable systems which was temporarily saturated after moderate and large rainfalls, due to a low permeability of the native soil in combination with a ball valve at the pavement outlet. Therefore, if anoxic zones are created it is possible to significantly reduce nitrate concentrations. Prior to the creation of these zones it would be recommendable to evaluate the concentration of sulphate in the infiltrated water to avoid the generation of bad odours produced by sulphide production. The concentration of ammonium in the water potentially infiltrated was below 0.16 mg N/l, which is the value established to classify water bodies with high status in the Spanish legislation (RD 817/2015) that develops the provisions of the Water Framework Directive (DIRECTIVE 2000/60/EC). In contrast, the surface runoff generated in the high intensity rainfall simulation did exceed that value.

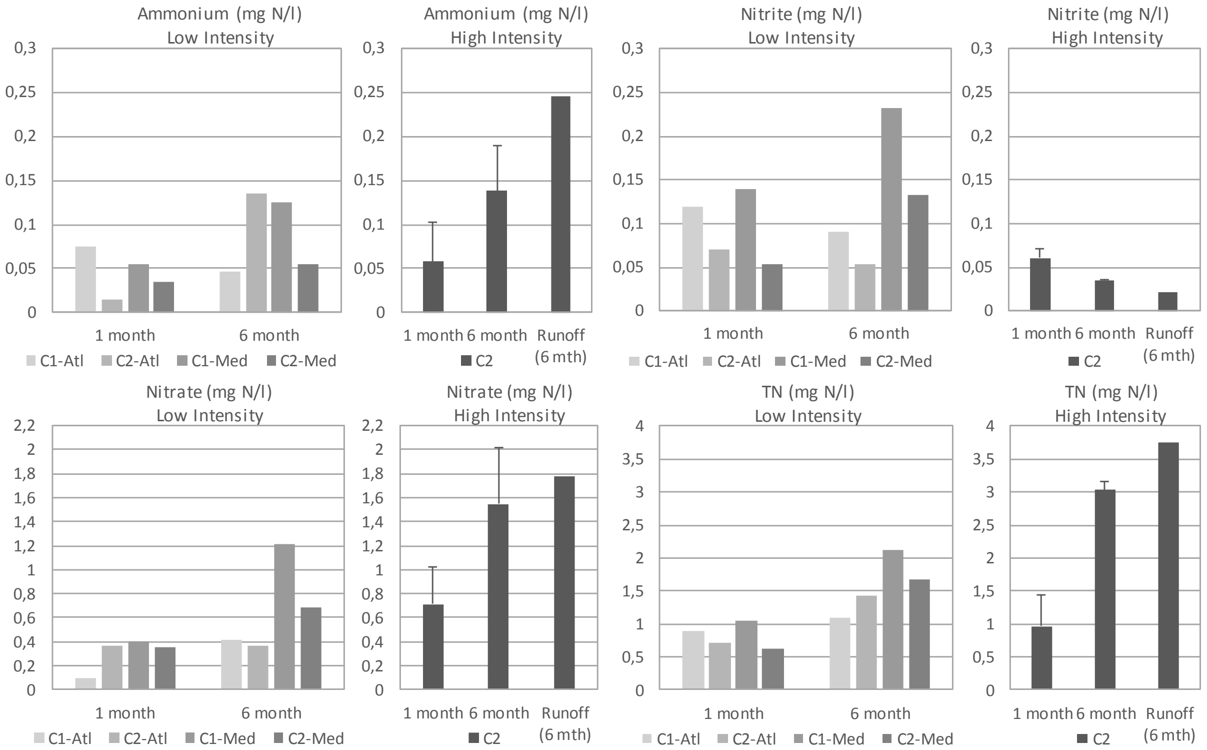

Figure 6. Nitrogen forms in the different assays performed (C1: configuration type 1; C2: configuration type 2; Atl: Atlantic rainfall regime; Med: Mediterranean rainfall regime; Low intensity: 16 mm/30 min; High intensity: 22 mm/10 min). All values refer to infiltrated water except when the x-axis indicates runoff, which refers to surface runoff.

The phosphorus concentrations in the infiltrated water increased with increasing build-up levels, ranging from 0.036 to 0.478 mg/l of total phosphorus (Figure 7). The effect of rainfall intensity is more noticeable for the tests performed under one-month build-up levels, i.e. for this degree of accumulated dust, the phosphorus concentration was clearly higher in the high intensity simulation (0.045 mg TP/l on average for the low intensity tests versus 0.19 mg TP/l for the high intensity tests). For the six-month build-up level, the rainfall regime also influenced the concentration of phosphorus in infiltrated water, since considerably higher concentrations were reached in tests under the Mediterranean regime and high intensity (about 0.45 mg TP/l), compared to those of the Atlantic regime. The surface runoff produced in the high intensity tests presented a concentration much higher (0.87 mg TP/l) than that of the infiltrated water (0.46 mg TP/l). This result highlights the environmental benefit of infrastructures like permeable pavements, which help to reduce the surface runoff thus protecting the receiving waters. This reduction of phosphorus loads into the receiving waters is especially important in the case of lentic fresh water bodies, since phosphorus is normally the nutrient limiting the eutrophication process. The value established to classify water bodies in good status is 0.16 mg P/l (RD 817/2015). This value was exceeded in simulations performed at 6-month build-up level for Mediterranean rainfall regime and, in the case of the high intensity test, both in the infiltrated water and in the surface runoff.

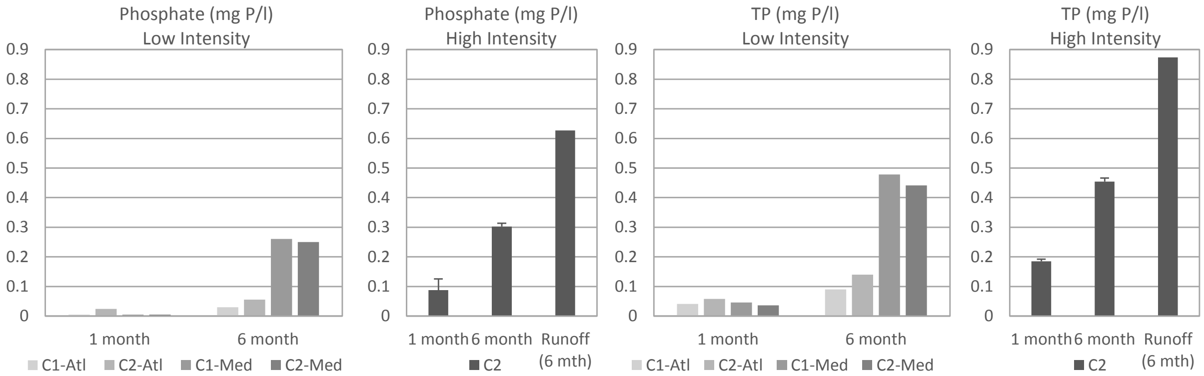

Figure 7. Phosphorus forms in the different assays performed (C1: configuration type 1; C2: configuration type 2; Atl: Atlantic rainfall regime; Med: Mediterranean rainfall regime; Low intensity: 16 mm/30 min; High intensity: 22 mm/10 min). All values refer to infiltrated water except when the x-axis indicates runoff, which refers to surface runoff.

The complete data series of water quality variables obtained in the average rainfall regime tests are shown in Figure 8. COD, TN and TP increased over time, especially in infiltrated water from the pavements subjected to Mediterranean rainfall regime, where the concentrations were significantly higher than those from Atlantic regime ($p<0.05$). This increasing trend is considered to be associated with the increasing pollution build-up level on the pavements surface. The reason for the greater increase in the infiltrated water under Mediterranean regime is thought to be related to the lower rainfall frequency, so that the mobilized pollutants are concentrated in a smaller volume of infiltrated water. Conversely, TSS presented a decreasing pattern over time mainly related to the washing of the gravel that composes the pavement layers, as previously commented. For this variable, as in the previous ones, the concentration reached in the infiltrated water in pavements under Atlantic regime was significantly lower than that under Mediterranean regime ($p<0.05$).

In addition, two surface runoffs potentially generated were chemically characterised: one for the Atlantic rainfall regime with a dry antecedent period of one week, and another for the Mediterranean regime with two weeks of antecedent dry period. The results respectively obtained were the following: 139.8 and 344.5 mg COD/l, 154.4 and 380.3 mg TSS/l, 0.038 and 0.088 mg NH_4^+-N/l, 0.021 and 0.027 mg NO_2^--N/l, 0.69 and 0.80 mg NO_3^--N/l, 1.72 and 2.78 mg TN/l, 0.099 and 0.213 mg PO_4^{3-}-P/l, 0.969 and 1.720 mg TP/l. On average, these values were significantly higher than those reached in the infiltrated water ($p<0.05$) (Figure 8) when the complete data series is considered, even including those obtained after 6 month of pollution build-up. These results reveal the great benefit of this kind of SUDS.

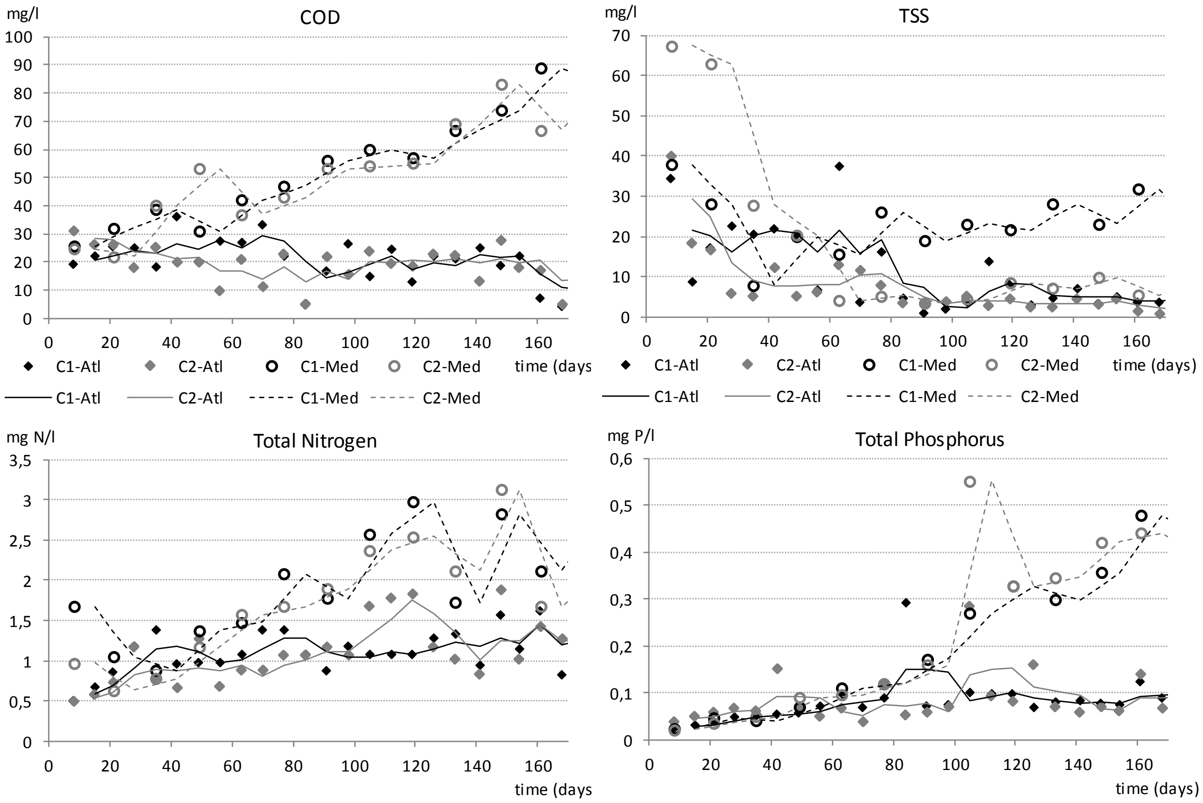

Figure 8. Temporal evolution of water quality variables in infiltrated water for the average rainfall regimes (C1: configuration type 1; C2: configuration type 2; Atl: Atlantic rainfall regime; Med: Mediterranean rainfall regime). Dots represent the data and lines the moving average with a period of three data.

So far, the results obtained have been analysed for the concentration of different variables, but it is also important to analyse the results in terms of released mass load. Table 4 shows the percentage of mass leached within the infiltrated water with respect to the total mass present in the dust and dirt accumulated on the pavement surface. It can be seen that the mass released was relatively low, TN being the most easily leached contaminant with 25% of the total mass released. This result also indicates that in the pavements subjected to the Atlantic rainfall regime, with a higher rainfall frequency, the percentage of pollutants released compared to the total deposited on the surface was greater than in pavements under the Mediterranean regime. That is, although the concentration of the different variables was greater in the water filtered in the Mediterranean regime pavements, as the filtered volume was considerably lower, the total mobilized mass was lower than in the Atlantic climate pavements. In general, in the tests carried out under conditions of low rainfall intensity, the percentages of mass released increased as the degree of pollution increased. In the high rainfall intensity tests the opposite occurred: the percentage of mass released was greater in the one-month build-up level. With respect to the pavement configuration, in general the mass leached from the pavements with complete configuration (C1) is lower than that from the simple configurations (C2).

The leaching capacity of the different types of rainfall tested was calculated by dividing the mass released by the mass of dust and dirt deposited and the total volume of rainfall applied. These results, also presented in Table 4, indicate that when the amount of dust and dirt deposited was lower (1 month) the rainfall was able to leach more pollutant per unit mass and volume. The results also show that when it rained intensely, the mobilization and filtration of pollutants was greater than in low intensity conditions, for both degrees of build-up. So, it is highly recommendable to perform an adequate cleaning program with higher frequency during times of heavy rainfall.

Table 4. Pollutants released in the water infiltrated in the different pavement configurations, rainfall regimes and intensities.

Rain intensity	Config.	Build-up (months)	TSS (%)	TSS (mg/kg/l)	COD (%)	COD (mg/kg/l)	TN (%)	TN (mg/kg/l)	TP (%)	TP (mg/kg/l)
Low Intensity	C1-Atl	1	0.4	273.2	10.8	328.9	12.1	10.2	2.5	0.5
	C1-Atl	6	0.3	35.5	12.7	64.7	25.0	3.5	8.4	0.3
	C2-Atl	1	0.5	331.1	12.2	374.4	9.7	8.2	3.6	0.7
	C2-Atl	6	0.2	24.8	12.4	63.0	24.9	3.5	8.6	0.3
	C1-Med	1	0.2	282.3	4.2	258.8	6.8	11.5	0.9	0.3
	C1-Med	6	0.2	51.3	11.8	120.0	15.6	4.4	7.3	0.5
	C2-Med	1	0.7	915.3	5.3	326.1	6.4	10.8	1.2	0.4
	C2-Med	6	0.2	47.4	13.7	139.7	17.0	4.8	9.8	0.6
High Intensity	C2	1	0.1	156.3	7.1	641.7	8.7	21.8	7.5	4.2
	C2	6	0.1	54.3	3.7	168.5	5.6	7.0	4.0	1.1

Note: the columns of percentages are the mass of pollutant released with respect to the total mass present in the dust and dirt deposited on the pavement surface; the columns expressed in mg/kg/l represent the mass of pollutant released per mass of dust and dirt deposited and volume of rain applied.

Conclusions

Permeable pavements can significantly control runoff production at source, reducing the negative impacts on sewage systems and favouring the infiltration of water into the ground. The quality of the infiltrated water is much better than that of the surface runoff generated from an impervious pavement. Therefore, the impact on the receiving water bodies is significantly reduced thanks to the reduction in the pollutant load received: lower concentration and lower volume. Nevertheless, a non-negligible load of nutrients is released with the drained water, so the installation of reactive barriers in the gravel layers would contribute to further improving the quality of infiltrated water. In this regard, the potential creation of anoxic zones by regulating outflows would contribute to a reduction in the concentration of nitrates in the effluent and favour the infiltration of water into the ground.

The infiltrated water gives high initial values of electrical conductivity and pH that decline as the pavement is washed repeatedly over time. Six months after installation, the characteristics of the filtered water make it suitable for irrigation in terms of salinity, pH and content of organic matter and nutrients, if permeable pavements are planned to be used as rainwater harvesting systems. Therefore, the manufacturing processes should pay attention not only to hydraulic and structural aspects but also to aspects related to the quality of infiltrated water.

The results also demonstrate that an adequate cleaning program in dry conditions is essential, especially when high rainfall intensities are forecasted, since the capacity for mobilization and infiltration of pollutants is greater in these conditions. This is a key issue for the near future, as more intense and frequent extreme precipitations are expected.

Finally, a complete configuration in permeable pavements provides a capacity to retain larger water volumes under Mediterranean climate: the greater the thickness of the gravel layer, the greater the reduction of the effluent volume achieved and the lower the contaminant load that reaches the receiving environment. As the complete pavement configuration reduces the flows to a greater extent it is considered that the probability of generating surface runoff will also be lower. Therefore, in cases where the structural resistance requirements might not necessitate a complete configuration, such as in pedestrian zones, the environmental benefits of the complete configuration are such that they can eventually compensate a higher construction cost.

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