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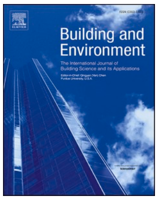

Comparison of permeable pavements effluent under Atlantic and Mediterranean rainfall regimes: A mid-term laboratory experience

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A R T I C L E I N F O

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A B S T R A C T

Sustainable Urban Drainage Systems (SUDS) can take many forms, but the main idea is to manage and use rainwater close to where it falls, i.e. at source. Permeable Pavements (PPs) are a specific type of SUDS aimed to laminate a rainfall event and reduce runoff pollution. This study describes the influence of dust accumulation, rainfall regime and the pavement configuration in the quantity and quality of infiltrated water in mid-term operation period (one or two years). The total drained volume has not been significantly different between PP configurations, but PPs under the Mediterranean (MED) rainfall regime are able to retain more volume (from 4.48 to 9.85 l/m^2) than those under Atlantic (ATL) regime (from 1.32 to 8.82 l/m^2). Regarding the quality results, initial values of pH and Electrical Conductivity (EC) in water infiltrated were considerably high and decrease with the number of washings, therefore more quickly under Atlantic rainfall regime (pH values from 11.5 to 7.8 and EC values from 2200 to 110). The water infiltrated from PPs subjected to a Mediterranean rainfall regime contain higher concentrations of all the pollutants studied (the higher values for ATL of COD, TSS, TN and TP were 37.5, 15.1, 2.41 and 0.300 respectively; while for MED were 97.0, 31.8, 4.73 and 0.637). PO_4^{3-} concentration exceeds the cut-off value in legislation of 0.16 mgP/l since the four months of operation for Mediterranean regime. The results suggest that it is important to pay attention to phosphorus species (specially in Mediterranean regime) in mid-term operation period of PPs.

1. Introduction

The growth of cities worldwide has led to significant impermeability of land surfaces and loss of existing vegetation, which alter the natural water cycle. When a rainfall event occurs in a natural landscape, water infiltrates the soil, evaporates, is taken up by plants (evapotranspiration), and sometimes enters rivers. In contrast, in urban areas, a large amount of rainwater becomes surface water (runoff). The consequences of this urban waterproofing (pollution and erosion problems) are increased by conventional drainage systems because their design focuses on rapid water evacuation to receiving waters. The capacity of these conventional systems is often compromised by the increase in impermeable areas that produces larger amounts of runoff, which are expected to increase further owing to climate change [1].

Sustainable urban drainage systems (SUDSs) are an alternative to prevent soil sealing. They can take many forms, but the main idea is to manage and use rainwater close to where it falls, i.e. at the source. The pillars of SUDS design are as follows: control the quantity of runoff, manage the quality of runoff to prevent pollution, create and sustain better environments for people, and create and sustain better environments for nature [2].

Permeable pavement (PP) is a specific type of SUDS. Many studies, conducted during the last 15 years, have shown the hydraulic benefits of PP, such as the reduction of surface runoff and peak flow attenuation, reduction of combined sewer overflows, improved groundwater recharge [3], and mitigation of the urban heat island effect [4–7]. However, there is less research on the second pillar of SUDS design (water quality), although the number of studies has increased in recent years [8–12]. Several aspects that remain to be studied are the influences of the rainfall regime and seasonality (especially in semi-arid zones), the influences of long-term removal processes, and the risk of mobilisation of captured pollutants.

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Research on the quality of water infiltrated through PP has shown that this type of pavement can alter the overall quality of stormwater by filtering materials and dissolving substances. First, construction materials can provide alkalinity, thereby increasing the water hydrogen potential (pH). The most alkaline infiltrated water is associated with porous asphalt pavements (PAs), followed by porous concrete pavements (PCs) and permeable interlocking concrete pavements (PICPs) [12]. These high levels are characteristics of newly exposed materials and do not persist after the materials are exposed to rain events [8,9,13,14]. The biological processes within the PP are limited by pH. pH values from 7.0 to 9.5 provide a suitable environment for nitrification bacteria [12]. Nitrogen can be transformed through biologically mediated processes within PPs if aerobic conditions are also possible [ammonium (NH_4^+) can be nitrified into nitrites (NO_2^-) and the into nitrates (NO_3^-)]. However, the denitrification of NO_3^- into N gas does not seem to occur; thus, this biological process requires anoxic conditions, which are unlikely to exist in PPs as they are designed to be free-draining [9]. Hydraulic detention times of at least 24 h are recommended for denitrification [15]. Second, higher pH values are related to lower phosphate (PO_4^{3-}) concentrations in the infiltrated water [12]. recorded a lower PO_4^{3-} concentration in PA outflow, which was much more alkaline than that of PC and PICP. Furthermore [9], showed that high PO_4^{3-} values in filtered stormwater are also associated with an alkaline environment, which was attributed to salt application during winter.

Multiple studies have demonstrated the significant role of PPs in pollutant removal. These systems are generally considered a good type of SUDS for removing total suspended solids (TSS), thereby resulting in higher removal efficiencies. Furthermore, TSS can be used to evaluate the particulate organic and inorganic pollutant retention by PPs (Kamali et al., 2016) [16]. also demonstrated that geotextile layers installed in PPs can increase the TSS removal efficiency by approximately 30%. Vehicle traffic is one of the main sources of pollution in urban areas. Thus, metals are often one of the primary sources of pollutants in urban runoff [17]. Typical metals found in storm runoff are copper (Cu), lead (Pb), aluminium (Al) and zinc (Zn) among others. PPs have also demonstrated significant removal of these pollutants (mainly by adsorption by pavement section materials), thereby preventing them from reaching the natural environment [9,10,17–19].

Most of the above-mentioned studies were performed in humid rainfall climates where rainfall is frequent and the rainfall intensity is usually low. However, PPs may be especially useful in semi-arid climates, such as the Mediterranean, where rainfall is intense and the rainfall frequency is very low and uneven throughout the year. In the Mediterranean rainfall regime, significant rainfall occurs within a short period, often resulting in surface runoff accumulation which hinders the daily activities in cities. In these cases, a significant amount of pollutants that have been deposited on the city surface for a long time are removed by runoff. Although SUDSs have been explored since the 90s, Mediterranean countries have improved their knowledge and experience in these urban drainage systems in the last 10 years. Research on the application of SUDSs in Mediterranean areas is still limited, representing 12% of the total research in Europe [20], especially regarding infiltrated water quality and long-term performance.

Quantity characterisation and modelling of runoff produced in SUDSs under the Mediterranean rainfall regime have been conducted by numerous researchers in the field [21–25], which obtained runoff reductions ranging from 40% to 100%. The quality characterisation of runoff has been a less-studied aspect of this climate [24,26]. agree on the important influence of the antecedent dry period, especially in semi-arid rainfall regime [27]. highlighted the need to control runoff quality at its source and separately from wastewater because of their different characteristics, and introduce the idea of including SUDSs in urban areas, which should be designed using water quantity and quality criteria.

Even fewer studies have focused on SUDS outflow data under the Mediterranean rainfall regime because SUDS monitoring is scarce [1,28]. showed the quantity and quality results of treated water by different types of SUDS constructed in the province of Valencia. The results demonstrated the effectiveness of the systems in terms of runoff reduction (peak flows and volumes) and water quality improvement under this rainfall regime. These studies also revealed that high loads of pollutants can be detected when SUDSs begin to work owing to the combination of residuals from the construction process or after a very long antecedent dry period. The studies could not characterise the quality of treated water more deeply (e.g. seasonability) because of their short data series. However, they are a good start for future studies on Mediterranean rainfall regime.

The effects of rainfall intensity and pollution build-up levels (dust and dirt accumulated on the pavement surface) on the water quality and quantity response of PPs under the Mediterranean rainfall regime were analysed by Ref. [29]. The authors demonstrated that an adequate cleaning program is essential to preserve the effectiveness of PPs, especially when high rainfall intensities are forecasted because the capacity for mobilisation and infiltration of pollutants is greater under these conditions.

All these studies have demonstrated that SUDSs are drivers of innovation and the transition towards a new stormwater paradigm for urban areas in the Mediterranean [1]. Nevertheless, more research should be performed to gain knowledge about the mid-term and long-term performances of SUDSs under semi-arid conditions.

This research raises the following hypotheses: the permeability and infiltration velocity in PPs are reduced over time if no cleaning is applied, and this effect is more important in the Mediterranean rainfall regime; water infiltrated through PPs has better quality than surface runoff water in the mid-term; the Mediterranean rainfall regime presents higher pollutant concentrations than the Atlantic rainfall regime; and finally, under the Mediterranean rainfall regime, a longer antecedent dry period between rainfall events should produce more important soiling of PPs over time, thereby decreasing the hydraulic and pollutant removal efficiencies of the pavement. Therefore, the main objective of our work is to quantify how PPs affect surface and ground water bodies in the medium-term depending on the rainfall regime. To this end, the quantity and quality of water infiltrated through PPs tested under Atlantic and Mediterranean rainfall regimes were compared. In addition, a secondary objective is to collect a robust dataset of the quantity and quality characteristics of water infiltrated through PPs to define, calibrate, and validate in the future a numerical model to better understand the pollutant removal capacities of these systems.

The main abbreviations used in the text are included in Table A.1 in Appendix A.

2. Materials and methods

2.1. Materials

The experimental setup consisted of a battery of five laboratory-scale infiltrometers. Each infiltrometer is shown in Fig. 1 (A). The chambers containing the pavement profiles were Plexiglass containers (bottom dimensions of 50 × 50 cm and height of 50 cm). Two pavement layer configurations were tested: full configuration (C1) and simple configuration (C2). Both sections are illustrated in Fig. 1 (D1 and D2). Configuration C2 had the same layers as C1, except for the bottom layer of washed limestone aggregate of 4–40 mm. The layer types and their construction thicknesses for the laboratory-scale porous modular pavement were chosen according to the CIRIA report [30] considering a traffic category of 3 (small car parks subject to cars, light vans, and motorcycle access) for C1 and 0 (no vehicular traffic) for C2. Moreover, the partners of the research project, which frames the works described in section 2.2, used these pavement sections, obtaining satisfactory results [31]. Both configurations were tested to understand the role of the aggregate layer. When the traffic load is not high (e.g. on sidewalks), the aggregate layer is dispensable because less structural strength is required. Considering the ICPI recommendations, bedding and sub-base

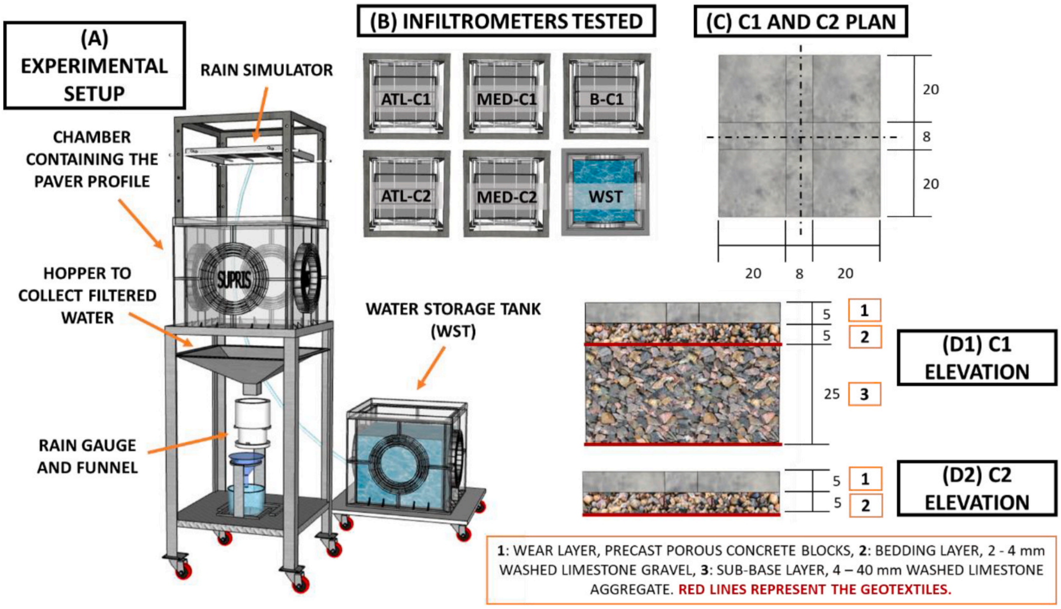

Fig. 1. Scheme of experimental setup (A), scheme of the five infiltrometers tested and the water storage tank (B), plan of both configuration C1 and C2 (C) and elevations of pavement configurations tested (D1 for C1 configuration and D2 for C2 configuration).

layer materials were selected. A 4–40 mm washed limestone aggregate was selected as the sub-base because it is very stable under construction equipment and has a high water storage capacity with a porosity of approximately 40%. A 2–4 mm washed limestone aggregate was used for the bedding layer, which also had a porosity of approximately 40%. The precast porous concrete blocks were characterised by high hydraulic conductivity values (Ks = 1.67 cm/min) and a porosity of approximately 20%. According to the information provided by the manufacturer, the components used in its production are: siliceous arid, white and grey cement, plasticiser, and water-repellent additives and pigments (iron oxides). For the wear layer construction, porous concrete blocks of different sizes were used, namely four blocks of 20 × 20 × 6 cm, four blocks of 20 × 8 × 6 cm, and a central block of 8 × 8 × 6 cm (Fig. 1 (C)). Thus, the construction of the PP was adapted as closely as possible to the dimensions of the chamber. The remaining 2 cm between the chamber wall and pavement section were sealed with silicone to avoid unwanted flows. Finally, two geotextile layers were used, namely a separation geotextile between the bedding and sub-base layer in C1, and a retention geotextile under the sub-base layer in C1 and under the bedding layer in C2 to avoid scouring of the fine aggregates. Both geotextiles had the same characteristics: nonwoven polypropylene-based geotextiles with a thickness of 0.15 mm, opening size of 0.09 mm, and vertical permeability of 90 mm/s. The rainfall simulator was based on that described by Ref. [31] and was composed of a water storage tank, a pump, and a grid of irrigation pipes consisting of 7 rows with 13 drippers per row evenly distributed and placed 50 cm above the pavement surface (Fig. 1 (A)). Care was taken to ensure that the mesh pipes were in the same horizontal plane so that a uniform distribution of rainfall on the pavement surface could be achieved. The rainwater was pumped from the storage tank and the pumped flow was regulated by a valve. The tank level was measured using a piezometer. During the test, the tank level was continuously checked every 5 min to ensure that the desired rainfall speed was achieved and corrected otherwise. A rain gauge was positioned below each PP to measure the infiltrated water flow, which was then collected and stored in a refrigerator until chemical analysis was performed, in less than 24 h. Before each event, it was experimentally verified that the rain gauge complied with the manufacturer's specifications (each tipping bucket was equivalent to a 2 mL volume of water). After each test, the total volume of infiltrated water collected was checked to ensure that it matched the total volume recorded by the rain gauge.

Deionised water was used [electrical conductivity (EC) of 10 μS/cm and pH of 7.1] to simulate rainwater. Real dust and dirt deposited on urban roads were used to simulate the build-up of pollution. They were collected by the university road cleaning services (Universitat Politècnica de València - UPV), using a mechanical sweeper under dry conditions. The main characteristics of the dust are listed in Table 1. More detailed information on the original deposited dust and dirt, such as the particle size distribution, is available in the study by Ref. [29].

2.2. Methods

2.2.1. Experimental methods

Two rainfall regimes, namely the Atlantic and Mediterranean, were statistically analysed [32]. The simulated rainfall reproduced the average rainfall regime of the city of Valencia, which represents Mediterranean rainfall conditions, and the city of Santander, which represents Atlantic rainfall conditions, in Spain. The events had a rainfall volume of 16 mm and a duration of 30 min (32 mm/h), with a weekly frequency for the Atlantic rainfall regime and a biweekly frequency for the Mediterranean rainfall regime [32]. Thus, the annual rainfall in the Mediterranean regime was half of the annual rainfall in the Atlantic regime. This simplified representation of both rainfall regimes is particularly useful for comparing the quantity and quality of the water infiltrated through PPs, thereby avoiding uncertainty regarding the temporal characteristics of the rainfall pattern, which are beyond the

Table 1
Characterisation of the dust and dirt used in the tests.

Physico-chemical variables	Average ± Stnd.Dev.	Particle size distribution (%dw)	Average ± Stnd. Dev.
Moisture (%dw)	2.02 ± 0.00	Gravel (>2 mm)	13.2 ± 0.6
COD (mg/g)	48.9 ± 3.1	Sand (0.063–2 mm)	85.0 ± 0.5
Total nitrogen (mg/kg dw)	1351 ± 197	Silt and clay (<0.063 mm)	1.8 ± 0.0
Total phosphorus (mg/kg dw)	302.5 ± 18.5		
Electrical conductivity (μS/cm)	890 ± 103		
pH	8.0 ± 0.1		

scope of this research. Each rainfall regime was tested in two infiltrometers, one with configuration C1 and the other with configuration C2. An additional infiltrometer with configuration C1, but without dust deposition, was used as the control (B–C1) (Fig. 1 (B)). The experiments were planned to be mid-term tests starting in January 2017 and lasting one year for PP with configuration C2 and two years for PP with configuration C1.

After each event, water filtrated through each PP was collected, refrigerated, and analysed. The physicochemical variables analysed were chemical oxygen demand (COD), biological oxygen demand at 20 days (BOD_{20}), total and volatile suspended solids (TSS and VSS), ammonium (NH_4^+), nitrites (NO_2^-), nitrates (NO_3^-), total nitrogen (TN), phosphates (PO_4^{3-}), total phosphorus (TP), aluminium (Al), zinc (Zn), turbidity, hydrogen potential (pH), electric conductivity (EC), dissolved oxygen (DO) and dissolved oxygen saturation (%satDO) and temperature. The standardised methods used for these physicochemical analyses are listed in Table A.2 of Appendix A.

The influence of progressive pollution build-up was studied by sprinkling dry sediment on the pavement surface. The applied deposition rate (5 $g/(m^2 \cdot d)$) was selected according to the information provided by the cleaning services and checked against references (15.00–20.00 g/m^2 was measured after two dry days by Refs. [33,34] obtained values of 1.50–2.45 g/m^2 of particles smaller than 0.150 mm for the first dry day and values of 0.25–0.30 g/m^2 for particles larger than 0.150 mm for the same dry time, and [35] recorded values of 0.45–2.38 g/m^2 after the first dry day). This verification with other studies was largely conducted by Ref. [29]. The deposition rate was the same for all the tests and was kept constant throughout the research period to evaluate the response of the PP to a surface overload of pollutants. After one year of operation, the surface of the PP was cleaned with a domestic vacuum cleaner and a brush for both configuration C2. The same was conducted for Atlantic configuration C1 after two years of operation. After cleaning, permeability tests were conducted using an LCS permeameter (according to the protocol described in **NLT-327/00** [43]) on each of the cleaned infiltrometers and B–C1. These tests were conducted for each infiltrometer at the 3–4 spots on the pavement surface.

2.2.2. *Statistical methods*

Statistical analyses were performed using the RStudio environment (version 1.3.959), which was integrated into the programming language R. The effects of the rainfall regime and pavement configuration on the results were analysed by comparing the time data series of each infiltrometer. Boxplot diagrams were represented separately for the first and second years of trials to visually detect possible differences. Moreover, the Mann - Kendall trend test was used to identify the total drained volume series, outflow physicochemical parameter series, and outflow concentration series trends over time with AM over PPs.

The statistical tests used were parametric if normality was satisfied (Student's t-test for related variables or Student's *t*-test for independent variables) and non-parametric otherwise (Wilcoxon's test for pairwise or Mann - Whitney test for nonrelated variables). Statistical significance was indicated by a probability of a type I error of 5% or less ($p \leq 0.05$). Because all the infiltrometers were located in the same laboratory and were tested under the same conditions, the samples were considered to be related. The time series of each year was considered independent only when the years of trials were compared.

Linear correlations between the variables were obtained using Pearson (with normal distribution variables) or Spearman (in the opposite case) correlation coefficients. For both the linear correlation analysis and the Mann-Kendall trend test, it was assumed that the coefficients were statistically significant with a probability of a type I error of 5% or less ($p \leq 0.05$).

When the chemical analysis presented values below the method detection limit, which only occurred for metal concentrations, half of the detection limit was assigned [36].

3. Results and discussion

3.1. *Mid-term water quantity performance*

Boxplot diagrams of the total drained volume in l/m^2 of pavement for each PP tested are shown in Fig. 2. From a total rainfall volume of 16 l/m^2 in each event, the total drained volumes were approximately 11 l/m^2 and 9 l/m^2 for the Atlantic and Mediterranean rainfall regimes, respectively. The total drained volume was significantly higher under the Atlantic regime for both configurations and during the two years of performance ($p < 0.05$). A higher previous dry period in the Mediterranean rainfall regime allowed greater retention of rainfall within the PP section, thereby indicating the importance of evaporation processes in PP performance. In contrast, there were no significant differences between the pavement configurations ($p > 0.05$). The extra level of aggregates in configuration C1, because of its coarser granulometry (particles of 4–40 mm), did not provide more retention in the PP section. Comparing both years, the total drained volume was not significantly different under the Atlantic and Mediterranean rainfall regimes ($p > 0.05$). All the p-values of the total drained volume significance analyses are presented in Table A.3 of Appendix A. No significant differences were observed between the total drained volumes during the first and second year of tests. The Mann - Kendall test also showed that there were no temporal trends in the total drained volume through PPs under the Atlantic and Mediterranean rainfall regimes, with coefficients of 0.1260 and 0.0048, respectively (both significant).

Regarding the hydraulic conductivity results, Table 2 shows that before operation a permeable pavement (B–C1) has a very high hydraulic conductivity (>180 mm/h) according to the classification proposed by the U.S. Soil Conservation Service. After one year of operation without cleaning, the hydraulic conductivity decreased to a lower order of magnitude (approximately 100 mm/h) under both rainfall regimes. After this period, the value seemed to stabilise or slightly increase (similar values of ATL-C2-Y1, MED-C2-Y1 and ATL-C1-Y2). Moreover, the PP sections presented important hydraulic conductivity variability depending on the measured point, which indicates the heterogeneity of the concrete blocks studied. At the end of the testing period, at least 75% of the points of ATL-C2-Y1, MED-C2-Y1 and ATL-C1-Y2 had hydraulic conductivities between moderately fast (120–180 mm/h) and moderate (60–120 mm/h).

The hydrographs of infiltrated water obtained for 12 months of pollution build-up in the different infiltrometers are shown in Fig. 3 (A). Configuration C1 demonstrated better rainfall damping behaviour than configuration C2, with lower peak flows, longer drainage times, and lower total drained volumes (the total drained volumes in infiltrometers ATL-C1, ATL-C2, MED-C1, and MED-C2 were 10.8, 12.2, 8.8, and 9.7 l/m^2, respectively). Moreover, PPs under the Mediterranean rainfall

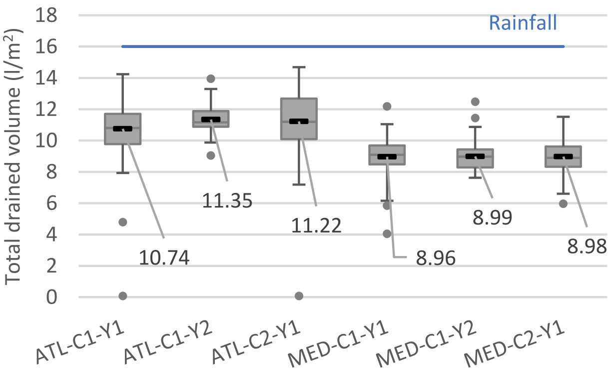

Fig. 2. Total drained volume boxplots diagrams. The numerical value of the averages is included in the graph. ATL-C1-Y1 (n = 53), ATL-C1-Y2 (n = 43), ATL-C2-Y1 (n = 52), MED-C1-Y1 (n = 27), MED-C1-Y2 (n = 24) and MED-C2-Y1 (n = 27).

Table 2
Hydraulic Conductivity for each corner of the pavement surface and average ± standard deviation in mm/h, of ATL-C2 and MED-C2 (cleaned after one year of performance), ATL-C1 (cleaned after two years of performance) and B–C1 (never soiled). N is the number of replicas.

Infiltrometer	Replica 1	Replica 2	Replica 3	Replica 4	Average ± Stnd. Dev (n)
ATL-C2-Y1	85.7	60.8	83.0	–	76.7 ± 13.7 (3)
MED-C2-Y1	32.9	102.5	100.3	78.9	78.6 ± 32.3 (4)
ATL-C1-Y2	79.6	202.6	88.4	27.1	99.4 ± 73.9 (4)
B–C1	1660.3	1134.9	270.0	471.7	884.2 ± 635.8 (4)

regime took longer to drain and retained more rainfall, because of the longer antecedent dry period.

For two years without maintenance, rainfall tended to drain more quickly through the PPs (Fig. 3 (B)). Although the volume drained during rainfall events was similar for the first and second years, this volume drained faster as the pavement clogged. In the one-year rainfall event, 90% of the drained volume was evacuated at 114 min (under the Atlantic rainfall regime) and 161 min (under the Mediterranean rainfall regime), whereas in the two-years rainfall event, these values decreased to 67 min and 135 min, respectively (Table A.4 of Appendix A). The slight increase in the hydraulic conductivity of configuration C1 in the second year of trials (Table 2), could also support the above idea. The infiltration of dirt particles deposited on the pavement surface might have caused preferential paths, which reduced the rainfall drainage time. However, no clear increase in the peak of the hydrograph was

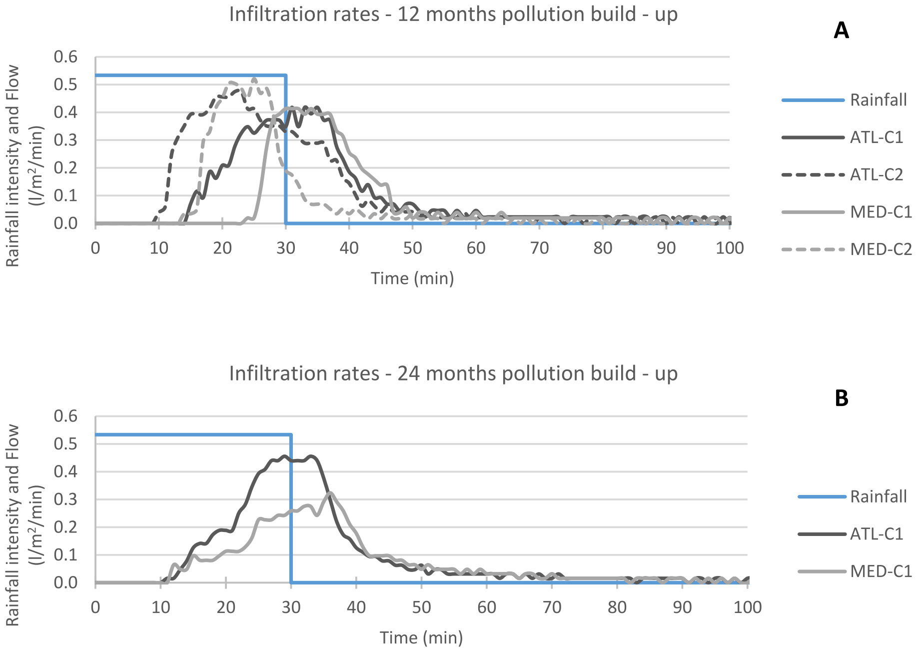

Fig. 3. Hydrographs of infiltrated water through the PP under Atlantic and Mediterranean rainfall events, after an operation time of 12 months without maintenance (A) and 24 months without maintenance (B).

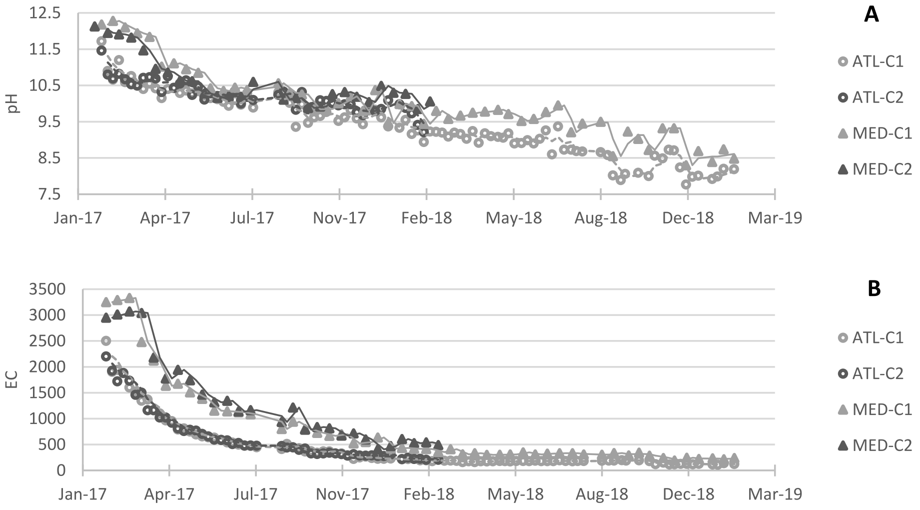

Fig. 4. Temporal evolution of pH (A) and EC (B) in filtrated water through the four infiltrometers tested. Dots represent the data (two years for C1 and one year for C2) and lines the moving average with a period of three data. ATL-C1-Y1 (n = 52), ATL-C1-Y2 (n = 43), ATL-C2-Y1 (n = 52), MED-C1-Y1 (n = 27), MED-C1-Y2 (n = 24) and MED-C2-Y1 (n = 27).

observed during the tests.

There was no runoff production during the tested period in any of the infiltrometers, which was because the rainfall intensity (32 mm/h) was much lower than the hydraulic conductivity of the PPs during both years of testing (Table 2).

3.2. *Effluent water quality characterisation*

3.2.1. *Physicochemical variables*

The initial pH values were considerably high, as shown in Fig. 4 (A). These values must have originated from the pavement materials (precast concrete blocks in particular) because the values decreased over time owning to the repeated washing of the materials regardless of the rainfall regime or configuration. pH values near 9 were reached after approximately the 50th wash (with a rainfall volume on the PPs of 800 l/m^2), after one year under the Atlantic regime and one year and ten months for the Mediterranean regime. The maximum value was 12.3 (MED-C1) and the minimum value was 7.8 (ATL-C1). Similar pH values were obtained by Refs. [8,12,13] and [14]; very high values were recorded throughout the first events, and then they gradually stabilised [9]. concluded that the high pH levels in the PC and PICP effluents are characteristic of newly exposed concrete but do not persist after the concrete is exposed to rain events. The Mann - Kendall trend test confirmed this observation with the following coefficients: 0.859 (ATL-C1; n = 95), −0.813 (MED-C1; n = 51), −0.743 (ATL-C2; n = 51) and −0.611 (MED-C2; n = 27), all of which were significant. Infiltrometers subjected to the Atlantic rainfall regime showed a slightly greater decline over time and higher Mann - Kendall coefficients because the higher the rain frequency, the more the pavement was washed.

The EC outflows showed a similar behaviour, with very high values at the beginning of the tests and a decrease as the PP was washed. However, while the decrease in pH was fairly linear, the EC decreased rapidly with an exponential trend (Fig. 4 (B)). For this variable, the Mann - Kendall trend coefficients had values of −0.811 (ATL-C1; n = 95), −0.878 (MED-C1; n = 51), −0.951 (ATL-C2; n = 51) and −0.863 (MED-C2; n = 27).

The temperature of the outflows varied from 17.0 °C in the coldest moths (January and February) to 27.5 °C in the hottest months (July and August). Aerobic conditions were detected in all the infiltrometers during both years of tests. Furthermore, in all cases (for both regimes and configurations), leached water had DO values higher than 5 mgO$_2$/l, which classifies water bodies as high status according to the Spanish legislation (RD 817/2015 [47]). In addition, the %satDO only reached values lower than 70.0% (cut-off value in RD 817/2015 [47]) in July 2017 (66.6%). For all the infiltrometers tested, the %satDO values varied from 5.50 mgO$_2$/l (66.6% of saturation) to 10.25 mgO$_2$/l (101.9% of saturation).

3.2.2. *Chemical oxygen demand (COD) and biological oxygen demand (BOD)*

Fig. 5(A) and (B) shows boxplots of the COD and BOD$_5$ concentrations, respectively. These concentrations under the Mediterranean rainfall regime were significantly higher than those under the Atlantic rainfall regime, mainly during the first year. As observed with the pH and EC, a higher rainfall frequency in the Atlantic rainfall regime diluted more the pollutants deposited on the pavement surface. The higher values shown in Fig. 5(A) and (B) correspond to the leached concentrations associated with the hottest months of the year, previous dry

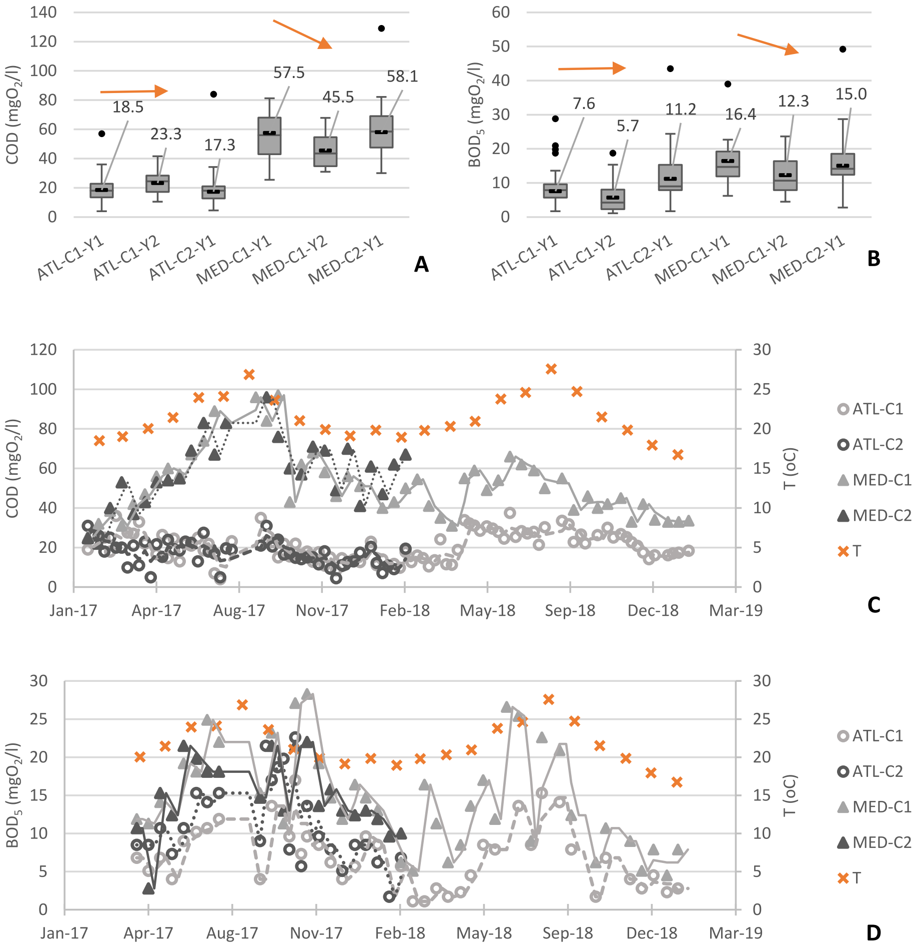

Fig. 5. Boxplot diagrams for Chemical Oxygen Demand (COD – Figure A) and Biological Oxygen Demand at 5th day (BOD$_5$ – Figure B) concentrations. The numerical value of the averages is included in the graph. The orange arrows represent the evolution observed between years. For COD: ATL-C1-Y1 (n = 52), ATL-C1-Y2 (n = 43), ATL-C2-Y1 (n = 51), MED-C1-Y1 (n = 27), MED-C1-Y2 (n = 24) and MED-C2-Y1 (n = 27). For BOD$_5$: ATL-C1-Y1 (n = 22), ATL-C1-Y2 (n = 21), ATL-C2-Y1 (n = 22), MED-C1-Y1 (n = 22), MED-C1-Y2 (n = 21) and MED-C2-Y1 (n = 22). Temporal evolution of COD (Figure C) and BOD$_5$ (Figure D) in filtrated water through the four infiltrometers tested, represented without outliers. Dots represent the data (from April 2017, when the measurements started, to January 2019 for C1 and from one year for April 2017 to January 2018 for C2) and lines the moving average with a period of three data. Moreover, the mean temperature of the infiltrated water is shown on the secondary axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

periods of more than two weeks (summer holidays), and the first year of trials when higher values of outflow concentrations were recorded. In the earlier dry periods the mass of dust and dirt uncleaned on the PP was higher; however, the PP was able to retain more water and the infiltrated water tended to be more concentrated. Comparing these values with the discharge limits of treated wastewater in Spain (COD of 125.0 mgO_2/l and BOD_5 of 25.0 mgO_2/l in **RD 509/1996** [45], which is a transposition of **Directive 91/271/EEC** [39]), the COD concentration never exceeded this cut-off and the BOD_5 was higher than 25.0 mgO_2/l in August of the first year of trials in all the PPs studied, and only exceeded this value in August with an outflow concentration of 26.6 mgO_2/l in the second year of trials. Furthermore, the COD and BOD_5 outflow concentrations remained generally stable during both years of operation under the Atlantic rainfall regime (for PPs with configuration C1, which were also tested also during the second year). Moreover, the thin boxplots showed little variability of the recorded data. In the effluent from the Mediterranean PP, greater data variability was measured (wider boxplots); conversely, a slight decrease was observed from year 1 to year 2 (with a significant difference between years of $p = 0.025 < 0.050$ for COD and $p = 0.019$ for BOD_5; very similar for BOD_{20}). In addition, Mann - Kendall trend test demonstrated a significant temporal trend for the infiltrometer MED-C1 with the following coefficients: 0.222 (COD), −0.312 (BOD_5) and −0.295 (BOD_{20}). This behaviour in PPs under the Mediterranean rainfall regime might have been due to more significant biodegradation during the second year of tests, owing to more conductive conditions for the process (higher availability of organic matter and pH values between 9.75 and 8.5).

Moreover, the COD and BOD_5 concentrations in the filtered water in the Mediterranean rainfall regime showed some correlations with temperature during both years of PP operation. The correlation coefficients are included in Table A.5 in Appendix. A. The values ranged from 0.668 to 0.453 during the first year and from 0.757 to 0.574 during the second year. The higher correlation between the BOD concentration and temperature reinforced the idea of greater bacterial activity during the second year of tests. Under the Atlantic rainfall regime, no significant correlations were observed between temperature and the COD, BOD_5, and BOD_{20} concentrations. This correlation can be discerned in the temporal series illustrated in Fig. 5(C) and (D).

The BOD_5/COD and BOD_{20}/COD relationships obtained for the effluent of the PPs for all the rainfall regimes and configurations were higher than those of the original dust and dirt deposited during the pavement operation. The deposited mass showed $BOD_5/COD = 0.10$ and $BOD_{20}/COD = 0.20$, whereas the infiltrated water had values near 0.25 and 0.45, respectively. This meant that the most biodegradable organic matter infiltrated the PP (mainly in the soluble state), whereas the most inert organic matter remained on the pavement. If an event whose intensity causes runoff occurs, then the organic matter that could arrive at the surface water bodies would be mainly inert; thus, its effect on the oxygen concentration of the water body would be lower.

The percentages of biodegradable organic matter with respect to total organic matter also showed a significant correlation with temperature, but only during the second year of assays with correlation coefficients of 0.679 (BOD_5/COD; ATL-C1-Y2), 0.513 (BOD_{20}/COD; ATL-C1-Y2), 0.490 (BOD_5/COD; MED-C1-Y2) and 0.375 (BOD_{20}/COD; MED-C1-Y2). The significant relationship between the temperature and BOD/COD during the second year of trials, but not during the first year, reinforces the idea of the development of bacterial activity when the pH conditions were more favourable.

3.2.3. *Total suspended solids (TSS), volatile suspended solids (VSS) and turbidity*

The first events showed significantly high TSS concentrations (Fig. 6 (C)) and turbidity in all the outflows. This was related to the washing of dust remaining on the gravel despite being thoroughly washed before the experiments [9]. also detected important traces of suspended materials (TSS) in water samples collected shortly after the installation of PPs. The Atlantic regime presented a shorter period of material washing than the Mediterranean regime. The higher the rainfall frequency, the greater the dilution capacity of the pollutants. The TSS concentration and turbidity of filtered water were highly correlated, with correlation coefficients of 0.9194 (ATL-C1), 0.8308 (ATL-C2), 0.7667 (MED-C1), and 0.9138 (MED-C2), all of which were significant.

Higher concentrations were recorded in the water that infiltrated the PPs under the Mediterranean rainfall regime and in the water that infiltrated the PP with configuration C1. Although aggregates of the pavement section were washed before construction, some dust could remain within the gravel. Accordingly, the extra aggregate layer in the PP with configuration C1 could contribute to a higher TSS concentration and turbidity in the water that infiltrated through MED-C1. Higher washing in the Atlantic regime might have reduced this effect. Therefore, care must be taken during the pre-washing of the granular materials. Fig. 6(A) and (B) shows these results as box-plots of the time series of the TSS outflow concentration and turbidity for the different infiltrometers tested, with the time series divided into both years of

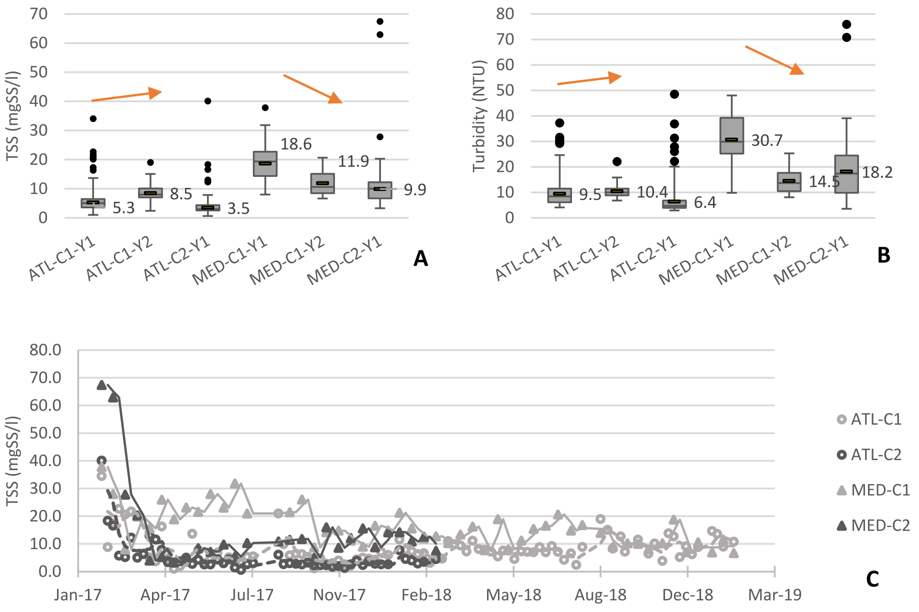

Fig. 6. Boxplot diagrams for Total Suspended Solids concentration (TSS – Figure A) and Turbidity (Figure B). The numerical value of the averages is included in the graph. The orange arrows represent the evolution observed between years. For both variables: ATL-C1-Y1 (n = 52), ATL-C1-Y2 (n = 43), ATL-C2-Y1 (n = 51), MED-C1-Y1 (n = 27), MED-C1-Y2 (n = 24) and MED-C2-Y1 (n = 27). Temporal evolution of TSS (Figure C) and Turbidity (Figure D) in filtrated water through the four infiltrometers tested, represented with the initial washing. Dots represent the data and lines the moving average with a period of three data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

operation for ATL-C1 and MED-C1. The outliers represent the values of the initial washing and the hottest months of the study period (July and August). The comparison between the TSS concentration in the infiltrated water and the discharge limit of treated wastewater in Spain (35 mg SS/l, **Directive 91/271/EEC** [39]), shows that the TSS outflow concentration only exceeded the limit during the start-up period of the PP section materials for all the rainfall regimes and configurations tested.

In the ATL-C1 infiltrometer, the TSS outflow concentration and turbidity seemed to increase smoothly from the first year to the second year of operation, but there were no significant differences between the time series of both years ($p = 0.371 > 0.050$ and $p = 0.863 > 0.050$, for TSS and turbidity, respectively). Instead, these pollutants in the infiltrated water decreased in the MED-C1 infiltrometer. Significant differences were detected between the data of years one and two ($p = 9.22E\text{-}07 < 0.05$ and $p = 2.44E\text{-}07 < 0.05$ for TSS and turbidity, respectively). The Mann - Kendall trend analysis also reinforced this observation with the following significant coefficients: 0.345 (TSS) and 0.275 (turbidity) for ATL-C1, -0.406 (TSS) and −0.513 (turbidity) for MED-C1. The concentration of particles in the water tended to be constant, which was related to the filtration capacity of the PP section regardless of the rainfall regime. After two years the PP filtration capacity was still high. This observation is consistent with the conclusions of other authors in the field. For example [37], found a minimal reduction in the infiltration capacity of PPs after many infiltration tests; from late 2010 to early 2013 [11], found that a smooth reduction in the hydraulic conductivity of 20% occurred after three hydrological years; and [12] did not observe surface clogging issues after an eight-year period of operation in a real permeable parking slot.

The VSS outflow concentration represented an average percentage of TSS of 33% in ATL-C1, 48% in ATL-C2, 35% in MED-C1, and 53% in MED-C2, and its behaviour was similar to that of COD or BOD.

3.2.4. Nitrogen species: ammonium (NH_4^+), nitrites (NO_2^-), nitrates (NO_3^-) and organic nitrogen (ON)

Fig. 7 (A) shows the boxplot diagrams of the TN concentration in the different infiltrometers and years studied. The concentrations of all the nitrogen species in the infiltrated water were higher in the Mediterranean regime than in the Atlantic regime. Moreover, the Mann - Kendall trend analysis did not indicate a significant temporal trend over time of the TN concentration.

The NH_4^+ concentration in infiltrated water was generally below 0.16 mg N/l, which classifies water bodies as high status according to the Spanish legislation (**RD 817/2015** [47]). The average and median values for each infiltrometer and year were 0.046 and 0.036 (ATL-C1-Y1), 0.040 and 0.030 (ATL-C1- Y2), 0.065 and 0.048 (ATL-C2-Y1), 0.058 and 0.048 (MED-C1-Y1), 0.065 and 0.052 (MED-C1-Y2), and 0.059 and 0.048 (MED-C2-Y1), respectively. This limit was raised by MED-C1 in August and September in both years of trials and by ATL-C2 and MED-C2 during these months of the first year of trials. In ATL-C1, the NH_4^+ outflow concentration did not exceed this value during both years of trials. However, the measured NO_3^- concentrations, with a maximum of 2.12 mg N/l (in July and September of year 2), were below the value established to declare vulnerability to NO_3^- contamination (11.30 mg N/l) according to **European Directive 91/676/EEC** [40].

Fig. 7 (B) shows the percentage of nitrogen species. NO_3^- and ON were the predominant forms of TN. The percentage of NO_3^- increased in the second year of the trials. This might have occurred because the pH levels were more appropriate for nitrification ($pH < 9$). Moreover, such the pH levels were lower in the Atlantic rainfall regime, more biological activity of nitrifying bacteria could be developed in this regime, and a higher percentage of NO_3^- represented the TN concentration in the infiltrated water. The increase in the percentage of NO_3^- was accompanied by a slight decrease in the percentages of NH_4^+ and NO_2^-.

Nitrification could have occurred because the PPs were under aerobic conditions during both years of research, as mentioned in Section 3.2.1. Denitrification of NO_3^- into N gas did not seem to occur, because this biological process requires anoxic conditions, which are unlikely to exist in PPs as they are designed to be free-draining [9]. Other authors also examined the capability of PP to nitrify NH_4^+ into NO_3^-. The percentages of N species with respect to TN in the water that infiltrated PICPs found by other authors [9,12] are 4–15% for NH_4^+, 1–2% for NO_2^-, 66–81% for NO_3^- and 7–18% for ON, which are in agreement with the data reported in this study, although a higher percentage of ON was found.

ON was calculated as the difference between TN and inorganic species (NH_4^+, NO_2^-, and NO_3^-). Similar to the rest of the organic variables

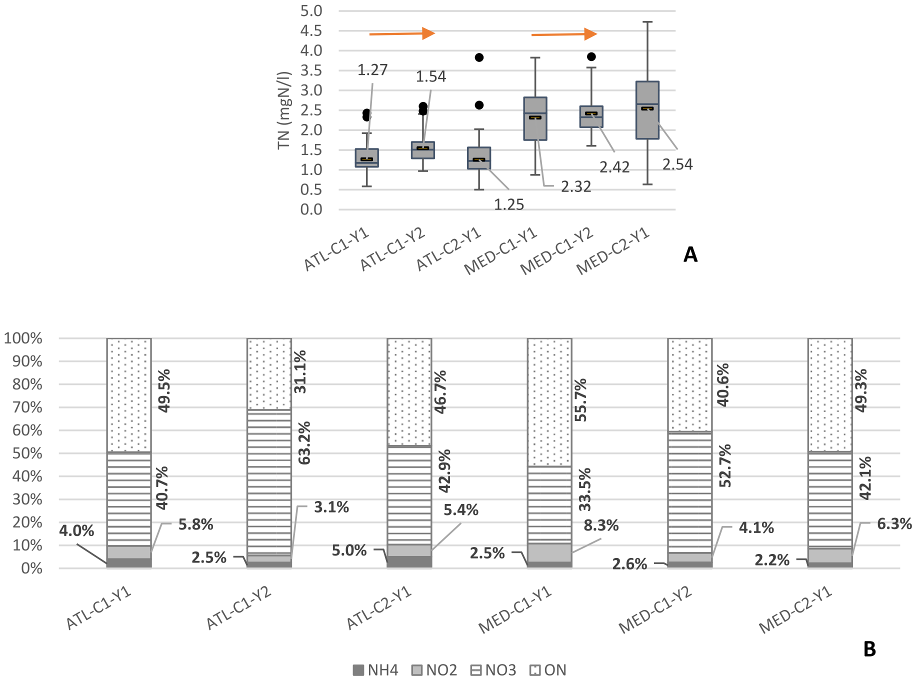

Fig. 7. Total Nitrogen – TN boxplots (**Figure A**). The numerical value of the averages is included in the graph. ATL-C1-Y1 (n = 52), ATL-C1-Y2 (n = 43), ATL-C2-Y1 (n = 51), MED-C1-Y1 (n = 27), MED-C1-Y2 (n = 24) and MED-C2-Y1 (n = 27). The orange arrows represent the evolution observed between years. **Figure B** represents the percentage of leached mass of Ammonium – NH4, Nitrites – NO2, Nitrates – NO3 and Organic Nitrogen ON with respect the leached mass of Total Nitrogen. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(COD, BOD, VSS and OP), higher concentrations were found in the effluent of the PP during the first year of tests, especially in the Mediterranean rainfall regime. The lower pH values reached during the second year inside the pavement section might have enhanced the biological activity during the second period. Moreover, the ON concentration tended to a stabilise over time, similar to the other organic variables, regardless of the rainfall regime.

3.2.5. Phosphorus species: phosphates (PO_4^{3-}) and organic phosphorus (OP)

Fig. 8 (A) shows boxplots of the TP concentration in each year of trials and the four main infiltrometers tested. The PO_4^{3-} and TP concentrations tended to increase over time in both rainfall regimes (with AM on the pavement surface). However, this increase was significant under the Atlantic rainfall regime ($p = 8.97E\text{-}13 < 0.05$ and $p = 1.32E\text{-}13 < 0.05$ between the time series of the first and second years of trials of the PO_4^{3-} and TP concentrations, respectively) and smooth under the Mediterranean rainfall regime ($p = 0.003 < 0.050$ and $p = 0.032 < 0.050$ between the time series of the first and second years of trials of the PO_4^{3-} and TP concentrations, respectively). The Mann - Kendall test indicated significant trends in the ATL-C1 time series concentrations, with coefficients of 0.609 and 0.601 for PO_4^{3-} and TP, respectively, and in MED-C1 only for the PO_4^{3-} concentration (coefficient 0.332). TP and PO_4^{3-} were the only pollutant species that showed a significant increase between the first and second years of trials.

The value established to classify water bodies in good status in Spain according to **RD 817/2015** [47], namely 0.16 mg P/l of PO_4^{3-}, was continually exceeded from May 2018 (approximately one year and three months after the start-up) by ATL-C1 and from May 2017 by MED-C1 (approximately three months after the start-up). Therefore, PO_4^{3-} should be a critical variable for defining cleaning periods, which must be more recent in the Mediterranean rainfall regime. The use of PO_4^{3-} adsorbing materials in the PP section, which are already used as constructed wetland substrates, could also be a solution.

The OP concentration was estimated as the difference between the TP and PO_4^{3-} concentrations. Similar to the other organic variables, the OP concentration showed an increase during the first year, mainly in the Mediterranean rainfall regime, but during the second year, the outflow concentration tended to be stable regardless of the rainfall regime. The percentage of the OP leached mass with respect to the TP leached mass decreased from the first to the second year of tests under both rainfall regimes, whereas this percentage increased for PO_4^{3-} (Fig. 8 (B)). These results reinforce the idea of bacterial development during the second year owing to the availability of organic species in the AM and pH conditions.

3.2.6. Trace metals: aluminium (Al) and Zinc (Zn)

The Al outflow concentrations seemed to decrease exponentially over time during the first year of the study (Fig. 9 (A)), whereas the Zn outflow concentrations seemed to increase over time (Fig. 9 (B)). These behaviours reflect that the Al in the infiltrated water mainly originated from the construction materials of the pavement section, whereas the Zn originated from the accumulated dust and dirt on the PP surface.

Table 3 compares the metal concentrations obtained in this study with the results of other studies in the field. Similar values have been obtained for Zn and Al concentrations in water infiltrated through PPs, although this study showed slightly higher Zn concentrations than most of the other studies, which was likely due to the high pollutant levels on the PP surface in this study.

The Al concentration defined in **Directive 2020/2184** [41] to ensure compliance with drinking water quality in Europe (200 μg/l) was exceeded in the infiltrated water of the four infiltrometers tested until the beginning of the second year of trials. After the washing of PP materials, this value was exceeded on only one day from August 2018 in MED-C1 (218 μg/l > 200 μg/l).

The Zn concentration in surface water bodies in Spain must be below 30 μg/l or 500 μg/l, depending on the water hardness, to meet the environmental quality standards (NCA, **RD 60/2011** [46]). If we consider that PPs subjected to the Atlantic rainfall regime discharge into soft waters ($10 < CaCO_3 \leq 50$), which are typical in the city of Santander, the cut-off value for the Zn concentration (200 μg/l) was practically surpassed from the beginning of the tests. If we consider that PPs subjected to the Mediterranean rainfall regime discharge into hard waters ($CaCO_3 > 100$), which are typical in the city of Valencia, the limit value for the Zn concentration (500 μg/l) was not exceeded.

3.2.7. Statistical analysis of the differences in effluent water quality between rainfall regimes and configurations

In general, there were no significant differences between the PP configurations ($p > 0.05$) for all the quality variables analysed in the infiltrated water; however, there were significant differences between the rainfall regimes during both years of trials ($p < 0.05$). An extra aggregate layer in the PP configuration did not provide significantly greater filtration of pollutants, but more frequent washing of the pavements subject to the Atlantic rainfall regime further reduced the infiltrated pollutant concentration.

Exceptions to the above are OD concentration, %satDO, Al, and Zn, which were not significantly different for both rainfall regimes and PP configurations. Only the Zn concentration in the water infiltrated through PPs with configuration C1 showed slight differences among the rainfall regimes during the first year of trials ($p = 0.0139 < 0.0500$). For the other studied variables, the first year of trials might have been an adaptive period for Zn in pavements with configuration C1; however, the p-value close to statistical significance shows that this difference is not very important. Significant differences were observed between the rainfall regimes for the N species outflow concentrations, except for the NH_4^+ concentration during the first year of tests ($p > 0.0500$; 0.2641 for C1 and 0.9497 for C2), which was probably due to the very low concentrations collected. Furthermore, the OP concentration was significantly higher PP effluent in the Mediterranean rainfall regime, except during the second year of trials, although the difference was very close to the defined limit ($p = 0.0571 > 0.0500$). Finally, after the start-up period, there was a statistically significant difference in the TSS concentration and turbidity among the configurations in the Mediterranean rainfall regime ($p < 0.05$). In contrast, there were no significant differences between the configurations in the Atlantic regime ($p > 0.05$). The

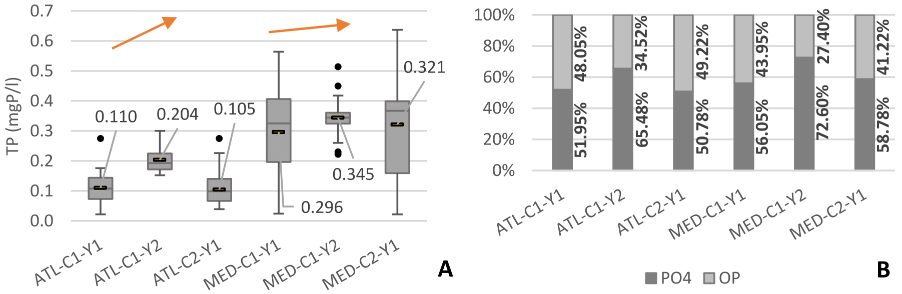

Fig. 8. Total Phosphorus – TP boxplots (**Figure A**). The numerical value of the averages is included in the graph. ATL-C1-Y1 (n = 52), ATL-C1-Y2 (n = 43), ATL-C2-Y1 (n = 51), MED-C1-Y1 (n = 27), MED-C1- Y2 (n = 24) and MED-C2-Y1 (n = 27). The orange arrows represent the evolution observed between years. **Figure B** represents the percentage of leached mass of Phosphates – PO4 and Organic Phosphorus OP with respect the leached mass of Total Phosphorus. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

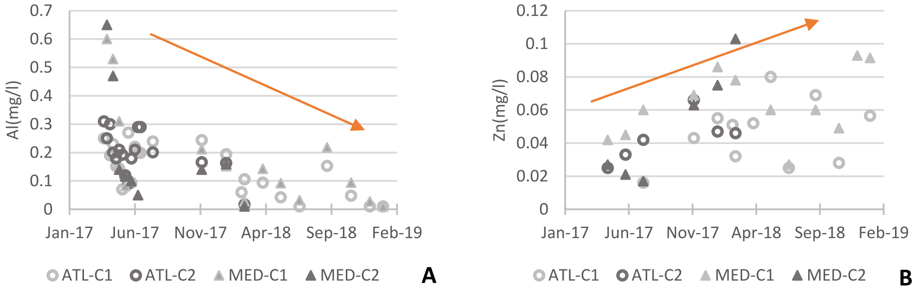

Fig. 9. Temporal evolution of Aluminium – Al (**Figure A** - left) and Zinc – Zn (**Figure B** - right) concentrations (unit: mg/l) in infiltrated water through the main four infiltrometers tested. ATL-C1-Y1 and ATL-C2-Y1 ($n_{Zn} = 7$, $n_{Al} = 17$), MED-C1-Y1 and MED-C2-Y1 ($n_{Zn} = 6$, $n_{Al} = 9$), ATL-C1-Y2 and MED-C1-Y2 ($n_{Zn} = 6$, $n_{Al} = 7$).

Table 3

Comparison of metals average and median concentrations (Aluminium – Al and Zinc – Zn) of the current study with other studies. The range of variation of the metals average and median concentrations found in the literature is indicated in brackets and in bold type.

Variable	Statistic	Current Study				Other studies
		ATL-C1 Y1/Y2	ATL-C2	MED-C1 Y1/Y2	MED-C2	
Al (µg/l)	Mean	175/42	198	229/92	204	**[215–792]** 261[a], 215[b], 792[d], 320[e], 281[f]
	Median	194/42	200	152/92	140	**[123–544]** 215[a], 164[b], 544[d], 205[e], 123[f]
Zn (µg/l)	Mean	36/52	43	63/63	51	**[16–27]** 19[a], 16[b], 18.3[c], 27[e], 16[f]
	Median	33/54	44	65/60	45	**[12–52]** 14[a], 12[b], 52[d], 24[e], 24[f]

[a] [9]: PICP with AquaPave® blocks.
[b] [9]: PICP with Eco-Optiloc® blocks.
[c] [18]: PP.
[d] [19]: PICP.
[e] [10]: PICP with AquaPave® blocks.
[f] [10]: PICP with Eco-Optiloc® blocks.

extra aggregate layer in configuration C1 in the Mediterranean rainfall regime, which was less washed, supplied a greater amount of solids to the infiltrated water.

The exact p-values of the statistical significance analyses are presented in Tables A.6 – A.9 of Appendix. A.

4. Conclusions

This study reinforces hydraulic and mainly water quality benefits of PPs over traditional urban drainage systems. Moreover, it has made it possible to study the influences of pollution build-up and the PP configuration on the water infiltrated through these infrastructures in the mid-term (one and two years). As a novel study, the differences in the quantity and mainly the quality of water infiltrated through PPs under Atlantic and Mediterranean rainfall regimes were analysed. The analysis of the effects of these three variables on the results has made it possible to verify or reject the proposed hypotheses.

First, it can be concluded that the accumulation of dust and dirt on the pavement surface reduced the PP permeability and increased the infiltration velocity time. This occurred in a similar way for both rainfall regimes, without clear differences. Furthermore, the longer dry period between events under the Mediterranean rainfall regime favoured the retention capacity of PPs.

Regarding quality results, the capacity of PPs to improve the quality of urban runoff was greater under the Atlantic regime than the Mediterranean rainfall regime. The pollutant concentrations in infiltrated water infiltrated through PPs were higher in the Mediterranean regime than in the Atlantic regime. Moreover, the longer the antecedent dry period, the greater the influence of temperature on the concentration of infiltrated organic matter. In addition, it is important to focus on the construction of PPs and to use correctly washed granular materials that affect water quality as little as possible.

Phosphorus species, specially phosphates, are likely to limit the maximum allowable clean-up frequencies of the pavements, being more restrictive in the Mediterranean regime. Therefore, one of the short-term goals for the research group will be to schedule experiments in PP sections with phosphates absorbing materials, such as those already used in constructed wetlands substrates (i.e. drinking water treatment plant sludge and active carbon).

Finally, the experimental setup used made it possible to assess the effects of the water infiltrated through the PPs on surface and ground water quality. Thus, it fulfilled the purpose for which it was designed. This setup also provides a robust database for the future definition of numerical models to simulate the pollutant removal and retention capacity of PPs.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2021.108332.

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