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COMPARATIVE ANALYSIS OF THE OUTFLOW WATER QUALITY OF TWO SUSTAINABLE LINEAR DRAINAGE SYSTEMS

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ABSTRACT

Three different drainage systems were built in a roadside car park located on the outskirts of Oviedo (Spain); two Sustainable Urban Drainage Systems (SUDS), a swale and a filter drain, and one conventional drainage system, a concrete ditch, which is representative of the most frequently used roadside drainage system in Spain. The concentrations of pollutants were analyzed in the outflow of all three systems in order to compare their capacity to improve water quality. Physicochemical water quality parameters such as DO, TSS, pH, EC, TPH and Turbidity were monitored and analyzed for 25 months. Results are presented in detail showing significantly smaller amounts of outflow pollutants in SUDS than in conventional drainage systems, especially in the filter drain which provided the best performance.

KEYWORDS: BMP, concrete ditch, filter drain, SUDS, swale, water quality.

INTRODUCTION

During the last decades, urbanization growth has significantly increased waterproofing of natural areas (Eigenbrod et al. 2011), causing problems in stormwater management (Pearson et al. 2010), disruption of natural water balance (Suriya and Mugdal 2012), diffuse pollution (Brattebo and Booth 2003), lack of urban services (Acioli et al. 2005) and loss of natural wealth (Fresno et al. 2005). High intensity rainfalls often surpass the infiltration capacity in urban land producing runoff and diffuse pollution as one of the most dangerous problems. Diffuse pollution is generated when rainfall washes down atmospheric pollutants and then picks up surface pollutants with different point and non-point sources (Campbell et al. 2004).

Pollutants in runoff are directly related to land uses (Novotny 2003). More specifically in the case of roads, high percentages of pollutant agents can affect surrounding water and soil due to the influence of the traffic effect (CEDEX 2009). Several studies (Barrett et al. 1993) have confirmed that runoff road pollutants produce immediate and chronic toxic effects. Depending on the drainage management of any waterproof area, such as a road or a motorway, all the pollutant substance deposits will be washed away and carried into the drainage systems or discharged into the environment (CEDEX 2009).

Sustainable Urban Drainage Systems (SUDS) have been used to solve problems related to water quantity, quality and amenity (CIRIA 2001). Swales and filter drains are linear drainage systems included in SUDS that improve stormwater management, especially in roadside and parking areas. Furthermore, SUDS are an aesthetic solution which can be integrated into the environment (Fresno et al. 2005) improving the landscape. These systems collect the stormwater runoff from the adjacent impervious surfaces and transport it toward storage systems or sewage systems, allowing water infiltration into the subsoil during this transportation. These systems reduce runoff peak flow and reduce pollution by filtering water through their different layers (National SUDS Working Group 2003). In groundwater protected areas or when it is necessary, these systems can be sealed underneath in order to prevent infiltration processes in a specific stretch (CIRIA 2001).

After an exhaustive search in the main scientific databases, several studies about swales and filter drain performance and their outflow water quality have been found: Schueler (1994), Barrett et al. (1998), Lloyd et al. (2001), Bäckström (2002), Schlüter et al. (2002), Borst et al. (2007), Stagge et al. (2012), Winston et al (2012), Kachchu Mohamed et al (2014), Lucke et al (2014). Nevertheless, no comparative studies were found with the particular conditions, construction and methodology used in this research.

The main aim of this research is to analyze and compare the capacity of two SUDS-based linear drainage systems to reduce water pollutants concentration in a suburban roadside car park with low traffic and therefore with low pollution levels. The first step of the research was the analysis of several physicochemical water quality parameters: pH, Electrical Conductivity (EC), Dissolved Oxygen (DO), Total Suspended Solids (TSS), Turbidity and Total Petroleum Hydrocarbons (TPH). After that, the water quality results were statistically analyzed in order to find any significant difference among the systems.

MATERIALS AND METHODS

This research was carried out in three full-scale drainage stretches built in a roadside car park located on the outskirts of the Northern Spanish city of Oviedo. This place is close to the Castle-Hotel of 'La Zoreda' Forest an extensive green area far away from urban centers, and therefore a place with low traffic density. There are three stretches of 20m, corresponding to two sustainable drainage systems: swale and filter drain, and a third corresponding to a concrete ditch used to represent the surface runoff (Figure 1).

The pavement slope in both longitudinal and transversal directions was 2.5% and the drainage area of each linear drainage system was 100 square meters. The linear SUDS systems were designed and built with the following cross section elements:

- Pervious surface to allow the infiltration of the runoff.
- Limestone base layer with a size distribution of 4-20mm.
- Upper polypropylene based geotextile (Polyfelt TS20).
- Sub-base layer made of limestone aggregates of 20-40mm.

— Under all these layers, the natural soil has been waterproofed by using a geomembrane in order to avoid infiltration into the natural soil.

A control manhole was built at the end of each stretch in order to sample the sub-superficial outflow from the SUDS-based system and the surface runoff from the conventional system. The three stretches collect the runoff from the same drainage area, so the runoff volumes collected by each system could be expected to be the same. Moreover, the three stretches were placed at the same location and the water sampling was carried out at the same time, so the water quality differences between the runoff treated by each system are assumed not to be significant allowing the comparative analysis by using concentrations.

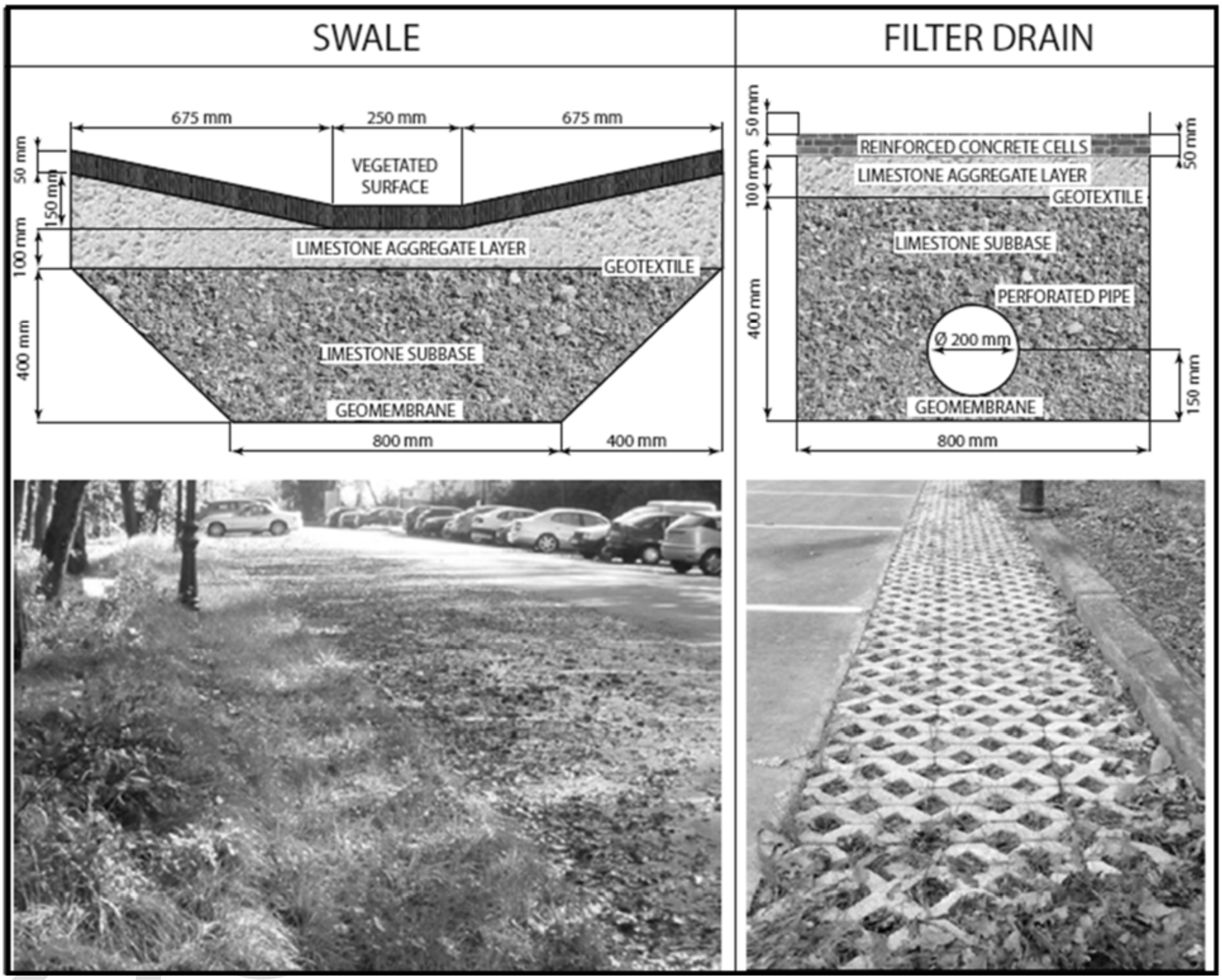

Figure 1. Cross Section and photograph of the linear systems analyzed

The research period started in August 2009 and lasted 25 months until August 2011. During the 25 months of the experimental program no specific maintenance was applied, so in autumn and winter periods, large amounts of leaves were deposited on the systems surfaces. This organic matter was probably the main pollution source and it affects the systems performances by reducing the infiltration capacity and affecting water quality results, especially DO, TSS and Turbidity values.

Three water samples from each drainage system were taken once a month, after the end of the rainfall events, in 1 liter containers. For water sampling, the first step was the manual mixing of the water stored in the manhole for 30 seconds in order to resuspend the solid particles deposited at the bottom of the storing chamber. The DO, pH and EC measurements were performed on site by submerging the probes (Table 1) in the water stored in the control manhole and, at the same time, the sample containers were submerged into the manhole in order to sample the stored water. Finally, after sampling, the storage chamber was cleaned and the samples were kept at 4±1°C until the TPH, TSS and Turbidity analysis were performed in laboratory by using the test methods shown in Table 1. The results shown in this paper are the outcome of the average value of the results obtained for each sample.

Table 1. Physicochemical water quality parameters monitored.

PARAMETER	UNIT	METHOD	INSTRUMENTATION	DETECTION LIMITS
Total Petroleum Hydrocarbons (TPH)	mg/L	ASTM D7066-04	Horiba OCMA-310 absorption infrared oil detector with the solvent S-316	0.1 mg/L
Dissolved Oxygen (DO)	mg/L	Hach Method 10360 (US-EPA Approved for 40 CFR 136)	Hach HQ 40D Multi-parameter meter with LDO10103, CDC401 and PHC30103 probes	0.01 mg/L
pH	-	Hach Method 8156 (US-EPA accepted for SM 4500-H+B)		-
Electrical Conductivity (EC)	µS/cm	Hach Method 8160 (US-EPA accepted for SM 2510 B)		1 µS/cm
Total Suspended Solids (TSS)	mg/L	US-EPA Method 160.2 (UNE-EN 872:2006 in Spain)	IF platform, glass microfiber filters, vacuum pump, analytical balance (0.1 mg), desiccator and laboratory oven.	0.1 mg/L
Turbidity	NTU	US-EPA 180.1	Hach 2100 P Turbidimeter	1 NTU

In order to properly characterize the results obtained, total rainfall volumes associated with the sampling program were obtained from the Spanish Meteorological Agency (AEMET) in the weather station 1249I, located 4 km away from the experimental site. The 25 monitored storm events were selected in order to cover the full range of the rainfalls that normally occur in the north of Spain. With this aim, five groups of rainfalls were established in order to properly select the rain events: very light rain (<5mm), light rain (5-10mm), medium rain (10-15mm), heavy rain (15-20mm) and very heavy rain (>20mm).

The water quality results were statistically analyzed by using IBM SPSS 22 ® in order to find possible significant differences between outflow water qualities obtained from the systems studied.

The first step of the statistical analysis was to analyze the normality of the data obtained by using a Shapiro-Wilk test or a Kolmogorov-Smirnoff Test, depending on the number of samples of each population analyzed. Once the normality of the data distribution had been determined, the next step was to determine the homoscedasticity by using a Levenne Test, assessing the null hypothesis of the equality of variances.

Depending on the normality and homoscedasticity of the data distribution, different tests were applied: parametric tests for homoscedastic and normally distributed parameters, and non-parametric tests for non-homoscedastic and/or non-normally distributed parameters. Considering that all the observations were independent of each other two kinds of test were used: the T-Test or the Mann-Whitney U-Test for two independent populations, and the ANOVA or Kruskal-Wallis test for more than two independent populations. These tests compare the results obtained from each population, assessing the null hypothesis of equality of distributions, and indicating whether the observed differences among the results for each population were statistically significant.

RESULTS AND DISCUSSION

The box plots of the water quality results for the 25 storms monitored and the outliers of the distributions, marked in the charts with points and an adjacent number that represent the data register, are shown in Figure 2.

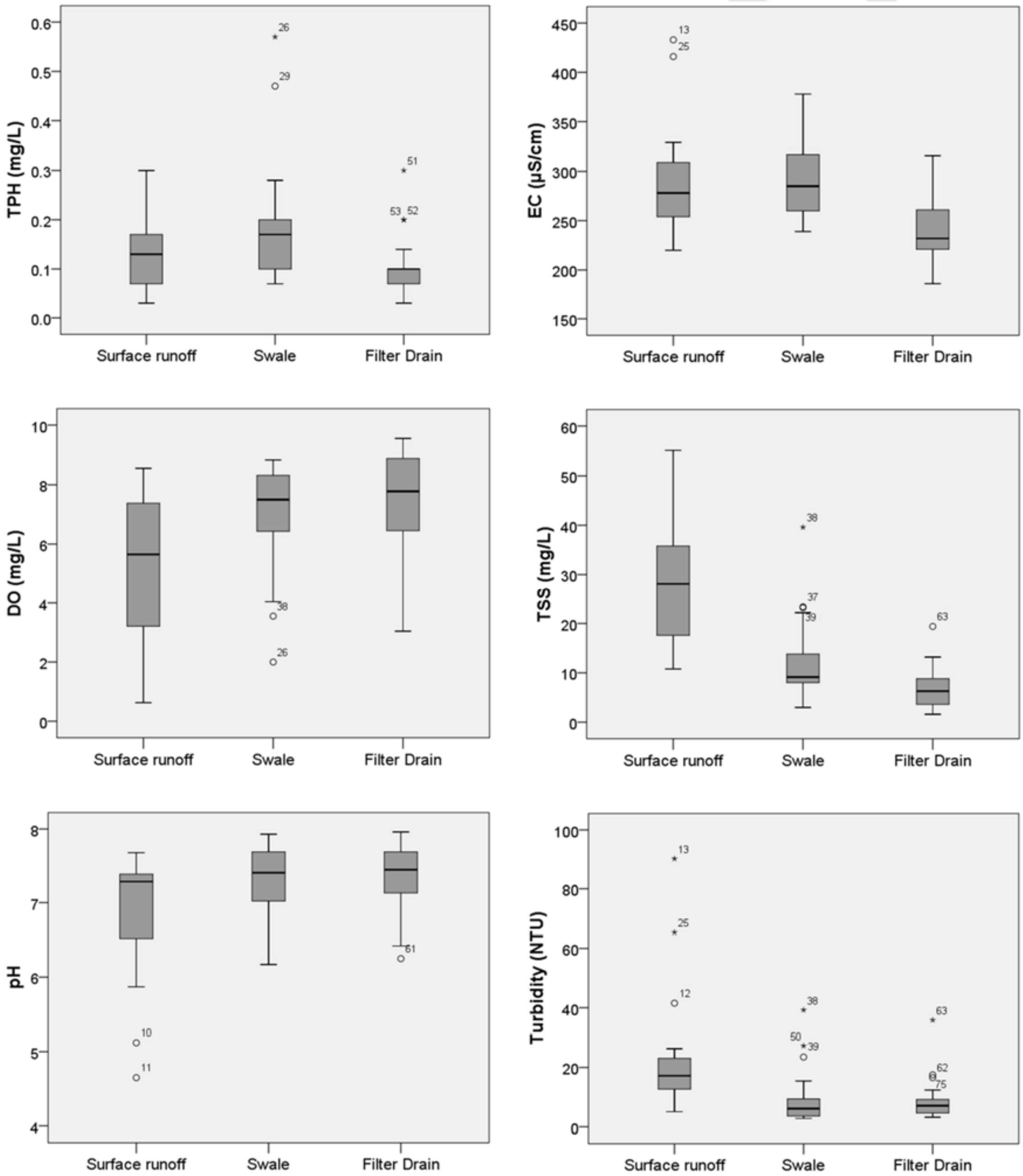

Figure 2. Water quality results in the three systems over the 25 months of monitoring

The total rainfall volumes of the storm events monitored were obtained by the Spanish National Meteorological Agency and are shown in Figure 3.

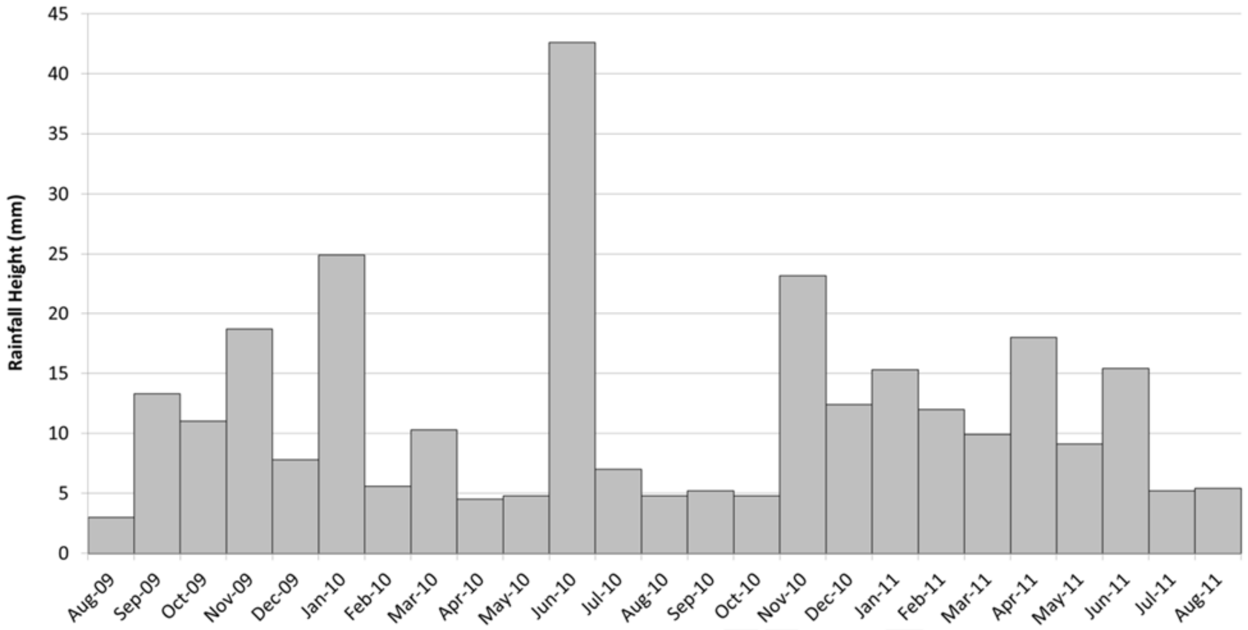

Figure 3. Rainfall volumes of the storm events monitored

A Shapiro-Wilk test was carried out in order to analyze the normality of the data obtained, showing a non-normal distribution for all the parameters studied. After a logarithmic transformation, DO concentrations and pH values remained non-normally distributed, while the rest of parameters showed a normal distribution. In order to use the same test for all the parameters, and considering the presence of non-normally distributed parameters, a means' comparison was made applying the non-parametric Mann-Whitney U-Test.

These results shown that there are significant differences between the surface runoff and the outflow of the two SUDS studied in DO, pH, TSS and Turbidity (p-value<0.05), there being a significant difference in EC results for surface runoff and filter drain (p-value <0.05). Comparing the two types of SUDS analyzed, it could be observed that there are significant differences in EC values, TPH and TSS (p-value<0.05), while DO, pH and Turbidity results showed no significant differences between swale and filter drain (p-value>0.05).

The registered values of TPH were very low during the monitoring period due to the light traffic in the experimental site. Considering that the data plotted in Figure 2 were obtained as the average value of the three samples taken in each sampling, some of the results plotted in the box-plot can fall below the detection limits of the TPH analyzer (ie. 0.1 mg/L; 0.0mg/L; 0.0mg/L). Analyzing the data obtained, no significant differences were found between the surface runoff and the SUDS studied. However comparing the two SUDS, significant differences were found between average registered values (p-value <0.05), showing 42% less hydrocarbon concentration in the filter drain outflow than in the swale´s.

The average values of DO are 18% higher in the swale and 35% higher in the filter drain than the DO values observed in the surface runoff, the statistical analysis demonstrating that these differences were significant (p-value<0.05). Considering the nearby vegetated area and assuming the same pollutants inflow, the higher values of DO in SUDS could be explained by the filtration through the geotextiles and granular layers, which reduces the organic matter content and the oxygen depletion by biodegradation in these systems. The leaves deposited on the systems surface could be biodegraded there and later washed off by the runoff reaching the manhole where the samples are taken so reducing DO values. Moreover, turbulence along with the mixing that can take place in the SUDS systems can increase the DO in the outflow of these systems, increasing the observed differences between SUDS and surface runoff. Comparing the two SUDS studied, no significant differences were observed; however, lower values of DO were found in the swale outflow, probably due to some depletion of DO by the vegetated surface of this system.

The pH values remained in the range of 6-8 for the outflow of all systems, being slightly higher in the SUDS system, showing similar results to those that previous studies have found (Schlüter et al. 2002). Surface runoff shows a significantly lower outflow pH than the SUDS (p-value<0.05) due to the alkaline nature of the limestone used in their granular layers and the longer permanence of water in these systems due to the lower water velocity.

The registered data of EC values seemed similar in the surface runoff and in both SUDS systems, but the statistical analysis showed a significantly lower EC in the filter drain with a reduction of 16% compared to surface runoff (p-value <0.05) and 17% compared to the swale (p-value<0.05). Greater contact of water with the limestone sub-base increases the dissolution of some chemical compounds in the aggregate that could increase EC values. The presence of perforated pipe in the filter drain cross section reduces the contact time of water with the limestone sub-base, collecting the infiltrated water and transporting it to the manhole, so reducing EC values respect to the swale.

The outflow TSS and Turbidity results registered in SUDS were significantly lower than in the surface runoff. Average TSS outflow concentrations were 76% lower than in the surface runoff, while the Turbidity was 59% lower, both reduction rates being in agreement with the data provided by Schlüter et al. (2002) for a longer filter drain system with higher TSS and turbidity inflows. On the other hand, average TSS concentration in the outflow of swale was 56% lower than in surface runoff, while average registered turbidity was 54% lower. The TSS results obtained show a similar reduction rate to the median value of TSS reduction in vegetated swales provided by Barrett (2008) based on the international BMP database. These are within the range of reduction rates reported by Stagge et al. (2012) and Lucke et al (2014) for longer vegetated swales. Nonetheless, the observed TSS reduction rates in the swale were lower than those obtained in other studies (Schueler (1994), Lloyd et al. (2001), Bäckström (2002)), probably by the lower TSS inflow, reported as an important factor in the TSS reduction rates of vegetated swales by Winston et al. (2012) and Lucke et al. (2014). These studies reported a background TSS in these systems in the range of 40-50 mg/l due to the scouring of sediments along the swale, making it difficult to quantify the reduction rates of TSS with low TSS inlet. Nevertheless the results obtained showed an average outflow TSS concentration slightly lower than 10 mg/l, probably by the presence of geotextile in the cross section of the vegetated swale, which reduces the TSS background avoiding the scouring of sediments. Comparing the two SUDS systems, significant differences were found due to the lower concentration of TSS in the outflow of the filter drain, which shows a reduction of 45% in average values compared to the swale probably influenced by the presence of a perforated pipe, that reduces the solid content by reducing the water washing over the sub-base aggregates, and therefore, the amount of solid particles washed off by the infiltrated water.

CONCLUSIONS

Throughout the 25 months of monitoring, low pollution levels were found in the surface runoff, limiting the conclusions of the present research.

Water quality results showed that the outflow water from SUDS systems was less polluted than the surface runoff confirming the filtering effect provided by geotextile and granular layers.

Significant differences between Filter Drain and the surface runoff were found in terms of DO, pH, EC, TSS and Turbidity, while there are significant differences between the swale and surface runoff in DO, pH, TSS and Turbidity results. These differences were especially important in the case of DO, TSS and Turbidity, confirming SUDS capacity to reduce water pollutants associated with solid particles.

The use of geotextile in both SUDS analyzed reduced the TSS concentration in the outflow in comparison with previous studies, reaching TSS concentrations of 10 mg/l and avoiding the possible scouring of sediments.

Comparing the two SUDS studied, the filter drain system shows a lower level of average pollutants concentration than the swale in all water quality parameters analyzed, being significant in EC, TSS and TPH values.

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