HYDRAULIC PERFORMANCE OF PERMEABLE ASPHALT AND PICP IN SWMM, VALIDATED BY LABORATORY DATA

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ABSTRACT

Traditional urban development practices disrupt the natural water cycle, increasing surface runoff volume/velocity and reducing water quality, amongst other impacts. Those negative impacts can be reduced adopting sustainable urban drainage system (SUDS) techniques, such as pervious pavements. porous asphalt (PA) and permeable interlocking clay/concrete pavers (PICP) are two types of pervious pavements. Both are similar to traditional asphalt and pavers, but superficial layer has a high porosity for allowing infiltration of rain, and base/subbase layers contain a high void fraction to allow water retention. In order to analyse these types of pavements and assess how they affect the general urban stormwater network, the SWMM model has been widely used. Even so, more confidence in the selected parameters is needed, especially when modelling homogeneous areas by means of low impact development (LID) units. To do so, laboratory tests have been implemented using a rainfall simulator, testing PICP/PA materials under different slopes (1% and 6%) and rain conditions (35 mm/h and 70 mm/h), and infiltrated water was measured for each layer independently. This paper validates, using the aforementioned laboratory data, the parameters needed for modelling PA and PICP in SWMM, as well as differences between them, showing that SWMM is a convenient tool to model single events on permeable pavements for regular storms.

Keywords: permeable pavement, pervious pavers, porous asphalt, SWMM, LID, model calibration.

1 INTRODUCTION

Traditional urban development practices have some negative impacts on the hydrological cycle: higher surface runoff, higher runoff velocity, lower time of concentration and lower water quality [1]. The philosophy of sustainable drainage systems is about maximising the benefits and minimising the negative impacts of surface water runoff from developed areas. Sustainable Urban Drainage Systems (SUDS) help facing these negative impacts by slowing down and reducing the surface runoff quantity from those areas. Thus, downstream flood risk can be better managed, and pollution risk reduced [2].

Multiple solutions can be addressed to mitigate aforementioned negative impacts while enhancing the positive ones. Pervious pavements are a logical stormwater management solution within the urban environment as they make effective use of available land, allow water to infiltrate through the paving surface and into the soil layers below, and they provide a hard surface for light vehicle use or pedestrians [3].

Porous Asphalt (PA) and Permeable Interlocking Clay/Concrete Pavers (PICP) are two common types of such permeable pavements. Both are similar to traditional asphalt and pavers, but superficial layer has a high porosity for allowing infiltration of rain, and base and subbase layers have a high void fraction to allow water retention.

Permeable pavement systems have become an important integral part of sustainable urban drainage systems despite the lack of corresponding high-quality research in comparison to

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other research areas [4]. Some research carried out to test permeable pavements (PA and PICP) and its performance under laboratory-controlled conditions have been done by Andrés-Valeri et al. [5], Huo et al. [6], Lucke and Beechman [7], Rodriguez-Hernandez et al. [8], Sañudo-Fontaneda et al. [9] and Sedyowati and Susanti [10].

On the other hand, it is frequent to use some kind of mathematical model to analyse the performance of the mentioned SUDS, for example EPA SWMM. Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used for primarily urban areas, where Low Impact Development (LID) Controls are equivalent to SUDS techniques, capturing surface runoff and providing some combination of detention, infiltration, and evapotranspiration. SWMM can explicitly model eight different generic types of LID controls [11], and permeable pavements are one of them.

However, the capacity of the SUDS is not usually assessed individually. In general, it is common to model heterogeneous subcatchments, which may or may not contain SUDS techniques. Thus, relatively large catchments are usually defined, with a diversity of surface areas, so it is difficult to find two equal catchments. For this reason, it is usually necessary to calibrate the parameters that define the catchments with real data.

In that respect, several authors have analysed LID units' performance as a part of a broader catchment [12]–[14], but there are little references about SWMM LID module exclusive analysis. For instance, Sañudo-Fontaneda et al. [15] concluded that the SWMM LID model presented high accuracy to replicate laboratory data when using the infiltration trench LID type.

Furthermore, subcatchment infiltration process can be defined in SWMM using the Horton method, modified Horton method, Green-Ampt method, modified Green-Ampt method or Curve Number [16]. But, if LID Controls are applied, it is also possible to model a subcatchment as an entire LID unit, and hydrological calculations are done considering material properties defined into that LID unit.

Besides, modelling runoff based on rainfall-runoff models requires spatial discretization of the catchment. It is of great importance in urban rainfall-runoff modelling to accurately define realistic subcatchments and flow paths. In that sense, catchment discretization can be defined as high or low resolution. When modelled in SWMM, model calibration and validation results showed that parameter sets reduce uncertainty of flow predictions if calibrated under micro-catchment delineation, compared against a macro-scale modelling [17]. In that regard, GIS based automatic catchment discretization could help getting such as micro-catchment delineation, with homogeneous subcatchments and parameters estimation based on their physical characteristics. Nevertheless, a well established automatic catchment-discretization approach based on GIS or other technologies is not still well developed [18].

The objective of this article is to find a robust parameter estimation to model PA and PICP with SWMM using the LID Controls approach, in order to perform a high resolution model, able to be connected to a GIS based automatic discretization, where surface defining parameters data can be extrapolated between subatchments.

2 METHODOLOGY

The general procedure used to calibrate the PA and PICP parameters of the SWMM LID module was to perform laboratory tests on three materials (gravel for storage layer, PICP and PA for pavement layer) used in two layers (pavement and storage) of permeable pavements. Two slopes and two rain intensities were studied with each material, and infiltrated water hydrographs were generated. That hydrograph data obtained from the laboratory tests was the basis to perform model parameter calibration. Both the laboratory tests and the calibration were carried out by analysing the layers individually, isolating the effect of one on the other.

2.1 Laboratory data

The laboratory tests were carried out on a hydrological test bench, GUNT HM 165, modified to work as a rain simulator. To avoid test bench overload, only half of the bench was used, being the tested surfaces of 1.00 m^2 (1.00 m x 1.00 m). The test bench was modified in such a way that a smooth and impermeable surface was generated, were 1 m^2 area material of different thickness was placed on (5 in Fig. 1). In order to simulate the rain, a grid of evenly spaced drippers was added in the upper part of the hydrological bank. A total of 81 drippers (9 x 9) were installed in a mesh generated from 16 mm diameter polyethylene pipes. The pipe network was attached to a wooden structure (4 in Fig. 1), which was kept horizontal for the different slopes analysed. For this purpose, wooden blocks were installed underneath the wooden structure. Water flow was measured by two rotameters of 5–50 l/h and 15–160 l/h (1 in Fig. 1), controlled by several valves (2 in Fig. 1). Besides, a 15 mm iPerl water meter has been installed as an additional control (3 in Fig. 1).

The duration of test rain was 15 minutes, common time of concentration for an urbanized area network collection points. It is also common to design traditional drainage networks with 10-year return period storms. For this reason, the rainfall intensities applied in the laboratory tests were 35 mm/h and 70 mm/h, corresponding to rains of 15 minutes duration and return periods of 2 and 10 years for the Igeldo meteorological station IDF curves [19], located in the municipality of Donostia/San Sebastián. In that respect, previous laboratory tests for permeable pavements selected rainfall intensities ranging from 5 mm/h to 60 mm/h [5], [9], [10]. For measuring the infiltrated flows and generate the output hydrographs, a hydrograph bucket was placed at the exit of the test bench (6 and 7 in Fig. 1). The measurement of the rain flow was made during 30 minutes (15 minutes with rain and 15 minutes without rain). The bucket had 16 containers with a surface of 17800 mm^2 each, and a capacity of 6.5 litres per container. In this way, using 14 of the 16 cuvettes, the duration of the hydrograph was divided into 28 non-homogeneous intervals.

Figure 1: Modified hydrology bench and volume measuring device. (1) Rotameter; (2) Valves; (3) Water meter; (4) Drippers; (5) Material vessel; (6) Outflow; and (7) Hydrograph buckets.

As mentioned above, the selected intervals were not constant. For operational reasons, the minimum interval was 30 seconds. As a result, and taking into account that more detail was to be captured in the increasing and decreasing curve of the hydrograph, the limits of the selected intervals were (in mm:ss): 00:00, 1:00, 1:30, 2:00, 2:30, 3:00, 3:30, 4:00, 4:30, 5:30, 6:00, 7:00, 8:00, 9:00, 11:00, 13:00, 15:00, 15:30, 16:00, 17:00, 17:30, 18:00, 19:00, 20:00, 22:00, 25:00 and 30:00.

Once the corresponding modifications were carried out the hydrological bank was calibrated. Three tests were conducted out for each rain intensity measuring the outflow in the hydrograph buckets. Thus, the rainfall intensities set for the following tests, later used in the model, were 33.1 mm/h and 72.0 mm/h.

All the material used in the laboratory tests was required to be an ordinary construction material: two types of crushed limestone (for storage layer and for PICP joints), clay pavers and PA. The material used in the storage layer was limestone gravel with aggregate sizes between 4 and 12 mm, according to the specifications given by the quarry. The void ratio was determined in the laboratory by measuring the weight of water volume filling the pores of gravel contained in a 500 ml plastic beaker. Two types of measurements were made: one with compacted gravel and another one with uncompacted material. The compaction of the first was done manually, giving 50 impacts to the plastic beaker with a screwdriver. A total of 18 measurements were made, 9 for the compacted gravel and another 9 without compacting. Thus, it was determined that the void ratio of the compacted gravel was 0.78, while the void ratio of the non-compacted gravel was 0.98. As the tested gravel layer was also compacted with a plastic hammer, similarly to the tested one, the compacted void ratio value was used in the model.

The paving blocks were AQUATA clay paving blocks from Wienerberger. The pavers were 80 mm thick, with a cross-section of 200 mm x 63 mm and protrusions of 6 mm x 6 mm. According to that geometry, the empty volume of the pavers was 9.84%. The void generated by the paver joints was filled with gravel, similar the on in the storage layer. It was smaller limestone gravel with aggregate sizes between 2 and 6 mm.

Thus, the void content of the joint gravel was measured in the same way as the gravel in the storage layer, but in a 100 ml glass beaker. The void ratio of the compacted and non-compacted material were also measured. The value of the compacted gravel was 0.82 and for uncompacted gravel it was 0.96. In joint filling gravel, as the gravel was introduced without compacting, the value later used was 0.96. With that value and the aforementioned joint void volume, it was determined that the total void ratio for PICP was 0.05.

The asphalt used for the tests was the same as that used in another construction site in Donostia/San Sebastian, where porous asphalt was installed. The asphalt was spread in two layers, the first of 5 cm, where the maximum aggregate size was 16 mm (PA 16 45/80-65), and another one of 3 cm where the maximum aggregate size was 11 mm (PA 11 45/80-65). The asphalt was extended and compacted over an existing one; consequently, its wasn’t uniform. The void ratio of the asphalt was 20% according to the manufacturer. Since the asphalt had to be handled by hand, it was cut in pieces of 0.50 m x 0.50 m. In order to test it on the test bench, joints were sealed with standard silicone once over it.

The gravel was placed directly on the impermeable surface, while the PICP and PA were placed over some plastic cells that allowed the infiltrated water to flow freely to the same impermeable surface and, from there, out through the discharge point. In the case of PICP, a 1.9 x 1.9 mm^2 plastic mosquito net was installed to keep the small gravel in the joint spaces. All the materials had the side corresponding to the lower part free, i.e. it was not installed against a side wall.

(a) (b) (c)

Figure 2: Tested materials. (a) Gravel; (b) PICP; and (c) PA.

Considering that the initial moisture content was an important factor in the measured hydrographs, and in order to guarantee the same initial condition in all tested materials (see Fig. 2), the procedure for carrying out the tests was as follows: a rain of 140 mm/h was generated for approximately 5 minutes, in which the last minute was used to adjust the flow rate to that required for the test. The section was then allowed to drain for 5 minutes, at which point the test was started and the water coming from the outlet measured.

As a consequence, and with the intention of adjusting the initial moisture content in the calibration, several tests were carried out. The materials were prepared in the same way as mentioned before, but instead of carrying out the test it was left overnight to drain the stored water. That drained water was considered as the initial moisture content of the material. According to the measurements made, the initial humidity was considered to be 1% for the storage layer and 0.5% for the pavement layers.

With regard to pavement slopes, it is common to adopt, on traditional pavements, a minimum transversal slope of 1% to evacuate rainwater. On the other hand, the longitudinal maximum slope of accessible pedestrian itineraries vary in Spain from 6% to 8% [20]. Thus, a 1% and 6% values are selected for being tested.

In summary, three materials (storage layer, pavement layer with PICP and pavement layer with PA) were tested in the laboratory under two rain intensities (35 mm/h and 70 mm/h) and with two slopes (1% and 6%). In addition, each treatment has been tested three times, so that a total of 36 tests have been carried out. Each material has been tested independently.

2.2 Hydrological model

The hydrological model used was that corresponding to SWMM version 5.1.013, which allows LID units to be defined into the subcatchments. As mentioned above, a subcatchment of 1 m^2 has been considered, identical to the surfaces tested in the laboratory. In the model subcatchment defined, the permeable pavement occupies the entire surface, i.e. the subcatchment contemplates a LID unit that covers it entirely. Consequently, from the general parameters to be defined in a subcatchment, only surface area (1 m^2) was set. The rest of the general parameters (slope, width, roughness, etc.) were considered null, as they do not influence its characterisation while they are defined in the LID unit. Therefore, the LID Control tab has also been activated.

Table 1: LID unit parameters.

Layer	Parameters		Values	
	Name	Units	Modelling	Ignoring
SUR	Berm height	mm	0	0
	Vegetation volume fraction	-	0	0
	Surface roughness	-	calibrate	calibrate
	Surface slope	%	1–6	1–6
PAV	Thickness	mm	80	0.0001
	Void ratio	-	0.05 & 0.20	0.9999
	Impervious surface fraction	-	0	0
	Permeability	mm/h	1000	1000
	Clogging factor	-	0	0
	Regeneration interval	days	0	0
	Regeneration fraction	-	0	0
STO	Thickness	mm	77.4	150
	Void ratio	-	0.78	0.99
	Seepage rate	mm/h	0	0
	Clogging factor	-	0	0
DRA	Flow coefficient	-	calibrate	calibrate
	Flow exponent	-	calibrate	calibrate
	Offset	mm	0	0
	Open level	mm	0	0
	Closed level	mm	0	0
	Control curve	-	0	0

The SWMM LID unit, by which the permeable pavement has been defined, has several layers (soil layer was not considered): surface (SUR), pavement (PAV), storage (STO) and drain (DRA). Each layer is characterised by certain parameters, which are shown in Table 1. Two value sets are defined in that table: modelling and ignoring. The first corresponds to the values set in the model for each layer. The second column indicates the values that were used in the model when a layer was not being tested. For example, the storage layer was analysed without any material on it, consequently, and to ignore the effect of the pavement, this was defined with a minimum thickness and a maximum void ratio, so that rainwater goes directly to the lower layer (storage layer).

From those parameters, slope is the parameter varied between tests (together with the rain intensity); 1% and 6% were tested values. Some of the other parameters were measured in the laboratory or by the manufacturer; these parameters are the thickness and void fraction for different layers. Others were set based on the characteristics of the test bench, such as the berm height, considered null because the side of the lower part of the surface was free and the water could flow freely. In addition, the drainage offset was set at 0, as the lateral outlet of the lower zone was free. The seepage rate was also set to 0 mm/h, as the bottom surface was impermeable.

Also, some of the parameter values were set based on the material properties. Since the permeability of the pavements is much greater than the rainfall generated, it was not measured and a value equal to 1000 mm/h was considered. Furthermore, the clogging of the surface was not considered as the asphalt was and the gravel used in the PICP joints were new. It was also necessary to set some general parameters of the LID unit, which are shown in the LID editor of the subcatchment; these parameters are listed in Table 2. On the one hand, the width of the surface has been fixed at 1 m, according to the characteristics of the test bench. On the other hand, the value of the initial humidity has been set at 0.5% and 1%, as explained in the previous section. In addition, a junction has been selected in the LID editor to evacuate the water collected by the drain. This junction will be the one that collects the water infiltrated in the section, and whose flows will be used to generate the hydrograph of the model. This last hydrograph will be used to compare the results of the model with the results obtained in the laboratory.

Table 2: LID usage editor parameters.

Parameter	Units	Values
Surface width per unit	m	1
% Initially saturated	%	0.5–1

2.3 Calibration

The parameters of the hydrological model mentioned above were calibrated using the hydrographs generated in the laboratory. Modelled events performance evaluation was done using the Nash-Sutclife adimensional coefficient [21], given by eqn (1) below. Oi and Ō are laboratory observed data, and mean of the observed values, while Pi are modelled values. A NSE=1 indicates a perfect fit. However, since laboratory data is available for different events applied to the same pavement layer, it seems reasonable to compare the total sum of individual coefficients [22]

$$NSE = 1 - \frac{\sum_{i=1}^{N} \quad (O_i - P_i)^2}{\sum_{i=1}^{N} \quad (O_i - \bar{O})^2}. \tag{1}$$

Besides, as single events are common for studying peak flow and volume [1], percent error in peak (PEP) and percent error in volume (PEV) were also analysed, as shown in eqns (2) and (3), being P modelled values and O the observed values

$$PEP = \frac{P_{peak} - O_{peak}}{O_{peak}}, \tag{2}$$

$$PEV = \frac{P_{volume} - O_{volume}}{O_{volume}}. \tag{3}$$

As mentioned above, each layer was used to calibrate certain parameters. The storage layer was used to calibrate drainage parameters, coefficient and exponent, while the surface layer was used to calibrate roughness. Consequently, given the low number of parameters to be calibrated, it was carried out manually.

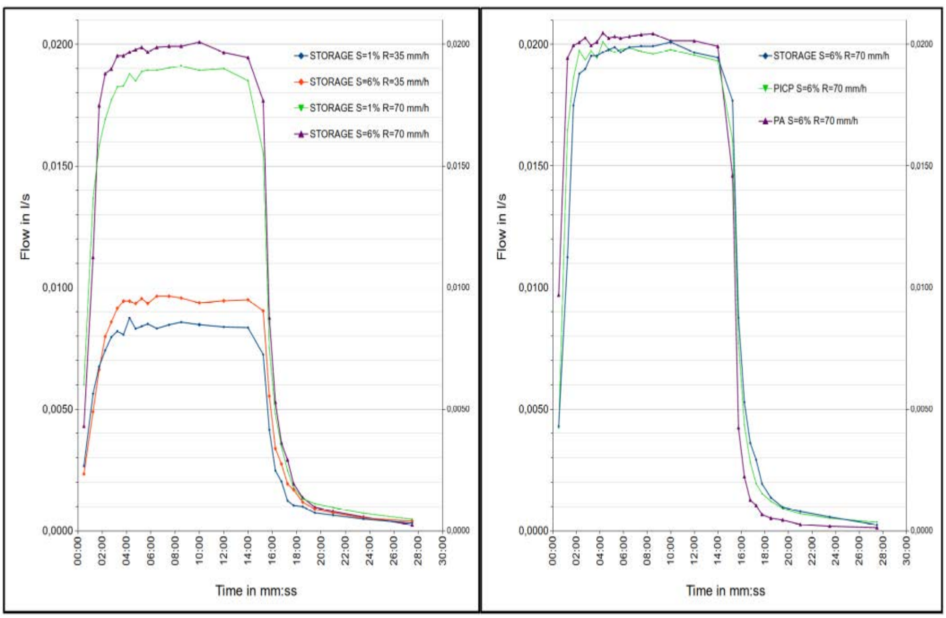
3 RESULTS AND DISCUSSIONS

First, the results obtained in the laboratory are presented. Later, the results obtained by calibration are presented and discussed.

3.1 Laboratory results

It is important to note that no surface runoff was observed in any test. As a result, no measuring element has been installed. In all three layers, the hydrographs obtained with the highest slope, 6%, show a higher peak flow compared to the flows corresponding to the 1% slopes, as might initially be expected (Fig. 3(a)). In this sense, the volume of water collected for the 6% slope is greater than the corresponding to the 1% slope; which also seems logical, since the greater slopes drain a greater volume of water for the same time period. Hence, minor slopes need more time to evacuate the same water volume.

In addition, the initial values of the flow are lower in the case of the steeper slope (Fig. 3(a)). It seems sensible to think that, after the initial preparation procedure (5 minutes of rain and 5 minutes of evacuation), the initial humidity or volume of water retained is lower in the case of the steeper slope because, as mentioned previously, the steeper slopes drain the infiltrated water faster.



(a) (b)

Figure 3: Measured hydrographs for different conditions on the (a) storage layer and (b) for different layers in 6% slope with 70 mm/h rain.

On the other hand, if the hydrographs generated by the two surface layers (PICP and PA) are compared with the storage layer, it can be seen that the initial flows are greater for the two surface layers than for the storage layer (Fig. 3(b)). It can be thought that in the surface layer the water must pass through a smaller section and can be them freely directed to the outlet; on the contrary, in the storage layer, water must pass through the gravel section transversely to reach the outlet. In the same way, the downward branch of the hydrograph, as soon as the rain stops, has a steeper slope in the surface layers.

Similarly, if we compare the two hydrographs of the surface layer with each other, it can be seen that the PA layer drains easier, compared to the PICP layer. It also seems logical, as the porosity of the asphalt layer is greater than the porosity of the paving and gravel layer. In general, the obtained hydrographs are in accordance with the expected ones, taking into account the considerations of the tests and the characteristics of the materials.

3.2 Calibration results

The coefficient and exponent of the storage layer were calibrated in the first instance. The values best adapted to the characteristics of the test bench were 10 for the coefficient and 1.8 for the drainage exponent. Sañudo-Fontaneda et al. [15] also found similar values for those two parameters in a similar test for an infiltration trench. According to calibrated NSE, results show an acceptable general performance for the model estimation, better for higher rain intensity than for the low one. The NSE values are better to those obtained, for example, by Sañudo-Fontaneda et al. [15] while modelling filter drains, where values ranged between 0.92 and 0.98. The results obtained for those values are summarized in Table 3.

Table 3: Storage layer calibration values with a coefficient of 10 and exponent of 1.8.

Parameter	Case (R = rain in mm/h and S = slope in %)			
	R = 35 S = 1	R = 35 S = 6	R = 70 S = 1	R = 70 S = 6
NSE	0.963	0.968	0.976	0.977
PEP (%)	9.1	-3.0	6.0	1.0
PEV (%)	7.3	-4.7	4.7	0.8

The data also shows that for small slopes the model overestimates the value of the peak, which also generates an overestimate in the output volume of the model. On the other hand, the peak flow values for the steeper slopes, as well as the volumes, present acceptable results that are fairly close to the data obtained in the laboratory.

According to pavement layers, the results are similar for both surface layers, with values for NSE greater than 0.90, in general, with the exception of one from PICP layer, in which the coefficient is considerably reduced. The data as shown in Table 4 confirms that the model fits better for steeper slopes.

Table 4: Pavement layer calibration values with a coefficient of 10 and exponent of 1.8.

NSE	Case (R = rain in mm/h and S = slope in %)			
	R = 35 S = 1	R = 35 S = 6	R = 70 S = 1	R = 70 S = 6
PICP	0.729	0.975	0.909	0.990
PA	0.909	0.934	0.984	0.964

4 CONCLUSIONS

The results show that the model fits well with the hydrographs generated by a single rainfall event on PICP and PA, indicating that the model's reliability is high when pervious pavements are modelled using SWMM's LID editor. Hence, physical parameters of the pavement are sufficient to model a permeable pavement. That shows laboratory defined parameters could be extrapolated to other similar catchments and implemented in a GIS based automatic catchment discretization, if homogeneous layers were properly defined.

Despite this, drainage layer parameters have an enormous influence on the outflow going out of the section. In this investigation the coefficient and exponent of the drainage layer were calibrated for a specific test bench, with a completely free side, but these parameters have no physical significance, model may be improved at this point. In addition, laboratory tests confirm that permeable pavements do not generate surface runoff for common rainfall events, at least when they are new.

Differences between the PICP and the PA were also observed but seems to be related to differences in void ratio. In any case, it would be desirable to go deeper into the characteristics of both, since there is a great variety of pavement types of pavements and possible layouts.

As far as future research is concerned, it would be interesting to analyse the performance of permeable pavements as opposed to their clogging. It would also be useful to analyse the behaviour of the pavement during continuous events, when the climatic characteristics of the environment influence its operation. Likewise, it would be desirable to analyse the specific performance of other types of LID, or how these could be automatically integrated into the model through GIS.

In conclusion, the research makes it possible to increase the reliability of the models used to analyse drainage networks that use SUDS techniques, the relevance of which will surely increase in the cities of the future: better adapted to the environment, more sustainable.

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