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Numerical Comparison of the Hydrological Response of Different Permeable Pavements in Urban Area

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Abstract: Floods are becoming more frequent, especially in urban environments where most of the surface is waterproofed. Permeable pavement (PP) can be applied as low impact development (LID) systems for runoff mitigation in urban areas. Their effectiveness can be assessed, case by case, by numerical simulations. In this study, the effectiveness of mitigating runoff of different permeable pavements has been evaluated. In particular, porous asphalt (PA), pervious concrete (PC), permeable interlocking concrete pavement (PICP) and grid pavement (GP) have been investigated using EPA Storm Water Management Model (SWMM) software. To this aim, a car parking area located in the University Campus of Palermo (Italy) has been taken as a case study, considering several scenarios, each having a different percentage and planimetric layout of a PP type combined with an impermeable pavement. All the scenarios were tested assuming four synthetic rainfall events, referring to return periods of 5, 10, 50 and 100 years, and a real high return period event that occurred in Palermo in 2020. The results showed that amongst the different PPs considered, only the PA, bounded at the bottom by an impermeable layer, was practically ineffective. The other three PPs, proved to be effective in a noticeable way and furthermore for each scenario studied, they proved to bear almost the same mitigated runoff. The results proved appreciable differences in runoff as a function of the location of the PP over the study area.

Keywords: low impact development (LID); permeable pavement; permeability; urban hydrology; SWMM

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1. Introduction

The construction of streets, squares and buildings leads to soil waterproofing, which dramatically changes urban hydrological balance, as water cannot infiltrate into the ground anymore. Therefore, dangerous runoff can occur even at medium intensity rainfall. In short, increasing impervious areas to the detriment of pervious areas can cause heavy hydraulic problems (e.g., [1,2]).

Many studies on the problems caused by soil waterproofing have been carried out over the world in the last few decades, aiming at obtaining good post-urbanization drainage and reducing environmental impact [3–6]. Several strategies have been developed which are often called by different names, such as sustainable drainage system (SuDS) in the UK, low impact development (LID) or best management practices (BMP) in Canada and the USA and water-sensitive urban design (WSUD) in Australia. The strategies for runoff reduction include the realization of pervious pavements (PP), swales, filter drains, green roofs, etc., usually indicated in the technical literature as LIDs. The different LIDs can be used individually or in combination, and their arrangement over the urban area has to be carefully studied.

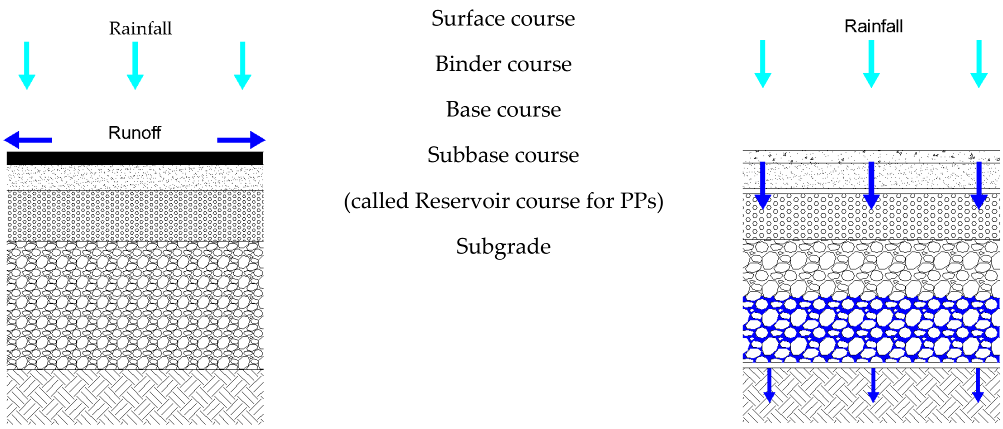
PPs have a major role in allowing water infiltration, which improves city resilience to rainfall events [7–10]. Their hydraulic performance can be assessed by both laboratory and field tests [11,12]. However, their effectiveness as a LID for a specific case has to be estimated at an urban scale, which is usually carried out by numerical simulations carried out with appropriate software. The EPA SWMM software is widely used. These simulations provide useful information for selecting the most appropriate PP in terms both of type and planimetric placing in combination with traditional impermeable pavements, which also perform better from a mechanical point of view than PPs. The present study focuses on runoff mitigation using PPs.

There exist four types of PPs, each one having specific hydraulic and mechanical characteristics [13]. These characteristics and their dependence on the characteristics of the single elements of the pavement, such as gradation, porosity, aggregate shape, etc., are still the object of studies (e.g., [14–17]). In the present paper, after the main characteristics of the four types of PPs are described, their effectiveness in mitigating runoff is compared for a study area located in the University Campus of Palermo (Sicily, Italy). The comparison is carried out by means of numerical simulations performed using EPA SWMM and concerns several scenarios, each relating to different areal percentages and planimetric layouts of PP and impermeable pavement, as well as different rainfalls.

2. Types of Pervious Pavements (PPs)

Pervious pavements (PPs) are a logical stormwater management solution in an urban environment, as they allow water to infiltrate through the pavement to the underlying course from which it is then discharged [4,18,19]. Because of their limited mechanical characteristics, PPs are commonly used in areas for light vehicles or pedestrian use [4,18,19], generally with speed limits up to about 90 km/h: as reported by some authors [13,20], a maximum of 1 million Equivalent Single Axle Loads of 80 kN is typically recommended for the whole service life. Moreover, because of high permeability, PPs are not recommended for areas that may have a high potential for pollutants, sediment deposition or organic matter accumulation [20]. PPs can also be applied as overlays on highways, as permeable friction courses or as open-graded friction courses [17,18,21].

In traditional pavements (Figure 1a), the upper layer is bounded by bitumen or concrete, ensuring good mechanical resistance to vehicle loads but making the pavement impermeable. By contrast, there are no waterproof layers in PPs (Figure 1b). These structures are characterized by large voids that allow water to infiltrate [2]. Overall, the stratigraphy of PPs is similar to that of traditional pavements, but each layer has higher porosity constituted by interconnected voids, which are necessary for allowing water drainage. The primary goal is to reduce runoff volume, thus promoting hydrograph attenuation [22]. In order to prevent the occurrence of appreciable runoff, the pavement permeability should be higher than the rainfall intensity [23].



(**a**) (**b**)

Figure 1. Schemes of traditional pavement (**a**) and pervious pavement (**b**).

In PPs, water that has passed through the upper layers and accumulated in the subbase course can move away by three types of drainage systems [1]:

- Type I, total infiltration system (Figure 2a): all the water infiltrates the subgrade;
- Type II, partial infiltration system (Figure 2b); because of insufficient permeability of the subgrade or other designer choice, a part of the water is drained by a pipe system;
- Type III: no infiltration system (Figure 2c); because of impermeable subgrade, all the water is drained by a pipe system.

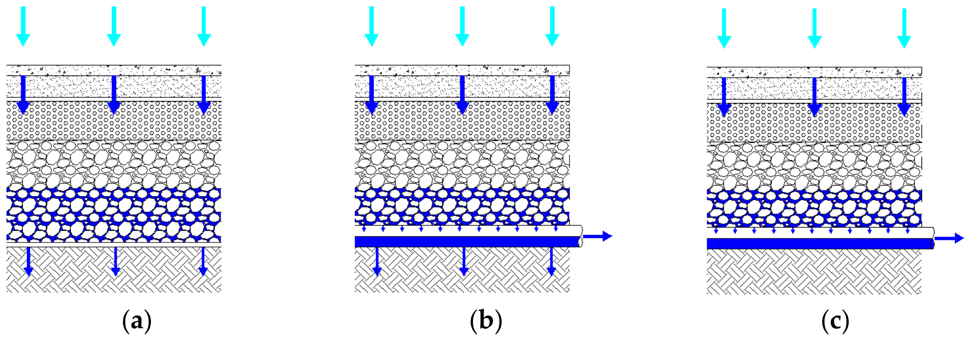


Figure 2. Types of drainage systems of PPs: (**a**) total infiltration; (**b**) partial infiltration; (**c**) no infiltration.

The choice of the drainage system depends on the site features and the subgrade permeability [18,23]. Simple infiltration in the subgrade is the easiest choice for granular soils, but it is unsuitable for fine soils such as clay soils and/or loamy soils, where infiltration is very slow. However, the solution of infiltrating the water to the subgrade may not always be good, for instance, in the presence of buildings nearby, as infiltrated water could reduce the soil's mechanical resistance causing subsidence [24]. Another problem may arise from the presence of groundwater, as pollutants on the pavement could infiltrate with rainwater and pollute the groundwater itself. However, there are many cases requiring a specific study.

The surface course can be made with different materials and layouts, usually in accordance with four major types (Figure 3): Figure 3a: porous asphalt (PA); Figure 3b: pervious concrete (PC); Figure 3c: permeable interlocking concrete pavement (PICP), also called concrete block permeable pavement (CBPP); Figure 3d: grid pavement (GP), made of either concrete (CGP) or plastic (PGP) [23]. PA and PC are also referred to as monolithic pavements and PICP and GP as modular pavements [4,25]. All types of PPs share common goals: (i) encouraging infiltration to reduce stormwater runoff, (ii) improving water quality through various filtering, chemical and biological treatments and (iii) providing water storage [19].

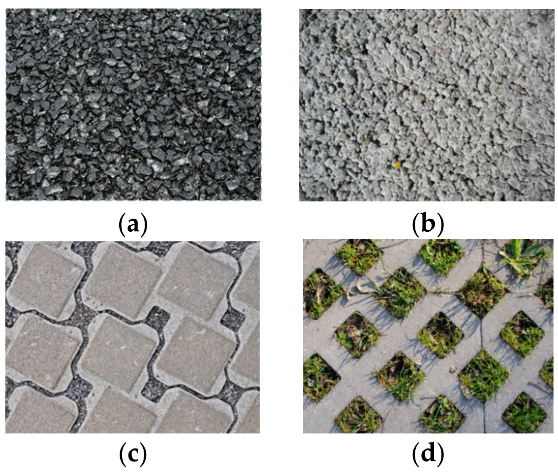


Figure 3. Different types of PP: (**a**) porous asphalt (PA); (**b**) pervious concrete (PC); (**c**) permeable interlocking concrete pavement (PICP); (**d**) grid pavement (CGP if in concrete or PGP if in plastic).

PA (Figure 3a) is similar to conventional asphalt but uses almost uniform coarse aggregates without the fines (passing either 0.063 mm for CNR/UNI or 0.075 mm for USCS) in order to create a greater void space allowing water infiltration [19,20,25]. In this type of pavement, voids usually range from 18% to 25% and thicknesses between 75 and 180 mm, depending on the traffic design volume [19].

PC (Figure 3b) is also made of almost uniform coarse aggregates without the fine ones [19,20]. The result is a rigid pavement with 15–25% of interconnected voids. The base layer is an open-graded aggregate, having 40% of voids. In a freeze–thaw climate, the minimum thickness is 30 cm [13,20].

PICP (Figure 3c) consists of impervious concrete elements arranged with intermediate pervious joints through which water infiltrates [20,23]. The total permeable joint area usually ranges between 5% and 20% of the whole pavement surface. The pervious joints are filled with the same sand as the bedding layer, usually 2–5 mm [19,20]. The pavement structures also include a subbase layer, usually 300–500 mm thick, made of 20–63 mm aggregates [19]. The permeability varies between 2500 and 4000 mm/h, where the minimum value is specified in the technical standards in order to prevent clogging [23].

GP (Figure 3d) consists of concrete (CGP) or plastic (PGP) elements, each having one or more holes filled by permeable material such as small aggregates (ASTM No 8 or No 89), sand or topsoil with grass. The concrete grid elements are defined in ASTM C1319 Standard Specification for Concrete Grid Paving Units. The whole permeable surface of CGPs is between 20% and 70% and looks like continuous grass [20], whereas PGP presents a permeable surface between 90 and 98% [19]; they can be made of recycled materials and are formed by geocells filled with aggregates or topsoil with grass.

PPs are suited for light vehicular traffic only, and therefore, they are frequently used for parking lots, pedestrian walkways, etc., while they are not recommended for loading areas or areas subject to high daily use [20]. Typical ranges of the main parameters of PP are summarized in Table 1.

Table 1. Range of values of PP parameters suggested in the technical literature.

Types	Thickness (mm)	Porosity	Permeability (mm/h)	Authors
PA	75–180	18–25%	7000–50,000	[19,26]
PC	100–300	15–35%	10,000–30,000	[20,25,27,28]
PICP	80		2500–4000	[19,23,29,30]
GP	80		3600	[20]

Besides runoff mitigation, the use of PPs involves a few other benefits, such as thermal mitigation, reduced pollutant concentration and groundwater recharge [18,31]. On the other hand, dealing with a PP system implies some drawbacks, such as the reduction in structural capacity of the pavement and the need for frequent maintenance activities (and related costs) to ensure the permeability requirements are satisfied during the service life.

Several authors (e.g., [19,29,32]) have compared the different types of PPs, showing that they are very effective in reducing surface runoff and flow peak. In particular, according to Gomez-Ullate and coauthors [32], the runoff reduction could be higher than 98%. The performances of all PPs in terms of peak reduction are similar to one another. Actually, the reduction in runoff of PICP changes depending on the different block shapes and assembly schemes that cause the joints to form continuous channels or not.

In the next section, an investigation of the effectiveness of PPs in a study case will be carried out using a hydrological-hydraulic model (EPA SWMM) framework.

3. Numerical Investigation on PPs Effectiveness in a Case Study

3.1. EPA Storm Water Management Model (SWMM)

EPA SWMM is a dynamic model used to analyze stormwater runoff produced by rainfall events and to design and/or verify urban drainage systems. The runoff component of SWMM operates on a set of subcatchments that receive precipitation and generate runoff and pollutant loads [33].

The model accounts for LIDs, which are practices distributed over urban areas, considering each of them as a fraction of or a whole subcatchment object [34].

A PP is represented in the model by a surface that receives direct rainfall and runoff coming from nearby areas as well as producing outflows towards the adjacent sub-catchments and a few horizontal layers beneath the former. Three layers are identified in PPs, namely *pavement*, *soil* (an optional layer) and *storage*. In the SWMM pattern, water moves through each layer for evapotranspiration and/or infiltration. In the bottom layer (the storage), the accumulated water infiltrates the subgrade and/or moves away by a drainage pipe system. In accordance with this pattern, a PP unit is modeled in SWMM by the classical continuity equations relating to each layer and the pavement surface [34].

3.2. The Case Study Used for the Investigation

A case study was used to investigate the positive effects of PPs. The study area is a car parking area located within the University Campus of Palermo (Sicily, Italy) (Figure 4a). The parking area is located along an inside lane of the campus, and the relating boundary line was considered in the study as a watershed (no run-on to the parking area). The S-W boundary line is a wall that hydraulically isolates the parking area. The whole area of the parking is 1387 m^2, of which only 1275 m^2 are given to a parking pavement, and the remaining part to flowerbeds and sidewalk (Figure 4b). The area is almost an inclined plane with a slope of about 1.5%, whose maximum slope direction is indicated by the arrow. The car parking area is divided into three transit lanes with parking spaces on both sides and a main lane of connection (on the S-E side). The subgrade in the area studied is constituted by nodular calcarenites, irregularly fractured.

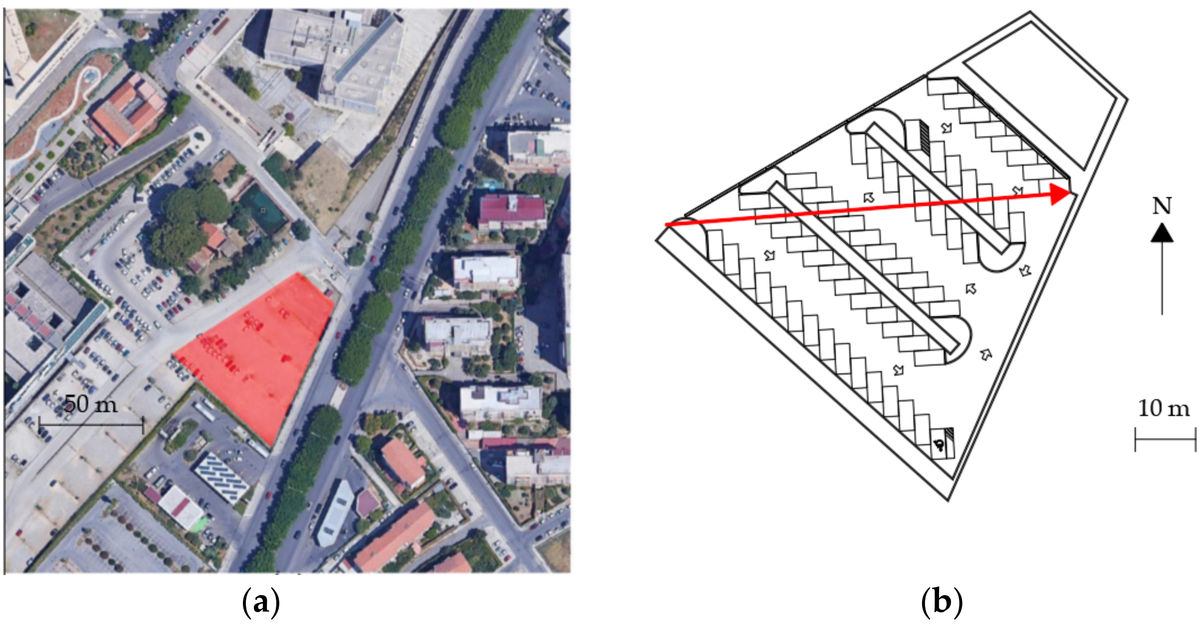


Figure 4. The car parking area taken as a case study: (**a**) localization in the University Campus; (**b**) plan of the parking area.

Figure 5 presents a flow chart that describes the single steps of the analysis carried out for the purpose of this study: first, the definition of the rainfall events was carried out, together with the selection of the modeling tool (EPA SWMM), then the choice of the car parking area along with its characteristics was made. The types of PP were selected: their layouts were defined, and different percentages of surface covered with the PP were associated with each scenario studied. Then, the runoff corresponding to each rainfall event was simulated for each scenario and the results obtained were eventually compared.

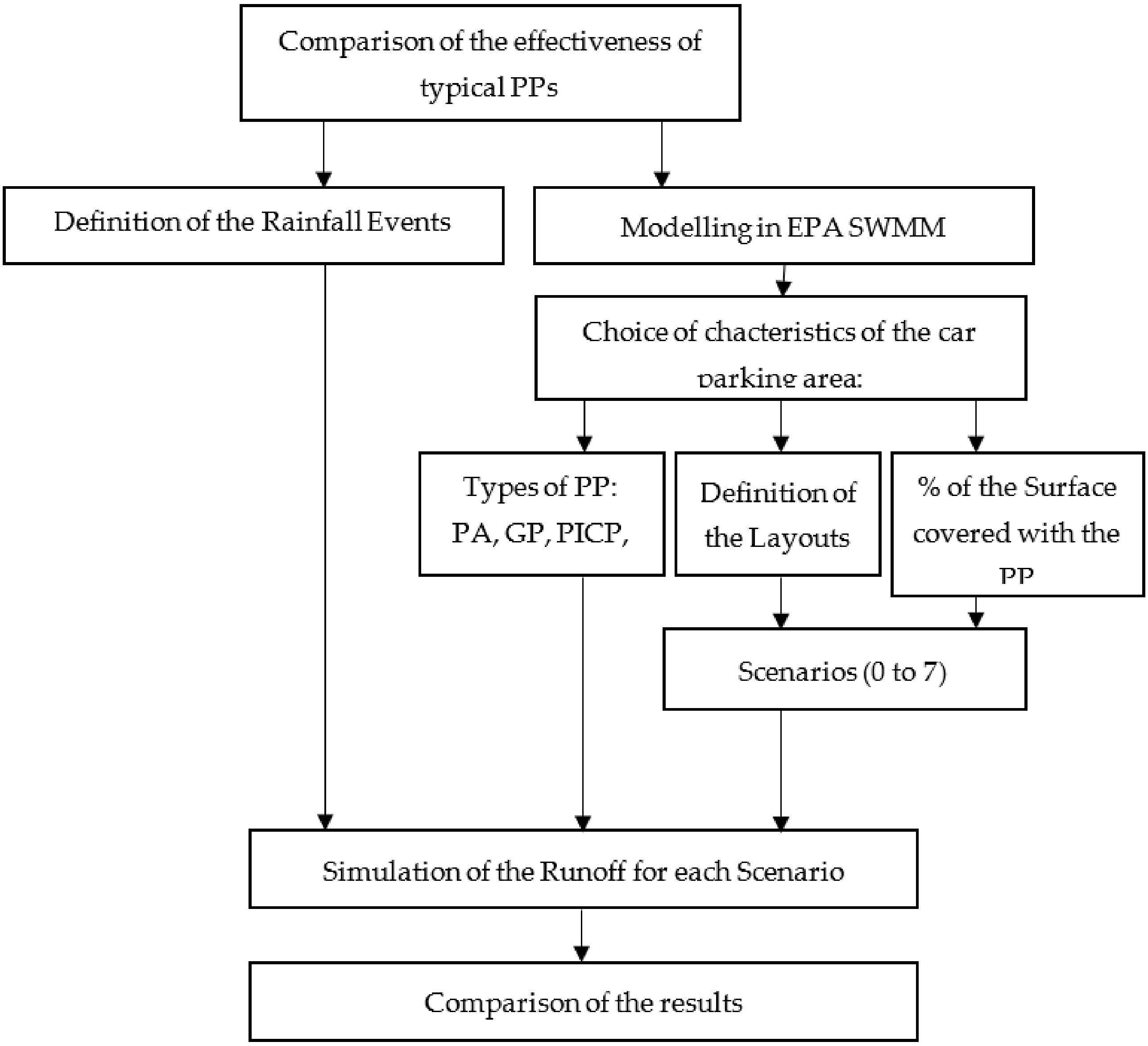


Figure 5. Method flowchart describing the study steps carried out.

Several simulations were carried out considering seven scenarios, each relating to a different areal percentage of permeable pavement and a different layout of permeable–impermeable pavements (Figure 6). Scenario 1 provides for the whole area covered by the PP (actually, 91.9% because of flowerbeds and sidewalk); Scenarios 2, 3 and 4 consider a permeable pavement covering, respectively, both sides (parking spaces) or only one of the sides of each of the three parking aisles, whereas Scenarios 5, 6 and 7 consider three different portions of the main lane only. For each scenario, the aforesaid four PP types were assumed in turn: PA, PC, PICP and GP, whose assumed characteristics are shown in Figure 7. Furthermore, scenario 0, assuming the whole parking area is covered by impermeable pavement, was considered a benchmark to assess the advantage given by each scenario providing for some permeable pavement.

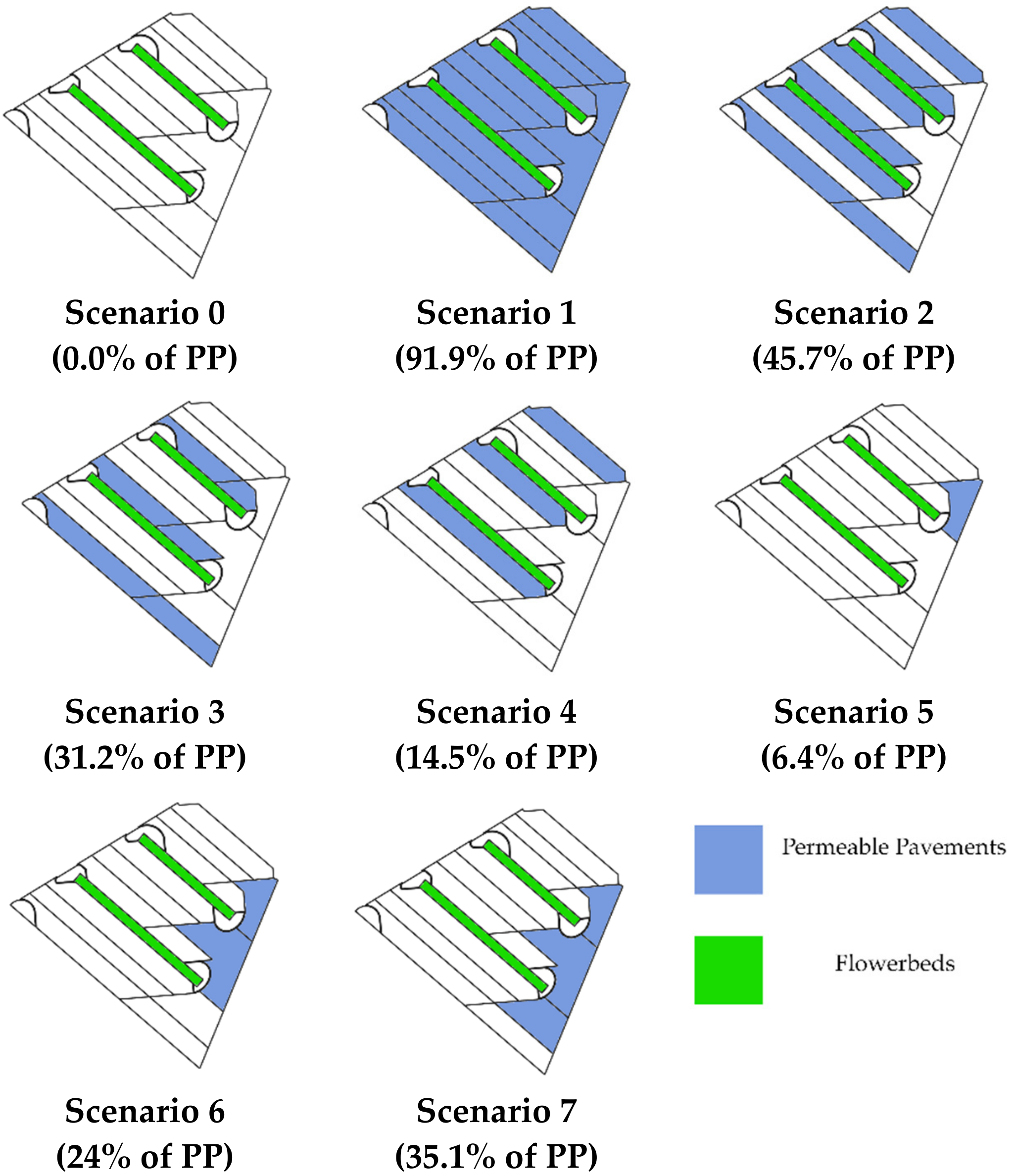


Figure 6. Scenarios examined: Scenario 0: no PP; Scenario 1: the whole pavement is covered by PP; Scenario 2: only the parking spaces are covered by PP; Scenario 3: only the parking spaces located upstream from the respective aisles are covered by PP (PP catch only rainfall fallen on itself); Scenario 4: only the parking spaces located downstream of the respective aisles are covered by PP (PP catches both rainfall falling on itself and run-on from the subcatchments upstream of it); Scenario 5: only the downstream subcatchment, which the runoff of the whole area flows into, is covered by PP; Scenario 6: only the two downstream subcatchments of the main lane are covered by PP; Scenario 7: the whole main lane is covered by PP.

PC, PICP and GP were modeled as constituted by two layers only, pavement and storage (Figure 7), and PA without a storage layer because of the presence of a very thin impermeable layer of bituminous emulsion used to assure adhesion between the surface course (the pavement in SWMM) and the layer below. The parameters required by SWMM to characterize each pavement were set as in Table 2; these values were the "worst" found in the technical literature. For the fractured calcarenites constituting the subgrade, a value of permeability equal to 36 mm/h was set. Amongst the possible types of drainage systems, infiltration was assumed (Type I, Figure 2a).

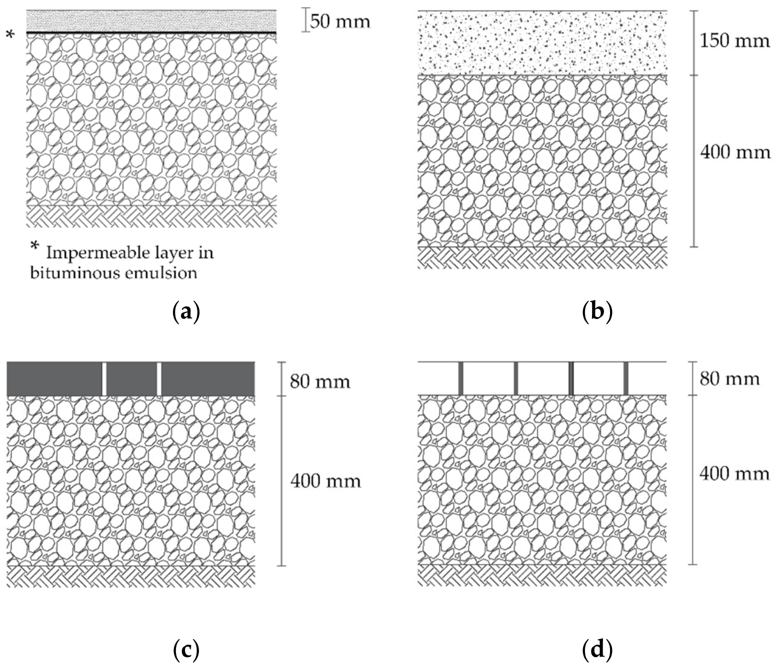


Figure 7. Thicknesses of the layers of each PP: (**a**) porous asphalt (PA); (**b**) pervious concrete (PC); (**c**) permeable interlocking concrete pavement (PICP); (**d**) grid pavement (GP).

Table 2. Parameters assumed for characterizing the PPs in the SWMM case.

	Layers	PA	PC	PICP	GP
Surface	Berm height (mm)	0	0	0	0
	Vegetation volume fraction	0	0	0	0
	Roughness (Manning's n)	0.01	0.015	0.015	0.015
	Surface slope (%)	1.5	1.5	1.5	1.5
Pavement	Thickness (mm)	50	150	80	50
	Void ratio (voids/solids)	0.18	0.15	0.2	0.2
	Impervious Surface fraction	0	0	0.95	0.2
	Permeability (mm/h)	7000	10,000	2500	3600
	Clogging factor	0	0	0	0
Storage	Thickness (mm)	0	400	400	400
	Void ratio (voids/solids)	0	0.4	0.4	0.4
	Seepage rate (mm/h)	0	36	36	36
	Clogging factor	0	0	0	0

For modeling purposes, the car parking area was divided into 20 subcatchments, including 5 specific subcatchments for the sidewalks. The areas occupied by flowerbeds (roadway dividers) were neglected since they were considered totally permeable (i.e., making no contribution to the runoff). The subcatchments were connected to each other in accordance with the slope of the area. As the performance of PPs in mitigating runoff mainly depends on infiltration and storage, nodes and links were not modeled. As for runoff, SWMM considers a normal flow ruled by Manning's equation on an equivalent rectangular subcatchment.

For all the combinations of scenarios and PPs, four synthetic hyetographs (i.e., storm events simulated through the statistical elaboration of historical rainfall data) with return periods of 5, 10, 50 and 100 years, named, respectively, T5, T10, T50 and T100, were considered. To this aim, the TCEV (Two-Component Extreme Value) method was used, adopting specific parameters for Sicily [35], relating to the considered return periods and the parking location. A rainfall duration of 1 h was assumed. For a close description of the process, a time interval of 1 min was chosen for rainfall depths, less than the expected concentration time. As for the rainfall depths minute by minute to be considered, the empirical relationship by Ferreri and Ferro [36] for short-duration rainfalls in Sicily (duration $d < 1$ h) was adopted:

$$\frac{h_{d,T}}{h_{60,T}} = 0.208 \cdot d^{0.386} \quad (1)$$

where d (min) is the rainfall duration, $h_{d,\ T}$ (mm) the related rainfall depth of return period T and $h_{60,\ T}$ (mm) the rainfall depth relating to d = 60 min and return period T. Synthetic hyetographs were produced following [37]. A further simulation was finally carried out using a real event, named R20, which occurred in Palermo on 15 July 2020 (Figure 8) whose estimated return period is about 90 years [38].

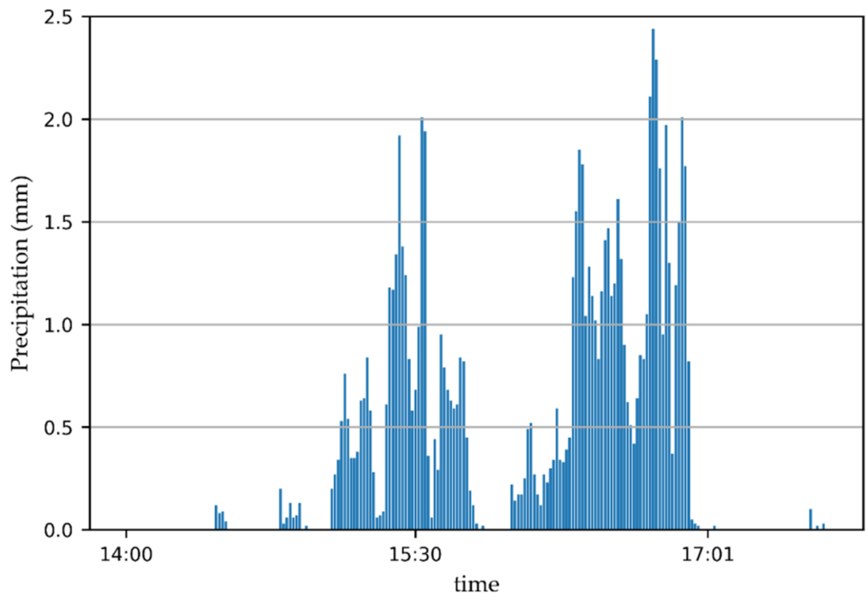


Figure 8. Hyetograph of the real event R20.

4. Results and Discussion

The parameter chosen to assess and compare the performance of the PPs was the runoff of the downstream subcatchment, which the runoff of the whole area flowed into.

Figure 9a,b show the runoff simulated for events T5 and T100. The runoffs of events T10 and T50 are consistent with the former and are not reported for brevity. All the hydrographs related to PPs are lower than that related to Scenario 0 (without any PP), thus proving the effectiveness of using PPs in reducing the surface runoff. PA provides hydrographs that are always higher than the other PPs due to the presence of the impermeable layer in bituminous emulsion under the surface course. Therefore, the void volume available in the surface course works as a small storage volume for the rainwater. Pavements PC, PICP and GP provide hydrographs practically superimposed with negligible differences for rainfall T5 and slightly visible for rainfall T100 (see Figure 9a Scenarios 4, 6 and 7). In a few situations, these PPs do not bear runoff (Figure 9a Scenarios 1, 6 and 7; Figure 9b, Scenario 1). The results relating to the real event R20 (Figure 9c) are consistent with the former ones, but during the second peak, the PP hydrograph approaches that of Scenario 0, probably because of the longer duration of the rain, which causes the filling of the storage.

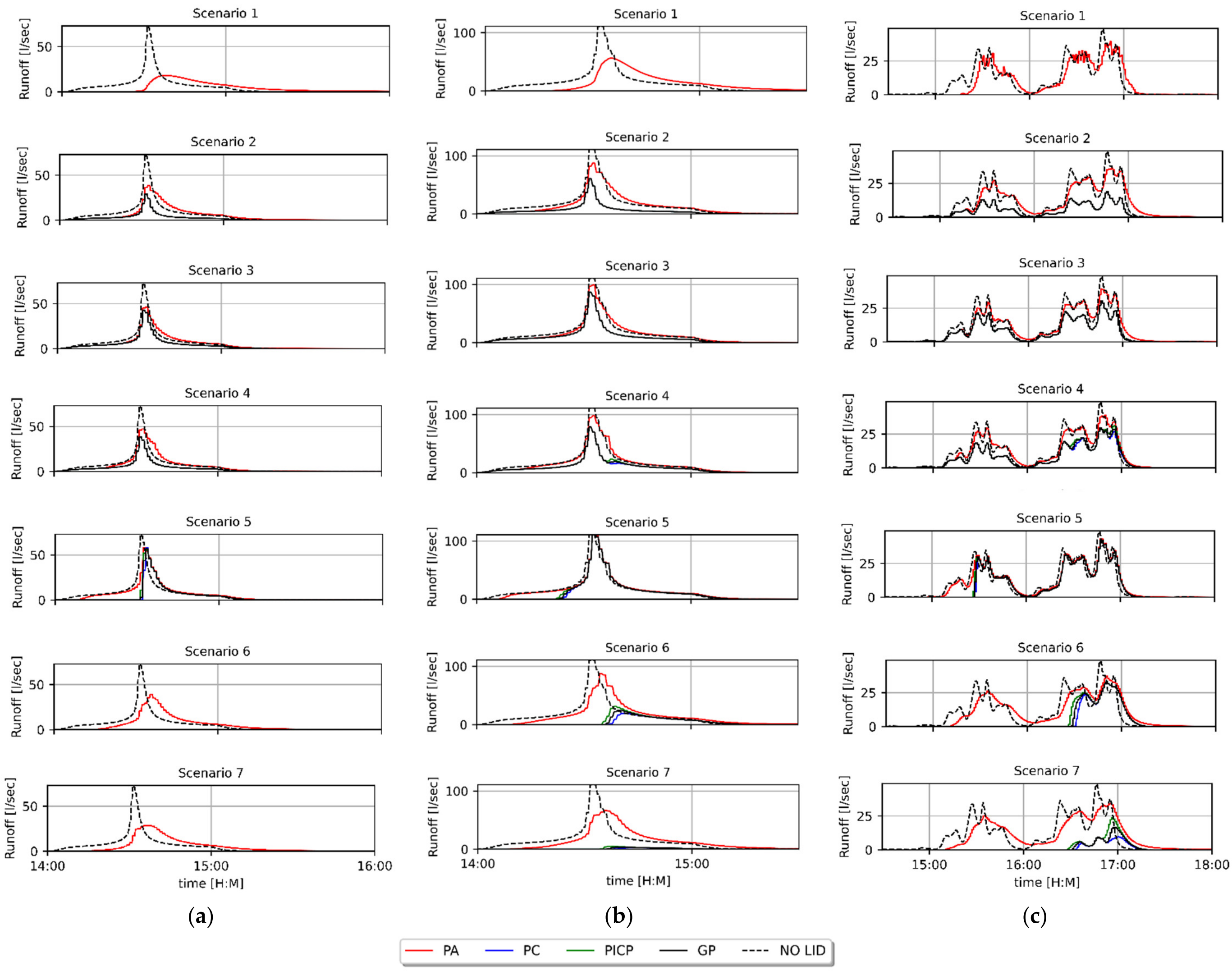


Figure 9. Runoff simulated for synthetic rainfalls: (**a**) T5 and (**b**) T100 and for real rainfall event (**c**) R20.

Figure 10, relating to events T5, T100 and R20, respectively, shows the histograms of the ratio between the runoff volume of each combination scenario—PP—and the volume of Scenario 0. In particular, for each scenario identified by the related PP areal percentage, the ratios relating to the four PPs are grouped around the areal percentage itself. This concise representation allows the effects on runoff reduction of PP type, PP areal percentage and permeable–impermeable layout to be easily compared to each other. For instance, for event T100 and scenario 4, the figure shows that PC, PICP and GP show almost equal ratios of about 0.6, noticeably lower than the PA ratio equal to 0.98. As expected, all the PPs prove to be more or less effective for runoff reduction with respect to Scenario 0. In detail, for each scenario, PA exhibits the lowest reduction in runoff, whereas PC, PICP and GP exhibit a very similar and more effective reduction in runoff.

In particular, the most effective scenario for the five rainfall events simulated is Scenario 1, which has 91.9% of its area covered by PP, and there is no runoff at all for PC, PICP and GP. In general, a different areal percentage of PP effects is noticeable on runoff production.

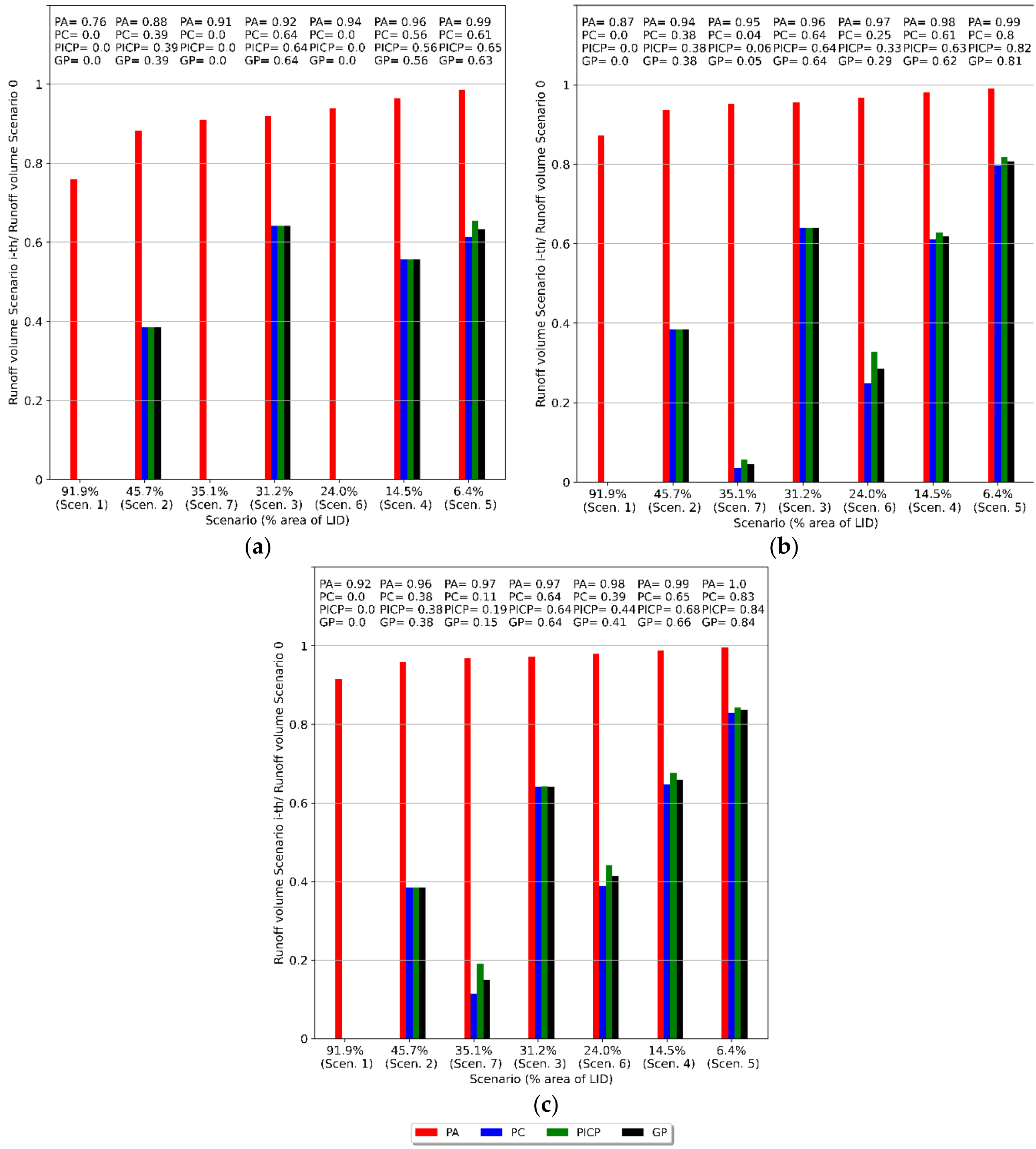


Figure 10. Comparison of the reduction in the runoff volume for all the combinations of scenarios and PPs related to events T5 (**a**), T100 (**b**) and R20 (**c**).

However, it is interesting to note that a larger area covered by PP does not always imply better performance. This is the case, for instance, of Scenario 7, having a PP areal percentage of 35.1%, which shows noticeably lower ratios than Scenario 2, having an areal percentage of 45.7%. These results prove that the spatial layout of the areas covered by PPs is as important as the total amount of the areas themselves. Therefore, much care has to be paid to spatial layout in designing the pavement of an urban area.

Indeed, a further parameter to be considered when designing an urban pavement is the slope of the area due to its effect on runoff velocity and, consequently, on the concentration time. In this study, a constant value was assumed, which was equal for all the scenarios.

5. Conclusions

Nowadays, extreme rainfall events are becoming more frequent due to climate changes, and stormwater flows are a serious problem in urban areas, where the presence of streets, squares and buildings represents an impervious layer that strongly impacts the hydrological balance. A possible strategy for mitigating urban flooding by properly managing stormwater is given by the approach that makes use of the low impact development (LID). In this regard, permeable pavements (PPs) are types of LIDs that allow water to infiltrate from the road surface to the subgrade. PPs can be an alternative to traditional pavements, although they have some specific features to be taken into account. These features are reduced mechanical resistance due to their high void content, which makes them inadequate for high traffic volumes as well as the need for frequent maintenance to avoid clogging and the consequent reduction in permeable voids. Due to these technical and economic drawbacks as well as to a substantial lack of knowledge about these technologies, PPs are not widely widespread or promoted.

The main goal of the present study was to improve understanding of PPs, by comparing their hydraulic performances through simulations modeled with EPA SWMM. A car parking area was modeled, and different design scenarios and rainfall events relating to different return periods were simulated. The results of this study show that all PPs prove to be an effective solution for urban flood mitigation since they all greatly reduce the runoff in comparison to that simulated for the traditional solution, with an impervious pavement only (Scenario 0). In particular, PC, PICP and GP provide almost identical runoff values, except for during the rainfall event characterized by the highest return period. Furthermore, the results also prove that a strategic position of the PP in the whole area, mainly taking into account its geometric features and slope, provides an even better solution than that offered by a wider area covered with PPs, not considering the characteristics of the area.

In conclusion, the results of this study prove that the typical PPs are comparable in terms of hydraulic efficiency; therefore, the selection of the most appropriate may be based on mechanical, aesthetical and economic evaluations. Furthermore, it has been proved that covering the whole area with PP is not strictly necessary: besides, as mentioned before, such a solution is not always technically or economically feasible. Based on the results presented, a small PP area placed downstream of an impermeable one proves to reduce the runoff much more than that obtained with a larger PP area placed upstream. This conclusion can also be useful for designers and developers when considering the possibility of using PPs in an urban context.

Some limitations of the study must also be considered: PP performances were evaluated based on parameters found in the literature; a better understanding based on both laboratory and field measurements of these performances is necessary for fostering acceptance and diffusion of PPs as a key LID technology.

Further studies will also have to involve the evaluation of the influence of the area slope, which was not investigated in the present paper, as well as that of the size of the area.

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Conflicts of Interest: The authors declare no conflict of interest.

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