Impact of Permeable Pavement on Stormwater Runoff in Urban Areas: A Case Study of Leiria

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Abstract. The human occupation in high demographics density areas causes a series of environmental impacts. Among these impacts, special attention should be given to the alteration of hydrological cycle caused by the impermeabilization of the surface, which creates an increase in the peak flow stormwater runoff and a decrease in lag time, which are involved in urban flooding. This paper evaluates the impacts of permeable pavement as a sustainable solution to reduce stormwater runoff in Capuchos Urbanization, Leiria city. This area was chosen because it is a consolidated urban environment with information about water catchment and drainage network. A Storm Water Management Model (SWMM5.1) was developed to evaluate the performance of drainage network, for different rainfall intensity and with/without permeable pavement. The results show that permeable pavement preset to be a good solution to reduce the peak flow of stormwater drainage network and, consequently, the mitigation of the risk of flooding in urban areas.

Keywords: Urban area · Permeable pavement · Stormwater drainage network · SWMM

1 Introduction

It is undeniable that human presence has a great impact over the changes in the natural environment, mainly in regions with a great agglomeration of people, such as large cities. According to Araújo et al. [1], urban occupation through impermeable areas, such as roofs, sidewalks, pavements, parking lots and others, changes the hydrological cycle in urban areas, resulting in an increase of urban floods and degradation of the quality of water bodies in the receiving environment. It is also noteworthy that intense convective rains can be aggravated by the phenomena of heat islands, which are formed over the more urbanized surfaces [2].

According to Broekhuizen et al. [3], the stormwater drainage network traditionally adopted in urban areas is based on the use of pipes for a quick removal of local runoff, ignoring the possible consequences of floods and water quality downstream,

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being also financially expensive to construct and sustain networks. In this way, a sustainable stormwater drainage network tries to correct these problems by carrying out runoff management in a more natural way [4].

As defined by the Construction Industry Research and Information Association [5, 6], sustainable stormwater drainage network is a set of sustainable rainwater control and management techniques and has emerged as an alternative to the traditional stormwater drainage network in urban areas. In this study, the permeable pavements were conceived to manage the stormwater runoff management, to reduce the risk of flooding in Leiria's downtown [7]. The permeable pavements provide a paving system suitable for both pedestrians and vehicles, allowing rainfall to infiltrate superficially towards the lower layers [5, 6].

2 Study Area Description

The study was focused on the area of the Capuchos Urbanization, close to downtown Leiria (Portugal). This is a consolidated urban area where the characteristics of water catchment and drainage network are known (Fig. 1).

Fig. 1. Study area identification (Adapted from Google Earth, 2018)

The case study has a total area of 10.82 hectares, of which 62% are occupied by buildings, 31% are covered with pavements and sidewalks and 7% are green or permeable areas. The ground elevation is quite irregular, with land plots with slopes of 20%, and others flat. The occupation is mainly residential, with a single-family and multi-family buildings. Two important infrastructures that stand out are a school unit and a parking lot. Some commerce activities can also be found, but without great relevance.

The stormwater drainage network includes three outlet points: E1, E2 and E3. The E2 outlet is connected to Leiria downtown's stormwater drainage network, where the risk of flooding is real. Each outlet point defines a small water catchment of the stormwater drainage network for study area (Fig. 2): i) Network E1 has 218 m and the pipe diameter is 300 mm, ii) Network E2 has 409 m and pipe diameters of 300 and 400 mm, and iii) Network E3 has a 411 m and pipe diameter of 300 mm, and 400 mm closer to the outlet point. The pipe material is concrete [8].

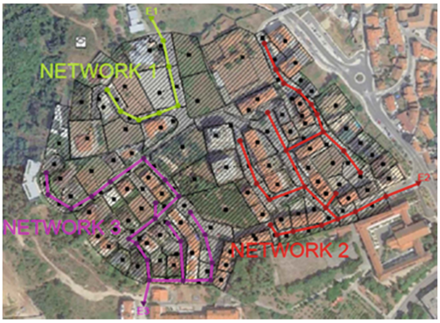

Fig. 2. Stormwater drainage network.

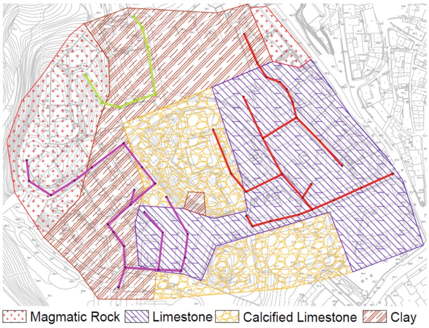

Fig. 3. Definition of the geological units.

Regarding the soil permeability, it was assessed based on the Geological Map of Portugal provided by the National Energy and Geology Laboratory - LNEG, namely “Folha 23-C – Leiria” [9], and the geological nature of the outcropping materials (magmatic rock, clays and limestone). The magmatic rock, which was much altered and fractured, was considered permeable, the clays were considered impermeable and the limestone, which was found in thin layers and sometimes calcified, was considered semi-permeable.

Based on a visual inspection carried out in the study area, it was possible to establish more precisely the geological units that have more influence on the stormwater drainage networks in the study area (Fig. 3). Also, it was possible to describe the correlation between the types of soil found and the respective permeability rates adopted (see Table 1).

Table 1. Permeability rates.

Soil type	Permeability rates (m/s)
Magmatic rock, altered and very fractured	10^{-2} m/s (high permeability)
Limestone rock	10^{-5} m/s (average permeability)
Calcified limestone rock	10^{-7} m/s (low permeability)
Clays	10^{-9} m/s (very low permeability)

3 Hydrological and Hydraulic Modelling

To evaluate the advantage of permeable pavement, different scenarios were performed for the case study – with different rainfall intensity. A Storm Water Management Model

(SWMM5.1) was developed to evaluate the performance of stormwater drainage network. The Infrastructural Department of Leiria Council provided the set data of the drainage network.

For each small water catchments shown in Fig. 2 (E1, E2 and E3) three categories for land cover were defined: i) buildings; ii) pavements and sidewalks; and iii) green areas. The land cover categories were established considering the different level of rainwater infiltration. The categories "buildings" was carried out to respect the configuration of the existing land plot subdivisions. The Municipal Planning Directive of Leiria (2018) establishes 80% for construction area. It is important to highlight that the plots without occupation were considered built, thus admitting possible future construction. All plots were considered earthworks to simulate construction conditions, so a slope of 1% was considered. The categories "pavements and sidewalks" were defined as the area currently intended for sidewalks and street public roads. In this case, it was decided to consider the value of 100% impermeabilization, since the infiltration capacity in this type of covering material can be neglected. The categories "green areas" include the areas defined by the Municipal Planning Directive of Leiria as leisure place, where the maximum construction area is 20%.

The soil's infiltration capacity is another parameter that will have influence in the modelling since it determines the rainwater runoff. The Soil Conservation Service (SCS) method was chosen to obtain its numerical results. According to the Environmental Protection Agency (EPA, 2015), this method is an approximation for estimating the runoff, as this value is obtained from the difference between the soil infiltration capacity, determined through the Curve Number (CN), and the accumulated precipitation volume. The CN varies according to the land cover, the soil type and the soil drying time. According to Environmental Protection Agency (EPA) [10], the soil drying time varies between 2 and 14 days, and the soil types are divided into groups A, B, C and D, as established by the United States Department of Agriculture [11]. The parameters used are summarized in Table 2.

Table 2. Parameters for establishing SCS-CN.

Soil type	Soil group	Drying time (days)
Magmatic rock, altered and very fractured	A	7
Limestone rock	B	7
Calcified limestone rock	C	14
Clays	D	14

According to EPA [10], the layers of permeable pavement system are, generally, surface layer, soil layer and storage layer. The surface layer indicates the portion that directly receives the rainfall and runoff from boundaries areas, stores excess inflow in depressions, and generates runoff into the stormwater drainage network or for downstream areas. It is in this layer that the paving blocks and filling material is used, in the case of modular systems, or porous concrete/asphalt. The soil layer consists of a sand layer with the purpose of providing filtration and accommodation base for a paving blocks layer. The storage layer represents the base and sub-base of the pavement, created by a bed of pebble or gravel used for rainwater retention. For the support soils with low permeability or low resistance drains must be installed in the storage layer.

For the case study, the permeable pavements with two layers were specified, one composed of the pavement, the layer that will receive the runoff, and the other composed of the storage layer, which will be responsible for rainwater retention. A drain has been established to empty the storage layers. The pavement layer includes a thickness of 100 mm, void ratio of 0.2 and permeability of 150 mm/h. The storage layer has thickness of 300 mm, void ratio of 0.4 and permeability according to the soil type. Finally, a drain network with 100 mm diameter was used at the bottom of the storage layer, whose contribution is measured from the flow exponent. The value recommended by EPA [10] is 0.5 and the flow coefficient that is obtained through Eq. 1.

$$C = \frac{2 \times D^{\frac{1}{2}}}{T} \tag{1}$$

where: C is the flow coefficient; D is the distance from the drain network to the surface (mm); and T is the time in which the volume rainwater retained must be drained (hours). It was established a 24-h period for emptying the storage layer.

Figure 4 shows the precipitation for the return period of 10 and 20 years (time step: Δt = 10 min), used to evaluate the performance of stormwater drainage network with/without permeable pavement.

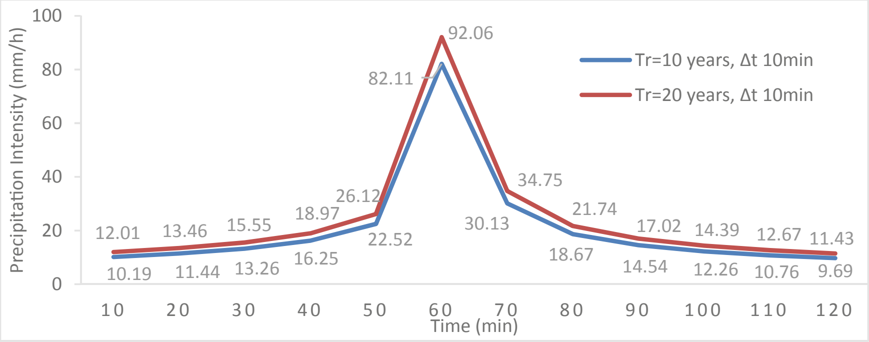

Fig. 4. Precipitation for the return period of 10 and 20 years, Δt = 10 min.

4 Results

4.1 Lag Time

For the lag time analysis of the stormwater drainage networks, a modelling of precipitation with uniform intensity was performed for the return periods of 10 and 20 years (time step: 10, 15 and 20 min). The lag time is defined as a time taken to reach the maximum flow at reference section (E1, E2 and E3). The use of three different precipitation intensities is justified by increasing the database for estimating the value of lag time. Table 3 presents the results of lag time for all networks and return periods. It was noticed that all networks had some reduction in the lag time recorded. This happens because the permeable pavement temporarily retains the runoff.

Table 3. Results of lag time.

Permeable pavement		Return period 10 years	Return period 20 years
Network E1	Without	30 min	30 min
	With	60 mins	60 min
Network E2	Without	35 min	30 min
	With	115 min	150 min
Network E3	Without	25 min	25 min
	With	80 min	75 min

4.2 Peak Flow

For the peak flow analysis of the stormwater drainage networks, a modelling of precipitation for the return periods of 10 and 20 years was performed (Fig. 4). The peak flow is defined as a maximum flow at reference section (E1, E2 and E3). Table 4 presents the results of peak flow for all networks and return periods.

Table 4. Results of peak flow.

Permeable pavement		Return period 10 years	Return period 20 years
Network E1	Without	412.91 l/s	465.82 l/s
	With	280.33 l/s	331.60 l/s
Network E2	Without	735.14 l/s	756.78 l/s
	With	338.99 l/s	448.88 l/s
Network E3	Without	638.13 l/s	669.04 l/s
	With	411.13 l/s	522.91 l/s

It was noticed that all networks had some reduction in the peak flow recorded, and the greatest reduction was observed in network E2. This happens because network E2 is over soil with average permeability (Fig. 3), which increases the infiltration of rainwater. For the return period of 20 years, it is possible to conclude that the registered peak flow is higher, because this return period presents rains of greater intensity.

4.3 Stormwater Runoff

Here a comparative study of the stormwater runoff on water catchments will be carried out, before and after the implementation of the permeable pavement. Return periods of 10 and 20 years were used (Fig. 4). Table 5 presents the runoff results for all networks and return periods.

Table 5. Results for stormwater runoff.

Permeable pavement		Return period 10 years	Return period 20 years
Network E1	Without	362.69 l/s	420.13 l/s
	With	241.45 l/s	288.54 l/s
Network E2	Without	227.35 l/s	263.10 l/s
	With	82.02 l/s	97.88 l/s
Network E3	Without	201.07 l/s	234.00 l/s
	With	91.77 l/s	110.98 l/s

For the return period of 10 and 20 years, the stormwater runoff presents reduction values in the same order of magnitude, which indicates similar behavior. However, a larger stormwater runoff is observed for the return period of 20 years, because of the higher rain intensity. The best results were obtained from network E2, because it is over soil with average permeability (Fig. 3), which increases the infiltration of rainwater.

5 Conclusions

With the increase in the world's population, the influence of human beings on the environment becomes increasingly clear, such as the alteration of the urban hydrological cycle. The results of a case study show that permeable pavements can be used as a sustainable solution to reduce the stormwater runoff in urban water catchments, as well as to reduce the peak flow and increase the lag time in stormwater drainage network, reducing the risk of flooding. It was possible to observe lag time increments greater than 30 min (reaching the maximum value of 1 h and 55 min). The reduction of the peak flow was also significant, ranging from 32% to 54%. And the reduction of the stormwater runoff reduced between 10% to 20%, on soil with low permeability, and 100% on soils with high permeability.

It is important to note that network E2 offers the best performance with permeable pavements, which shows how much this kind of technology can have its potential increased based on the soil infiltration capacity: network E2 is on area of predominantly calcareous soil (average permeability), while networks E1 and E3 there are predominantly installed over clayey soil (very low permeability). It was observed that the soil in water catchments of the network E2 is 10,000 times more permeable than the soil found in water catchment of the networks E1 and E3.

As a future work, more research is required about the cost benefits analysis of the project proposed.

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