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WATERCOURSE FLOW ANALYSIS- USE OF PERMEABLE PAVEMENT: CASE STUDY IN SANTA FÉ DO SUL - SP*

ABSTRACT

Soil impermeabilization caused by urbanization can alter the hydrological cycle and lead to high flow peaks, and eventually, floods. One of the possible solutions is the use of permeable pavements, allowing water to drain and thus return to the water table. This study aimed to analyze rainfall percolation through permeable pavement installed near the Mula stream in Santa Fé do Sul and its impact on the flow. The latter was surveyed 7 times from 04/2022 to 10/2022 with monitoring consistently conducted in three sections of the water body: upstream, downstream and in the middle of the stretch. From April to July, flow was monitored without the use of the drainage pavement whereas from August to October porous concrete pavers were used instead. The sections had a small, rectilinear and regular section. Flow increased by 8.65% for in-situ permeable pavement – thus proving its impact in surface runoff. In addition, the permeable pavement presented satisfactory permeability (>10-3m/s), and compressive strength (>2.0MPa) results meeting NBR 16416 (ABNT, 2015) norms. It was concluded that the use of permeable pavement in light-traffic areas (e.g. around the basin) is not only possible but also beneficial since it allows rainwater to infiltrate the soil and return to the stream, thereby increasing surface runoff.

Keywords: Porous pavement. Flooding. Urbanization.

ANÁLISE DA VAZÃO DE UM CURSO D'ÁGUA DEVIDO AO USO DO PAVIMENTO PERMEÁVEL: UM ESTUDO DE CASO EM SANTA FÉ DO SUL – SP

RESUMO

A impermeabilização do solo devido à ocupação urbana pode alterar o ciclo hidrológico e causar altos picos de vazão, consequentemente, enchentes. Uma das soluções é a adoção de pavimentos permeáveis, criando uma superfície drenante e permitindo o retorno da água ao lençol freático. Nesse contexto, este trabalho teve como objetivo analisar a percolação pluviométrica pelo pavimento permeável no córrego da Mula em Santa Fé do Sul e seu impacto na vazão. A vazão foi monitorada em 7 levantamentos realizados no período de 04/2022 a 10/2022. Para isso, foram feitos monitoramentos em três trechos do corpo hídrico, a montante, a jusante e no meio do trecho, de abril a julho, sem o uso do pavimento drenante. De agosto a outubro, foi feito o monitoramento da vazão nos mesmos pontos, mas com o uso da placa de concreto poroso. Os trechos apresentavam seção de pequenas dimensões, retilíneo e regular. Com o uso do pavimento permeável in loco, ou seja, no córrego estudado, foi possível notar o aumento da vazão em 8,65%, o que comprova sua interferência no escoamento superficial. Além disso, o pavimento permeável apresentou um resultado satisfatório quanto à permeabilidade (>10-3m/s), e resistência à compressão (>2,0MPa) estando de acordo com a NBR 16416 (ABNT, 2015). Concluiu-se que é possível a utilização de pavimento permeável em áreas de tráfego leve, ou seja, ao redor da bacia, pois, permitirá que as águas da chuva infiltrem no solo e retornem ao córrego, aumentando o escoamento superficial.

Palavras-chave: Pavimento poroso. Inundações. Urbanização.

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1 INTRODUCTION

Urban development in large cities can create various environmental problems, including, among others: solid waste, sewage discharge into rivers, emission of polluting gases, floods.

The economic and social impact of worsening floods is undeniable. Cities, mostly, are affected by severe infrastructure and housing damage, environment degradation, built environment devaluation, the spread of diseases, population impoverishment, to name only a few (MIGUEZ, 2015).

In this context, irregular changes to the original characteristics of land use in urban areas, is one of the factors of high environmental impact. According to Virgillis (2009), rapid city growth (especially last century's urbanization) aggravates flood problems, as it tends to remove the original vegetation cover which increases soil sealing.

What can be done to reduce flooding in urban areas? The literature shows that one of the approaches currently being studied, already implemented in some cities, is permeable pavement.

Permeable paving in urban areas offers an innovative approach to urban centers planning, as it allows a faster flow of surface water.

In view of the above, this study aims to analyze rainfall percolation by permeable pavements in the region of the stream of the Santa Fé do Sul watershed - SP and to analyze its impact on annual flow variation. The permeable and impermeable pavement plates used were made at the Civil Engineering lab of Unifunec, using a trace described in the work of Almeida and Braga (2021).

2 METHODOLOGY

A bibliographic research was chosen to carry out this case study as it allowed researchers to examine everything written, said or filmed on the subject (MARCONI; LAKATOS, 2003).

Our applied research was conducted at the civil engineering lab of Unifunec where 2 concrete pavement slabs were manufactured- one permeable, the other impermeable- and subsequently placed along the aforementioned stream, to analyze their effect in the flow.

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2.1 Materials

CP V cement; Coarse aggregate composed of basaltic gravel 1; Water; PVC and Wood Forms; Epoxy adhesive; String; Tape; Countdown; PET bottle cap, Masking tape.

2.2 Procedures for permeable concrete execution

To achieve the expected results, the following steps were carried out in the Civil Engineering laboratory of Unifunec:

- With the aid of a concrete mixer, permeable and traditional concrete slabs were executed - using a trace shown in Table 1 which had been previously tested by Almeida and Braga (2021).
- A "slump test" was performed next, as per assay NBR 16889 (ABNT, 2020) standards.
- Thereafter, the permeable and traditional concrete slabs were molded, each sized 30x40 cm .
- 8 samples (10cm diameter, 20cm thick), 4 for each concrete trace, were molded and their resistance tested after 7 days and 28 days of curing.
- 24 hours later, they were demolded and placed in a curing tank at room temperature. The same process was carried out with the plates.
- Permeability test done according to NBR 16416 standards (ABNT, 2015). Concrete permeable pavements - Requirements and procedures.

To obtain the differences in relation to strength, compression, and permeability, two different traces were used (Table 1)- one being a traditional concrete baseline and the other apermeable concrete trace, according to the work of Almeida and Braga (2021).

Table 1 - Traces with cement (CP V- ARI) of high initial strength.

Names of samples	**Mass ratio of each material in the mix (by weight)**					
	Cement	**Sand**	**Gravel 1**	**Gravel 0**	**A/C**	**Plasticizer Additive**
Pervious Concrete	2	0	4	1	0,5	4%
Traditional Concrete	1,5	2	4	1	0,45	7%

Source: Almeida and Braga (2021).

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2.2.1 Permeability Test

During the test, the permeability coefficient was defined by timing how long 20 liters of water took to permeate the pavement. Equation 1 shows how k was calculated based on NBR 16416 (ABNT, 2015):

$$k = \frac{C \times m}{d^2 \times t} \qquad (1)$$

Being:

k: permeability coefficient.

m: mass of water infiltrated (Kg).

D: Diameter of the infiltration cylinder (mm).

T: Time required for all water to percolate (seconds).

C: SI System Unit Conversion Factor = 4,583,666,000

According to said standard, the permeable pavement coating must have a permeability coefficient greater than 10-3m/s.

2.3 Study of watershed flow in the field

To evaluate the water body’s flow, three of its stretches were monitored: upstream, downstream and in the middle of the stretch. The first 4 measurements, taken from April to July, were carried out before installing drainage pavements, and the remaining 3 gauges after drainage pavement was in place, from August to October. The stream is located in the urban basin of Santa Fé do Sul, SP (Figure 1), with geographic coordinates latitude 20°11'43.71"S, longitude 50°55'41.43"W and altitude 415m, in small regular sections (1m median width, 40 cm maximum depth), rectilinear (aprox 6m).

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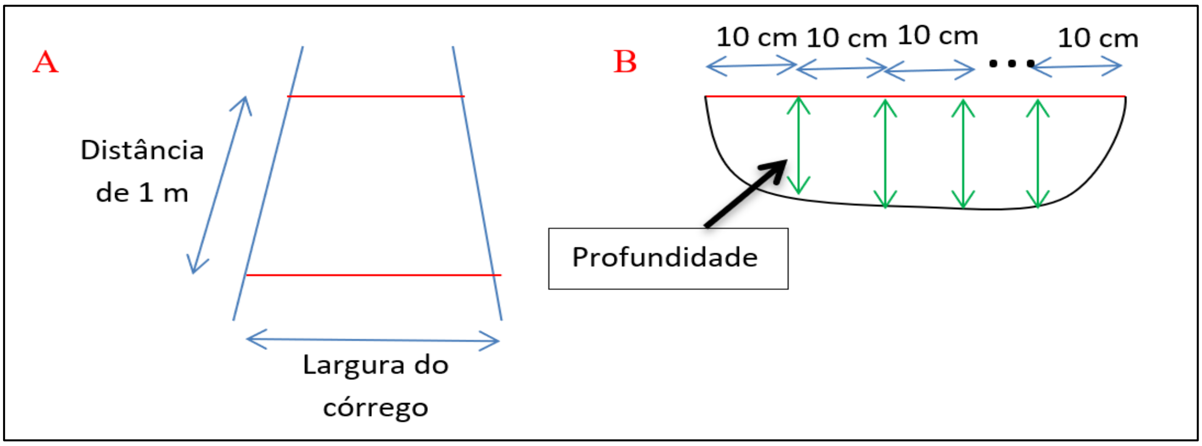
Figure 1 - Urban watershed of Santa Fé do Sul, SP.

Image Source: Google Earth, 2021.

2.3.1 Data collection

From 04/2022 to 10/2022, the water variable was surveyed 7 times, at intervals of approximately 30 days. The time of data collection was postponed for 48 hours after rainy days, in order to regularize flows. Absolute flows were obtained by the float method using the 2 river channel width measurements shown in Figure 2.

Figure 2 - Float method- Representation of flow measurements: A - cross-section; B - longitudinal section.



Source: By the authors.

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2.4 Flow Calculation and other parameters of the hydrographic basin

Stream flow analysis was performed using the float method, with data collected every 30 days. In case of rain on the day or two days prior, two other days were waited for the flow to stabilize.

Three stream sections were chosen for flow analysis. One meter distances were set using string. As shown in Figure 2, depth was then measured at 10 cm intervals on both sides of the stream, in order to outline and obtain the stretch area (data processed by AutoCad).

Using a stopwatch and string, we measured and marked the time taken by a PET bottle cap to travel a one meter distance.

Inputting the above data into Equations (2) and (3), we obtained the flow of each of the 3 stream segments:

$$V = 0{,}85.\left(\frac{D}{T}\right) \qquad (2)$$

Being:

V - Flow velocity (m/s);

D – Distance (m);

T – Average time of 5 float travel times.

$$Q = V.A \qquad (3)$$

Being:

Q - Flow rate (m³/s)

V - Flow velocity (m/s);

A – Average of the areas of the sections (m²);

The methodology used to evaluate the basin's surface runoff, which is the© amount of rainwater that runs off after precipitation, can be obtained by Equation 4:

$$C = \left(\frac{2}{1+F}\right).\left(\frac{C_2}{C_1}\right) \qquad (4)$$

Being:

F – Basin form factor (dimensionless);

C1 – Form coefficient (dimensionless);

C2 – Volumetric flow coefficient (dimensionless).

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The basin shape factor is determined by equation 5:

$$F = \frac{L}{2.\left(\frac{A}{\pi}\right)^{0,5}} \qquad (5)$$

Being:

L – Length of the main bed (km);

A – Drainage area (km2).

The basin shape index is determined by equation 6:

$$C_1 = \frac{2}{1+F} \qquad (6)$$

Being:

C1 – Form coefficient (dimensionless);

F – Basin shape factor (dimensionless).

The volumetric flow rate is obtained by Equation 7:

$$C2 = \frac{\sum Ai\ x\ Ci}{A} \qquad (7)$$

Being:

C2 -Flow coefficient;

Ai - Area of each land use and occupation,

Ci - Surface runoff coefficient of land use and occupation.

The characterization of land use and occupation, urban waterproofing and hydraulic connectivity with urban allotments, as well as the surface runoff coefficient have been detailed and studied by Boyd, Bufill and Knee (1993; 1994); Lee and Heaney (2003); Fontes and Barbassa (2001, 2003), Garotti and Barbassa (2005); Garotti, Imoto and Barbassa (2007). Their research provided important relationships to other easily accessible urban parameters (occupancy rate, lot area, for e.g) which facilitate the estimation and use of the runoff coefficient in the urban planning process.

3 RESULTS

3.1 Laboratory tests

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In order to use the trace of Almeida and Braga (2021), the sand and gravel properties had to be determined before the concrete dosing. After water contents were determined (sand's moisture content was 0.14%, while the gravel's was 1.10%) the granulometry test was performed.

3.2 Concrete Characterization

a) Lowering of the cone ring: After producing the concrete and before molding the specimens, a "slump test" was performed, standardized by NBR NM 16889 (ABNT, 2020), to analyze the fresh concrete's consistency, resulting in a slump value of 11 cm.
(b) Test specimen Molding: Figure 3 shows 8 samples (10 cm diameter, and 20 cm height)- one for each composition- produced as per NBR 5738 (ABNT, 2016). After 24 hours, they were demolded and placed in a curing tank at room temperature for 28 days.

Figure 3 – Molded specimen

Source: by the authors.

c) Axial compressive strength test - It followed the NBR 5739 standard (ABNT, 2007) and was performed on 4 specimens, two permeable and two impermeable, at 7 days, and the others, at 28 days. Figure 4 shows the axial compression test at 28 days. Chart 2 shows the results obtained.

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Figure 4 – Axial compression test at 7 days.

(a) Traditional Concrete (b) Pervious Concrete

Source: by the authors.

Table 2 - Tensile strength after axial compression tests.

-	7 days	28 days
Pervious Concrete	3.4 Mpa	4.5 MPa
Traditional Concrete	10.8 Mpa	14.4 MPa

Source: by the authors.

Chart 2 shows considerable differences between the various concrete types. According to NBR 9781 (ABNT, 2013), the minimum compressive strength required for light traffic pavements should range from 2 to 35MPa. Therefore, despite being hollower than common concrete, the lower strength results of our permeable concrete’s are satisfactory.

The reduced compression capacity of permeable pavements is intended for light loads-ideal for parking areas and streets with low traffic.

3.3 Permeability analysis: plates molding

300x400x60mm concrete slabs were molded to perform the permeability test. The plates and the specimens were molded concurrently. The permeable and impermeable concrete were laid on a flat surface, previously prepped with release agent. The concrete was poured in layers - each of them being compacted by 24 concrete-thickening strokes. After this process, it rested for 24 hours of initial curing, followed by demolding and submersion in a water container. The permeability test was performed, at 28 days (Figure 5).

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Figure 5 – Permeability test

Source: From the authors themselves.

3.3.1 Mechanical strength and minimum thickness

As per NBR 16416 (ABNT, 2015) specifications, the mechanical strength (minimum 60.0mm thick) of permeable light-traffic concrete slabs (squares and sidewalks, e.g.) must be greater than or equal to 2.0MPa.

According to NBR 16416 (ABNT, 2015) likewise, permeable concrete must follow the permeability levels established by the standard- shown in Table 3.

Table 3 - Permeability Levels

Permeability coefficient k								**Degree of permeability**
m/s		**mm/s**		**mm/min**		**liters/min**		
>	$1,00^{-3}$	>	1,00000	>	60,0	>	60,00	**Discharge**
$1,00^{-3}$	$1,00^{-5}$	1,0000	0,01000	60,0	0,6000	60,00	0,6000	**Average**
$1,00^{-5}$	$1,00^{-7}$	0,01000	0,000100	0,60	0,00600	0,60	0,0060	**Low**
$1,00^{-7}$	$1,00^{-9}$	0,0001	0,000001	0,01	0,00006	0,006	0,00006	**Very Low**
<	$1,00^{-9}$	<	0,000001	<	0,00006	<	0,00006	**Virtually waterproof**

Source: Adapted from NBR 16416 (ABNT, 2015).

3.3.2 Permeability analysis

Table 4 shows the tested permeability coefficient. The permeable concrete slab not only revealed high permeability (>10-3m/s) but also met the minimum NBR 16416 (ABNT, 2015) resistance requirements, making its use adequate for light-traffic places.

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Table 4 - Surface runoff coefficient.

Trace	Water (L)	Run-off time(s)	*k* (mm/h)	*k* (m/s)
Pervious concrete	20	389,2	23554,30	$6{,}54.10^{-3}$
Ordinary concrete	20	0	0	0

Source: By the authors.

3.4 Surface runoff

Figure 6 maps the coefficients and factors used to determine the basin's flow coefficient.

Figure 6 - Watershed of the analyzed stream.

Source: By the authors.

In order to obtain the surface runoff coefficient (C), the basin shape factor (F), the basin shape coefficient (C1) and the flow volume coefficient (C2) were calculated. Runoff coefficient results are shown in Table 5.

Table 5 - Surface runoff coefficient.

Calculation of runoff coefficient - C			
Shape Factor	**Shape coefficient**	**Flow volume coefficient**	**Surface runoff coefficient**
1,3765	1,1847	0,5791	0,4114

Source: By the authors.

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Flow variation determines how susceptible the basin is to flooding: higher variation leads to greater runoff volumes, in a short period. The basin shape factor is defined by the ratio of the average width of the basin to its axial length.

Data analysis (Table 5) shows an elongated basin shape with a 1,3 factor. Figure 7 shows flow variation (Table 6) surveyed in the field, during different months.

Table 6 - Absolute Flow Rates without permeable plates.

	Flow rate (m³/s)			
	April	**May**	**June**	**July**
Stretch 1	0,00397	0,00312	0,00334	0,00273
Stretch 2	0,0046	0,00346	0,00377	0,00384
Stretch 3	0,00722	0,00495	0,00397	0,00416

Source: By the authors.

To ascertain whether there is variation in the stream's flow caused by laboratory-made permeable pavers (used in sidewalks and/or in adjacent areas), measurements were taken at identical points and then compared. Table 7 and Figures 7, 8 and 9 represent the data obtained.

Table 7 - Absolute Flow Rates with and without the use of permeable plates.

	Flow rate (m³/s)					
	August		**September**		**October**	
	Without the plate	With the Plate	Without the plate	With the Plate	Without the Plate	With the Plate
Stretch 1	0,00249	0,00297	0,00340	0,00361	0,00321	0,00339
Stretch 2	0,00303	0,00322	0,00386	0,00438	0,00357	0,00397
Stretch 3	0,00423	0,00457	0,00497	0,00529	0,00439	0,00473

Source: By the authors.

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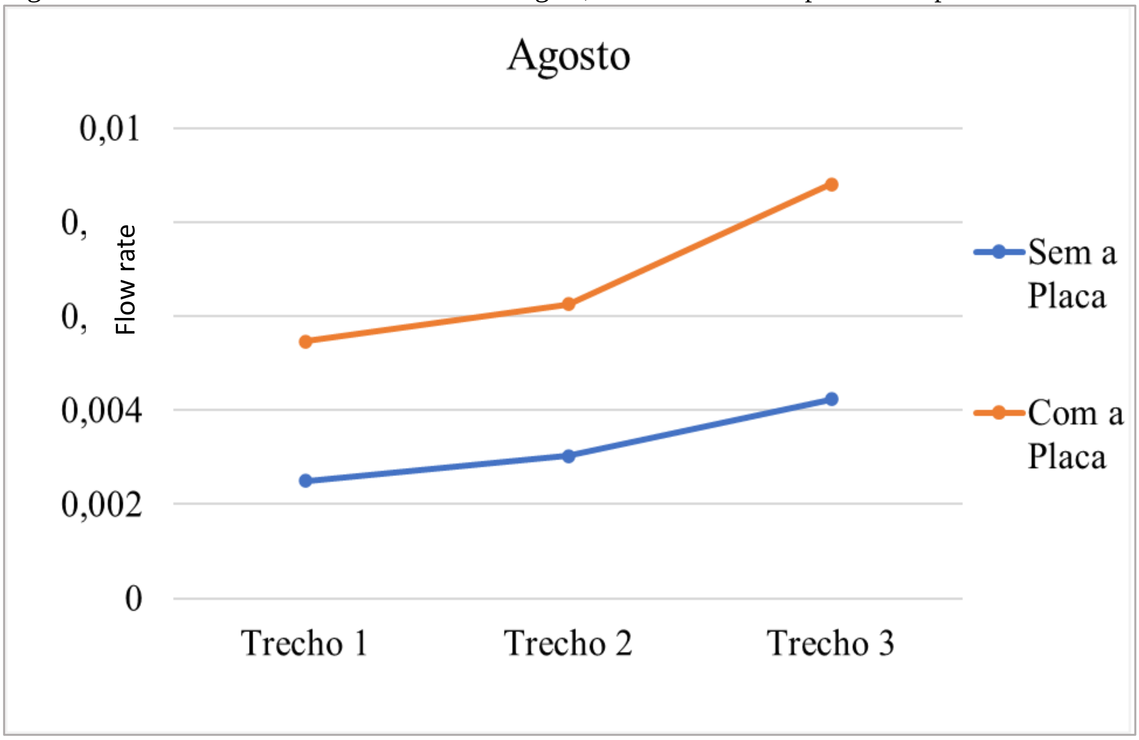
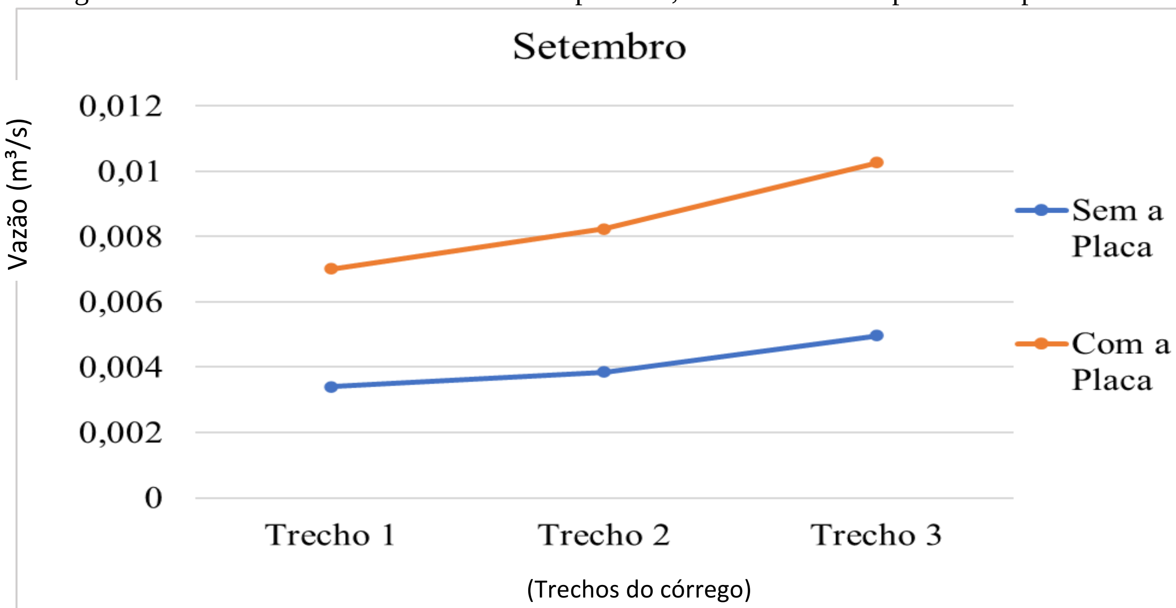
Figure 7 - Absolute flow for the month of August, with and without permeable plates.



Source: By the authors.

Figure 8 - Absolute flow for the month of September, with and without permeable plates.



Source: By the authors.

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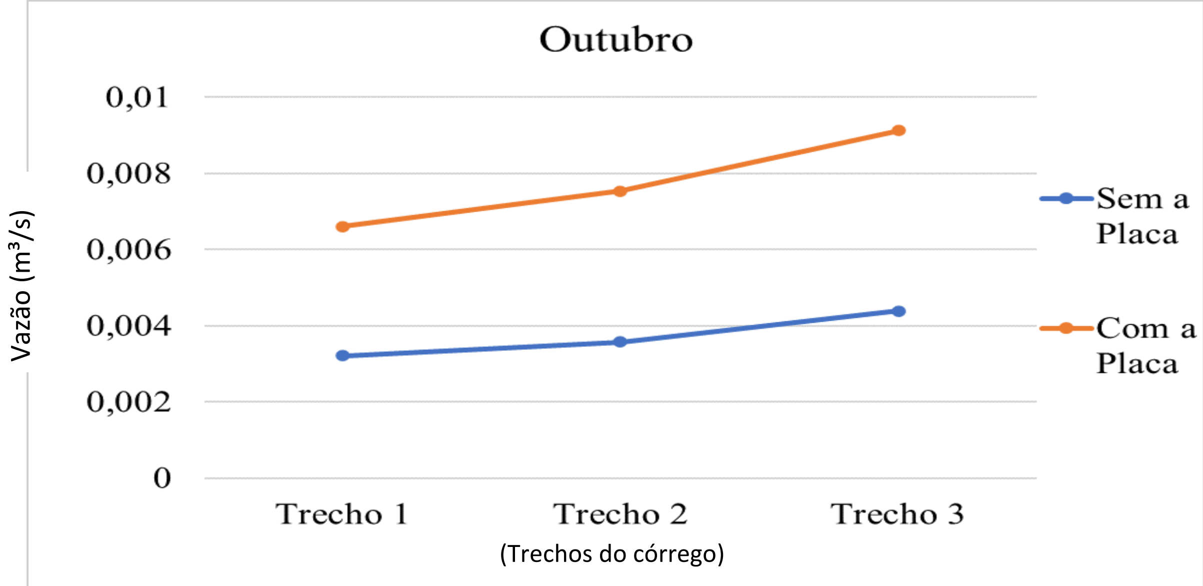
Figure 9 - Absolute flow for the month of October, with and without permeable plates.



Source: By the authors.

4 DISCUSSION

The data obtained allowed us to define the basin's shape which, being more elongated, poses lower risk of flooding. The latter, however, can be further mitigated by using permeable pavers which enhance surface runoff and return rainwater to the water table, and even to the stream.

This was proven by analyzing the in-situ measurements of the stream's flow- both with and without the use of permeable pavement. Permeable pavement use increased flow by 8.65%- thus attesting its impact in surface runoff. However, this was due to the permeable pavement's high permeability, with a coefficient (k) greater than 10-3m/s, according to NBR 16416 (ABNT, 2015).

Another factor analyzed was its compressive strength (>2.0MPa), confirming that its use in light-traffic locales is not only adequate but also beneficial in stream-adjacent areas.

5 CONCLUSION

This research's goal was achieved, since it was confirmed that the use of permeable pavers along the Mula Stream (in sidewalks and squares) allows rainwater to return to the stream- as shown by increased flows.

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This field study evidences demonstrations by several authors, namely: Virgillis (2009); Pinheiro, Pinheiro and Crivelaro, (2014); Abreu and Miranda, (2020), Almeida and Braga, (2021). It proves that permeable pavers (aka drainage pavement) reduce flooding by returning rainwater to watercourses, improving their flow, especially in urban areas.

It was hence concluded that permeable pavement use in light-traffic areas (around basins) allows rainwater to infiltrate the soil and return to the stream, thereby increasing surface runoff.

We suggest that new research be carried out, with different permeable concrete traces, using construction waste e.g., so as to reduce natural resources depletion. Another proposal would be to monitor the stream's flow throughout longer periods of time, to analyze its behavior vis-à-vis permeable pavement use at different points along the stream.

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