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Performance of infiltration trenches in different soils in native vegetation and urban area of the Federal District of Brazil

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ABSTRACT

The increase in flooding events in major cities has driven the search for new strategies that incorporate Low Impact Development (LID) units into urban drainage. This research analyzes the performance of infiltration trenches to determine flow and infiltration physical parameters in different soil types in the Federal District of Brazil (FDB), comparing urban area and preserved Cerrado biome. The results show that most soils in the Federal District of Brazil have good infiltration conditions, particularly the Red Latosol and Red-Yellow Latosol. Infiltration trenches were effective in storing significant volumes of water, especially during initial runoff events where favorable soil moisture conditions exist. The Regolithic Neosol exhibited low infiltrability, making its use for infiltration trenches not recommended.

Keywords: cerrado, infiltration trench, red latosol.

Desempenho de trincheiras de infiltração em diferentes tipologias de solo em área urbana e de vegetação nativa no Distrito Federal (DF)

RESUMO

O aumento de eventos de inundações em grandes cidades tem impulsionado a busca por novas estratégias que incorporem unidades de Desenvolvimento de Baixo Impacto (DBI) na drenagem urbana. Esta pesquisa tem como objetivo analisar o desempenho de trincheiras de infiltração para determinar parâmetros físicos de vazão e infiltração em diferentes tipos de solo no Distrito Federal (DF), comparando área urbana e bioma Cerrado preservado. Os resultados mostram que a maioria dos solos do Distrito Federal apresenta boas condições de infiltração, particularmente o Latossolo Vermelho e o Latossolo Vermelho-Amarelo. As trincheiras de infiltração foram eficazes no armazenamento de volumes significativos de água, especialmente durante eventos de escoamento inicial onde existem condições favoráveis de umidade do solo. O Neossolo Regolítico apresentou baixa infiltrabilidade, tornando seu uso para trincheiras de infiltração não recomendado.

Palavras-chave: cerrado, latossolo vermelho, trincheiras de infiltração.

1. INTRODUCTION

Lack of urban planning has resulted in frequent failures of urban drainage infrastructure due to the increase of peak flow associated with floods and economic damage (McClymont *et al.,* 2020; Fava *et al.,* 2022; Macedo *et al.,* 2022). Given these scenarios, an increasing interest in compensation techniques has been noted in different terminologies, such as Blue and Green Infrastructure, Low Impact Development (LID) solutions, Best Management Practices (BMP), Sponge cities techniques, Sustainable Drainage Systems (SuDSs) and Water Sensitive Urban Design (Lima *et al.,* 2022; Navarro *et al.,* 2022; Hoepers *et al.*, 2022), or a combination of some of these alternatives (Janbehsarayi *et al.*, 2023; Wang *et al.*, 2022) in the search for smart management of urban water in either parcel and watershed scales. These alternative solutions should consider the natural conditions of the basins and integrate the drainage system to the urban public spaces enhancing the environmental sustainability of urban areas. However, there are questions to explore related to the quantitative assessment of these solutions and associated development of public policies (Xu *et al.*, 2022).

These new approaches use drainage structures such as permeable boxes or infiltration trenches (Nunes, 2017; Zaidi *et al.*, 2015), not only to reduce floods, but also to enhance infiltration and contribute to aquifer recharge in areas with intense occupation and extensive impermeable surfaces (Santos and Koide, 2016; Shubo *et al.*, 2020; Ren *et al.*, 2020; Dillon *et al.*, 2020; Ulibarri *et al.*, 2021), given the guarantee of risk reduction of groundwater contamination (Allen *et al.*, 2017; Alamdari *et al.*, 2017; Charlesworth *et al.,* 2017; Nunes, 2017; Hägg *et al.*, 2020; Correa *et al.*, 2022).

The aquifer recharge process must be evaluated in the context of the watershed (river basin) considering the physical characteristics of the basin and urban geomorphology dynamics (Souza *et al.*, 2022) to understand the human impacts related to land use and occupation (Veneziani, 2014). Edwards *et al.* (2016) state that there are many gaps in studies that seek to understand how to quantify the volume of surface runoff that actually infiltrates and might be used in artificial groundwater recharge. Other authors also mention the need for research in verifying improvements in construction of recharge devices of groundwater recharge tools or techniques (Macedo *et al.*, 2017; Lucas *et al.*, 2015); assessment of nonpoint source pollution from infiltrated water volume (Silva *et al.*, 2010); and cost-efficiency analysis of the proposed measures.

The soils characterized as Red Latosols cover 38.65% of the DF territory, concentrated mainly on the top of plateaus in the Paranoa River plain lands and in the Preto River Basin (Campos *et al.*, 2009). It is important to develop new studies to evaluate specific attributes of soils in the field (natural conditions) which condition the factors for the formation and differentiation of its characteristics (Campos, 2009). In 2013, about 65% of the DF watersheds had problems related to water availability; among them six watersheds were in critical condition and the other twenty in alert situation (Alves *et al.*, 2013). The public water supply restrictions issued in 2017 and 2018 made the FDB government consider sustainable measures as actual alternatives to urban water management.

In 2017, the government in the FDB decreed Complementary Law nº 929 that requires the use of rainwater harvesting systems or reservoirs in new urban developments in order to retain, reuse and recharge artificial aquifers, aiming to recover aquifer recharge by at least 40%. According to Pereira and Alves (2019), there are few studies involving field tests characterizing infiltration trenches or other techniques in the FDB.

This work evaluates the performance of infiltration trenches using water-flow field tests in the following FDB soils: Latossolos Vermelhos (Red Latosols), Latossolos Vermelho-Amarelos (Red-Yellow Latosols), Plintossolos (Plinthosols) and Neossolos Regolíticos (Regolithic Neosols) following the Brazilian soil taxonomy system (Santos *et al.*, 2018). Based on the results, a field database will be created to guide water resource managers and urban planning managers on actions that facilitate the infiltration process in urban and rural areas.

2. MATERIAL AND METHODS

Assessment of infiltration trenches in the DF was based on field tests developed in two study areas. The first area is in the Biology Experimental Station (BES) located in the center of the Brasilia urban area. The other site was characterized by preserved soil characteristics in the Cerrado biome, located in the Água Limpa Experimental Farm (CWF). The University of Brasilia owns both areas and uses them specially for research purposes.

Figure 1 presents the two sites of study: BES and CWF. The BES site is in an urban area (UTM coordinates E= 191,111.04 m; N=8,258,200.84 m; zone 23S) at the Paranoa Lake bank where the water table depth is 3.70 m approximately (Almeida, 1994). The soil in the area is predominantly Red Latosol (RL), with an infiltration rate varying from 10^{-4} m/s to 10^{-7} m/s (ADASA, 2015). There are a few buildings close to the BES, and there are impermeable roads around the area. The CWF (UTM coordinates L = 185,792,0 m; E=8,234,529.0 m) is the site for the six infiltration trenches and associated soils, namely Red Latosols (RL), Red-Yellow Latosols (RYL), Plinthosols (PL) and Regolithic Neosols (NR). Most of the farm has the intact Cerrado biome, but there are also places dedicated to research on land use and agriculture.

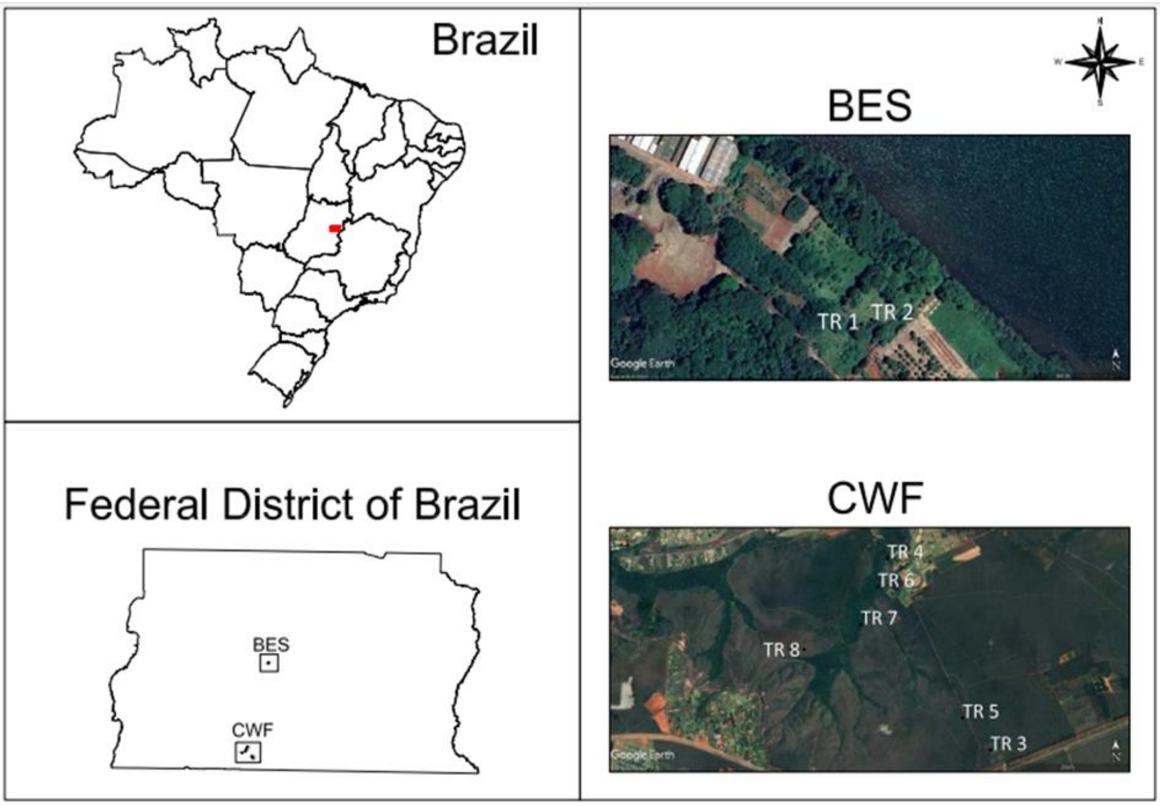

Figure 1. Study Area Locations.

Knowing the infiltration conditions in an area depends on information related to infiltration rate, soil texture, soil compaction, humidity, porosity, hydraulic conductivity (Infiltrability), vegetation, vertical flow of water, permeability, size and geometry of grains, types of sediment fraction, retention curve (Justino *et al.*, 2021; Oliveira *et al.*, 2021) and other parameters that are important for the understanding of LID´s solutions (Khurelbaatar *et al.*, 2021).

The soils were characterized based on the following information: dry soil density (NBR 7181/2016), minerals (X-Ray diffraction), granulometry (NBR 7181/2016), permeability

(Koide, 1990), infiltration rate (Double-ring infiltrometer) and soil-water retention curves (Pressure plate apparatus with data adjusted by Van Genuchten's equation).

The materials used for the construction of the infiltration trenches, in order of installation in field, were: geotextile layer Bidim Mexichem, sand layer (with an average thickness of approximately 0.05 m), gravel nº 1 layer (with an average thickness of approximately 0.35 m) and PVC pipes with holes along the surface, positioned in one of the corners inside the trench for measuring water levels. The water-level monitoring inside the tube consists of using a measuring tape to measure variation in level during flow tests.

Table 1 presents the dimensions of the trenches and Figure 2 shows one of the infiltration trenches in the field. To carry the flow tests, a feeding system was used exclusively for the infiltration trenches until they overflowed during the test. The equipment used includes ball valves, fittings, connecting pipes, and reservoirs of 350 L and 1000 L, positioned next to the trenches, as illustrated in Figure 2.

The flow test uses an exclusive intake to the infiltration trenches up to its full capacity. The equipment for the flow tests were two reservoirs (350 L and 1,000 L), pipes and a flow-control ball valve.

Table 1. Infiltration trenches dimensions and sites.

Trench	Site	Type of Soil	Width (m)	Length (m)	Depth (m)	V (m^3)
TR 1	BES	RL	0.65	0.70	0.70	0.32
TR 2	BES	RL	0.50	0.70	0.70	0.25
TR 3	CWS	RL	0.82	2.18	0.90	1.61
TR 4	CWS	RL	0.82	2.22	0.90	1.64
TR 5	CWS	RYL	0.80	2.50	0.84	1.68
TR 6	CWS	RYL	0.98	2.37	0.86	1.99
TR 7	CWS	PL	0.82	2.70	0.90	1.99
TR 8	CWS	NR	1.12	2.31	1.07	2.77

Figure 2. Infiltration Trench in (a) Red Latosol (TR4) and in (b) Red-Yellow Latosol (TR5).

3. RESULTS AND DISCUSSION

The bottom permeability of the trenches at the CWF presents a lower order of magnitude than those of the trenches at BES, indicating that water infiltrates faster in the CWF. This might also result from the characteristic high porosity in undisturbed Cerrado where the CWF/UnB is located. According to Oliveira *et al.* (2021), saturated hydraulic conductivity is extremely variable even in local areas. It is a challenge to define its value in basin scales, given the influence of soil granulometry and porosity (Godoy *et al.*, 2019).

The values for soil porosity range from 0.60 cm³/cm³ to 0.70 cm³/cm³ (Table 2), classifying them as highly porous soils (Resck *et al.*, 1991).

The presence of minerals such as gibbsite reflects the predominance of granular structure, resulting in soils that are more porous, more permeable, with greater aggregate stability in water, and lower soil density values (Ferreira *et al.*, 1999)

Comparing results of the permeability in TR 1 and 2 to TR 3 and 4, it follows the expected trend that regions under high anthropogenic influence generate lower permeability, given the increase of compression and constructions nearby (this is the case of BES). As Wang *et al.* (2022) mention, the efficiency of LID techniques is limited by soil characteristics such as permeability. Therefore, they should be designed to operate in areas where infiltration predominates.

Papa *et al.* (2011) determined saturated hydraulic conductivity in Red Latosol soil at CWF using the constant head permeameter method, finding the value of 8.28×10^{-4} m/s and classifying the infiltration as "very fast", being greater than 250 mm/h (Pizarro, 1978).

Gurjão (2010) obtained an infiltration rate of approximately 1.8×10^{-4} m/s to 6.5×10^{-4} m/s for similar conditions, while Silva (2012) recorded an infiltration rate of about 3×10^{-5} m/s, all for the Red Latosol at the University of Brasília, near the Experimental Biology Station.

In the areas of Red Latosols at the CWF, there are bushes and trees, representing greater interference of roots in the soil aggregation. Thus, the connectivity of the porous and the macropore volumes may be greater (Campos *et al.*, 2008). Table 2 shows the laboratory and field parameters.

It was not possible to determine the great majority of the NR physical parameters due to difficulties related to the rocky nature of these soils and not having adequate equipment to measure the parameters.

3.1. Inflow field tests

The infiltration trenches in the CWF are greater than those in the BES, accepting higher inflow volumes (at least four times higher) while maintaining similar infiltration time, agreeing with the order of magnitude presented in Table 2. One can see that the permeability rate at the bottom of the infiltration trenches at the CWF/UnB was two orders of magnitude lower than the ones at the BES, which means that the infiltration might be treated in areas of undisturbed Cerrado (natural).

The infiltration in the trench at the NR took approximately 24 hours to completely empty the total volume of water added to the trench. The rocky structure (lithic contact) helps to explain the difficulties of draining the water.

Figure 3 shows the results of the inflow tests.

Table 2. Physical parameters of the soil.

<table>
<tr><th rowspan="2">Trench</th><th rowspan="2">Particle Density (g/cm³)</th><th rowspan="2">Minerals</th><th colspan="3">Soils Texture (%)</th><th rowspan="2">Porosity (cm^3/cm^3)</th><th colspan="2">Permeability (m/s)</th><th>Infiltrability (m/s)</th></tr>
<tr><th>Medium Sand</th><th>Silt</th><th>Clay</th><th>10 cm</th><th>Bottom of trench</th><th>8 cm</th></tr>
<tr><td>TR 1</td><td>2.80</td><td rowspan="4">Gibbsite and Hematite</td><td>13.49</td><td>8.43</td><td>73.73</td><td>0.62</td><td rowspan="2">2.75×10^{-05}</td><td rowspan="2">7.55×10^{-06}</td><td rowspan="2">1.96×10^{-04}</td></tr>
<tr><td>TR 2</td><td>2.77</td><td>15.20</td><td>8.73</td><td>70.68</td><td>0.58</td></tr>
<tr><td>TR 3</td><td rowspan="2">2.50*</td><td>6.21*</td><td>23.30*</td><td>70.50*</td><td>0.69</td><td>6.42×10^{-05}</td><td>1.81×10^{-04}</td><td>8.28×10^{-04}</td></tr>
<tr><td>TR 4</td><td>7.30*</td><td>4.80*</td><td>87.90*</td><td>0.62</td><td>9.57×10^{-05}</td><td>4.58×10^{-05}</td><td>3.64×10^{-05}</td></tr>
<tr><td>TR 5</td><td>-</td><td rowspan="2">Gibbsite and Kaolinite*</td><td>29.69</td><td>25.84</td><td>44.47</td><td>0.62</td><td>1.18×10^{-04}</td><td>2.44×10^{-04}</td><td>2.19×10^{-04}</td></tr>
<tr><td>TR 6</td><td>-</td><td>50.19</td><td>39.95</td><td>9.86</td><td>0.64</td><td>5.27×10^{-05}</td><td>4.04×10^{-05}</td><td>9.57×10^{-07}</td></tr>
<tr><td>TR 7</td><td>-</td><td>-</td><td>52.11</td><td>47.11</td><td>0.16</td><td>0.67</td><td>7.79×10^{-05}</td><td>1.49×10^{-05}</td><td>9.57×10^{-07}</td></tr>
</table>

* Source: Papa *et al.* (2011).

According to Bekele *et al.* (2013), the hydraulic performance and low-rate cost-efficiency are two important features for the success of artificial recharge technologies, so the specific conditions of soils and their physical parameters are essential for the performance of infiltration trenches, justifying the studies that measure these properties on a local scale (Khurelbaatar *et al.*, 2021; Wang *et al.*, 2022). It is also important to consider analysis of the outflow water quality in order to avoid aquifer contamination due to first flushes.

The lack of field data related to physical parameters of water infiltration in FDB soils has an impact on the application of stormwater drainage and management legislation such as FDB Complementary Law nº 929/2017 (District Federal of Brazil, 2017). According to Jacob *et al.* (2021), 43.81% of the DF is Cerrado lato sensu, 44.38% are agriculture areas and 10.14% are urban areas; but there are few studies that evaluate the impact of urban occupation in natural landscape in terms of physical properties of soils.

The present work contributes information related to infiltration properties at the local level, and may inform new projects aimed at establishing sustainable strategies and solutions for stormwater drainage and management (Wang *et al.*, 2022; Xu *et al.*, 2022; Janbehsarayi *et al.*, 2023).

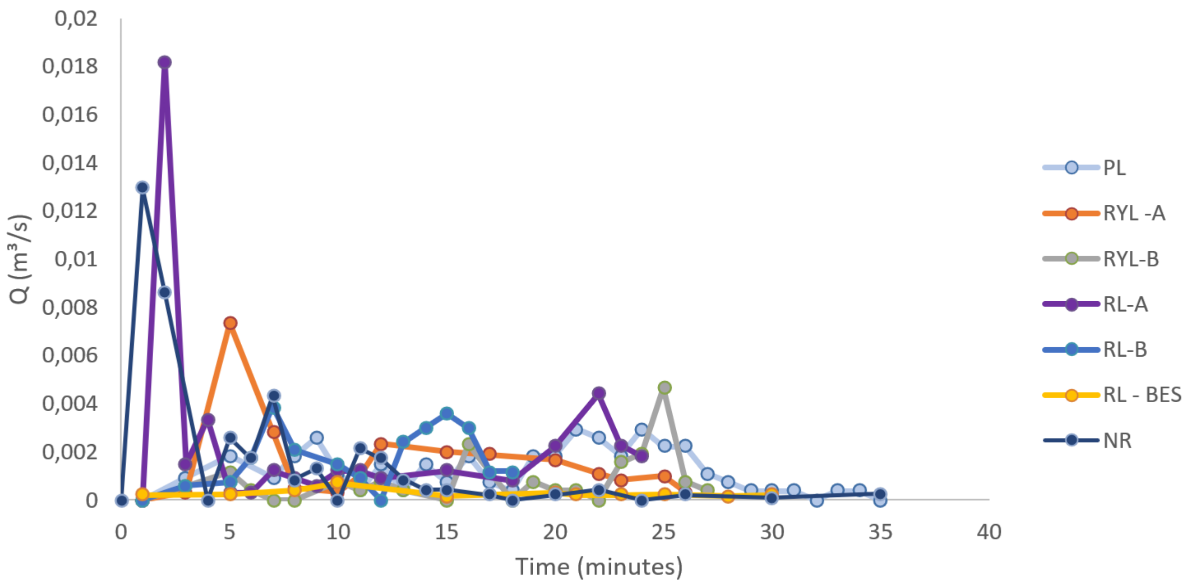

Figure 3. Infiltration inflow (Q) during the inflow tests.

4. CONCLUSIONS

Infiltration trenches might significantly reduce urban floods, being easy to build and presenting good performance to retain the volume of first flushes at the beginning of a high-intensity precipitation event, especially when the soil is not saturated yet (favorable soil moisture condition). Among the soils in the FDB, and after successive flow tests, only the Regolithic Neosol did not have good infiltration properties (given its natural lithological structure), presenting an infiltration time of around one day for the flow test volumes. On the other hand, the Red Latosol and the Red-Yellow Latosols presented good infiltration properties, which showed an infiltration time varying between 20 and 30 minutes.

Although the initial wet conditions of the soils may interfere with the infiltration rate, the use of infiltration trenches integrated to other infrastructures might benefit the reduction of flood events and their usual damages.

This research establishes an initial database that can assist infrastructure and water resource managers in selecting suitable locations for the implementation of infiltration trenches, promoting regulations to manage land use and occupancy.

5. ACKNOWLEDGMENTS

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