



Mix Sustentável



Simulação de técnicas compensatórias estruturais para mitigar o escoamento superficial em um município brasileiro sujeito a inundações

Simulation of structural compensatory techniques to mitigate surface runoff in a Brazilian municipality subject to flooding

Simulación de técnicas compensatorias estructurales para mitigar la escorrente superficial en un municipio brasileño sujeto a inundaciones

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Resumo: Desastres hidrológicos têm se tornado cada vez mais comuns nos últimos anos, principalmente devido à falta de planejamento urbano para drenagem de águas pluviais. Um amplo consenso na literatura é que as abordagens tradicionais de drenagem são obsoletas, insustentáveis e cada vez mais custosas ao longo do tempo. Isso destaca a necessidade de uma nova abordagem para a drenagem urbana. Técnicas compensatórias estruturais (TCEs), combinadas com modelagem matemática, tornaram-se ferramentas essenciais para alcançar o desenvolvimento urbano sustentável. Assim, este estudo avaliou o desempenho de

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duas TCEs — cisternas e pavimentos permeáveis — na redução de picos de inundação em bacias propensas a inundações. O software modelo de gerenciamento de águas pluviais (SWMM) foi utilizado para a análise, com as cisternas demonstrando desempenho superior. O método número de curvas–serviço de conservação do solo (CN-SCS) foi utilizado para a modelagem para avaliar o impacto de áreas urbanas nos valores do hidrograma. Os resultados sugerem que o método SCS deve ser usado com cautela quando aplicado a grandes bacias, pois exagera os valores reais do volume de escoamento.

Palavras-chave: SWMM; método CN-SCS; modelagem matemática; cisterna; pavimento permeável.

Abstract: Hydrological disasters have become increasingly common in recent years, primarily owing to the lack of urban planning for stormwater drainage. A broad consensus in the literature is that traditional drainage approaches are obsolete, unsustainable, and increasingly costly over time. This highlights the need for a new approach to urban drainage. Structural compensatory techniques (SCTs), combined with mathematical modeling, have become essential tools for achieving sustainable urban development. Accordingly, this study evaluated the performances of two SCTs—cisterns and permeable pavements—in reducing flood peaks in flood-prone basins. The storm water management model (SWMM) software was used for the analysis, with cisterns demonstrating superior performance. The curve number–soil conservation service (CN-SCS) method was used for modeling to assess the impact of urban areas on hydrograph values. The results suggest that the SCS method should be used with caution when applied to large basins because it exaggerates real runoff volume values.

Keywords: SWMM; CN-SCS method; mathematical modeling; cistern; permeable pavement.

Resumen: Los desastres hidrológicos se han vuelto cada vez más comunes en los últimos años, principalmente debido a la falta de planificación urbana para el drenaje de aguas pluviales. Un amplio consenso en la literatura es que los enfoques tradicionales de drenaje son obsoletos, insostenibles y cada vez más costosos con el tiempo. Esto resalta la necesidad de un nuevo enfoque para el drenaje urbano. Las técnicas de compensación estructural (SCT), combinadas con el modelado matemático, se han convertido en herramientas esenciales para lograr un desarrollo urbano sostenible. En consecuencia, este estudio evaluó el desempeño de dos SCT (cisternas y pavimentos permeables) en la reducción de picos de inunda-

permite o compartilhamento do trabalho com reconhecimento da autoria e publicação inicial nesta revista.

Contribuição dos autores segundo a Taxonomia CRediT

JPL: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing the Original Draft and Review and Editing, Visualization.
AKA: Conceptualization, Methodology, Software, Writing the Original Draft and Review and Editing, Visualization.
LSM: Investigation, Software, Writing the Original Draft.
IKA: Conceptualization, Methodology, Validation, Formal analysis, Writing the Original Draft and Review and Editing, Visualization, Supervision, Funding acquisition.

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Nothing to declare.

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ción en cuencas propensas a inundaciones. El software del modelo de gestión de aguas pluviales (SWMM) se utilizó para el análisis, y las cisternas demostraron un desempeño superior. El método del servicio de conservación de suelos con número de curva (CN-SCS) se utilizó para el modelado para evaluar el impacto de las áreas urbanas en los valores del hidrograma. Los resultados sugieren que el método SCS debe usarse con precaución cuando se aplica a grandes cuencas porque exagera los valores reales del volumen de escorrentía.

Palabras clave: SWMM; método CN-SCS; modelización matemática; cisterna; pavimento permeable.

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1 INTRODUCTION

Urbanized areas generate significantly more surface runoff from rainwater compared with areas in their natural state. This is primarily attributed to the soil impermeabilization resulting from the construction of roofs, parking lots, paved streets, and sidewalks, increasing the risks of hydrological disasters. Scheuren *et al.* (2008) and Centre for Research on the Epidemiology of Disasters – CRED (2023) indicated that hydrological disasters involve processes that result in flooding, inundation, gradual and sudden floods, and mass movements, such as landslides. Veról e Miguez (2019) reported that the greater the capacity to convert rainfall into runoff—owing to impermeable and regular surfaces that limit infiltration and retention—the greater the consequences of flooding. Hydrometeorological disasters occur with greater frequency and severity if the temporal trend of precipitation in the region is increasing (Leite *et al.*, 2023).

Although flooding has various definitions, most researchers agree that urban flooding is caused by the overflow of drainage systems and watercourses, causing water to accumulate in backyards, streets, sidewalks, and other urban infrastructures (Caprario *et al.*, 2019). This disaster result in significant consequences, including public health impacts (Huntingford *et al.*, 2007) housing market effects (Harrison; Smersh; Schwartz, 2001), impacts on urban transport infrastructure (Suarez *et al.*, 2005), and psychological stress and material damage (Linnekamp; Koedam; Baud, 2011). In 2007, over 170 million people worldwide were affected by hydrological disasters, resulting in serious economic losses (Scheuren *et al.*, 2008). In Brazil, from 2005 to 2010, 50.2% of municipalities reported urban flooding, with 60.7% of these located in urban floodplains (Medeiros, 2011). In the 2000s, flooding resulted in thousands of deaths annually and tens of billions of dollars in economic losses, with projections indicating increases in these figures in the future (Hirabayashi *et al.*, 2013). In 2022, 176 flood disasters occurred worldwide. These disasters resulted in 7,954 fatalities (272 of these deaths recorded in Brazil in February), affected 57.1 million people, and caused economic losses reaching US\$44.9 billion (Centre for research on the epidemiology of disasters – cred, 2023).

The gradual process of urbanization, resulting from population growth and the needs of the population, has become a determining factor in the increased frequency of disasters caused by climate events (Ferreira *et al.*, 2025). The projected increase in the frequency and intensity of heavy rainfall owing to climate change will increase local flooding caused by rainfall (Ipcc, 2013). Based on the projected increase in the global urban population from 55% in 2018 to 68% by 2050 (United nations - un, 2018) and the impacts of climate change, Lashford *et al.* (2019) emphasized that sustainable solutions for flood management are essential for the socioeconomic growth of nations. According to the IPCC (2013), combinations of sustainable measures, such as structural and nonstructural techniques, have significantly reduced fatalities during flooding events. Miguez, Mascarenhas e Verol (2011) stated that the traditional flood management approach typically focuses on improving canal transport, often involving the channeling and straightening of watercourses. They also stated that the urbanization process itself limits the expansion of these channels, making this approach inefficient over the years and creating an unsustainable scenario.

Miguez, Mascarenhas e Verol (2011) suggested that drainage systems must be designed to minimize

the impacts of urbanization on natural flow patterns. Thus, drainage systems must reproduce the hydrological characteristics of a basin as they existed before anthropization (Tucci, 1995).

Tucci (2003) reported that developed countries recognized the high costs of traditional drainage solutions and abandoned them in the early 1970s. By contrast, developing countries, such as Brazil, systematically adopted this measure, incurring significantly higher costs and losses. In addition to the high costs of construction, maintenance, and repair (Tucci, 2003; Hair; Clements; Pratt, 2014), traditional drainage systems are vulnerable to the current global challenges associated with climate change and rapid urbanization (Zhou, 2014). Their limited capacity and flexibility to adapt to climate change and increased urbanization increases the risk of urban flooding (Zhou, 2014; Caprario *et al.*, 2019). Therefore, traditional drainage systems are insufficient for effectively managing urban rainwater and require integration with more sustainable and economically efficient systems (Canholi, 2015).

Unlike traditional systems, which primarily focus on transferring floodwaters downstream, alternative drainage systems aim to mitigate the effects of urbanization on the hydrological cycle of basins. This is achieved by controlling excess water volumes resulting from surface impermeability. This control is achieved using structural compensatory techniques (SCTs) that facilitate the infiltration of rainwater and/or increase its transit time through temporary storage (Baptista; Nascimento; Barraud, 2015).

These techniques are considered alternatives to traditional methods because they consider the impacts of urbanization globally. This enables sustainable city expansion without incurring excessive costs. In addition, these techniques enable diverse uses by the community, such as parking areas, sports areas, and floodable parks or leisure areas (Castro; Baptista; Netto, 2004). In addition to reducing drainage volumes, alternative drainage techniques aim to reduce water pollution (Guitierrez, 2006). This reduction is possible owing to the retention and infiltration characteristics of these techniques, enabling the retention of pollutants normally carried by rainwater.

Various terminologies for alternative drainage systems exist in the literature, varying based on the region being analyzed. In the USA, low-impact development (LID) is used, while New Zealand refers to it as low-impact urban design and development (LIUDD). Australia refers to it as water-sensitive urban design (WSUD), the United Kingdom calls it sustainable urban drainage systems (SUDS), and France refers to it as techniques alternatives (Urrutiaguer; Edwards; Chandler, 2010; Eckart; Mcphee; Bolisetti, 2017). In addition, the term best management practices (BMP) is commonly used to refer to techniques that focus on reducing pollutants (Guitierrez, 2006). These terminologies are compatible and use compensatory technologies as a drainage solution, with their applications fostering the necessary conditions for sustainable urban development (Baptista; Nascimento; Barraud, 2015).

Selecting the best alternative drainage system is a multidisciplinary field of study that requires collaborative inputs from several experts (Zhou, 2014). The selection depends on a complex set of factors, including economic, climatic, topographical, and social factors (Jia *et al.*, 2012). Given this complexity, studies on the performance of compensatory techniques for different application scenarios are crucial, serving as a basis for decision-making by urban managers.

This study evaluated the performance of two SCTs—cisterns and permeable pavements—in reducing

surface runoff. These techniques were evaluated through mathematical modeling of their capacity to reduce peak flows and runoff volumes. Two heavy precipitation events officially recorded in 2014 and 2016 that resulted in hydrological disasters were analyzed. The storm water management model (SWMM) software was used for the analysis, and the data were processed in a geographic information system (GIS) environment. Modeling was also performed using the curve number–soil conservation service (CN-SCS) method to assess the impact of urban areas on hydrograph values.

2 METHODOLOGY

2.1 Study area

2.1.1 Selection process

The study area was initially selected on the premise of identifying Brazilian municipalities with 50,000 or more inhabitants that had recorded at least one hydrological disaster resulting from flooding caused by an intense rainfall event in the Disaster Information Form (FIDE).

The FIDE was introduced in August 2012 to replace the preliminary notification of disaster (NOPRED), damage assessment (AVADAN), and municipal or state decrees as the official record of disasters. It is accessible through the Integrated Disaster Information System (S2iD) of the Ministry of Integration (S2id, 2021). It contains several topics that describe the type of disaster, date of occurrence, identification of the city, area with affected population (whether rural or urban, or both situations together), causes and effects of the disaster, human, material, or environmental damage, public and private losses, and the reporting institution.

After selection based on the number of inhabitants, an analysis was conducted to determine whether the FIDE of these municipalities contained records of the amount of precipitation and its duration, causes and consequences of the disaster, and human and economic losses. Those located in regions where drainage systems could be influenced by tidal effects were excluded. Subsequently, the municipalities with records of telemetric data on precipitation and flow corresponding to the dates of occurrence of the disasters recorded in FIDE were selected.

2.1.2 Delimitation of the river basin

The “Qgis” software, version 3.16.16, was used to delimit the basin based on a digital elevation model (DEM) with a resolution of 30 m obtained from the TOPODATA database (Inpe, 2008). The “r.watershed” and “r.water.outlet” tools, both present in the “GRASS” extension of the “Qgis” software, were used. The location of the telemetry station was defined as the basin outlet.

2.1.3 Land use and occupation

The land use and occupation of the basin were determined using “Landsat 8” images with a spatial resolution of 30 m. These images were obtained from the “EarthExplorer” platform of the United States Geological Survey (USGS) and selected for a date close to the events of interest in this study. The visibility level, determined by the presence or absence of clouds, was also considered during the image selection. Combinations of spectral bands were created from these images and classified according to land use and occupation.

The supervised classification of land use and occupation was performed using the “Orfeo ToolBox” (OTB) add-on in “Qgis” using the nearest neighbor method. Several samples were selected to define each class, delimiting the polygons with pixels representing each area to be classified.

After determining the samples, the image classification statistics were generated using the “ComputeImageStatistics” command of the add-on. Subsequently, the classifier was trained with the image composition and class samples using the “TrainImagesClassifier” command. Finally, the “ImageClassifier” tool was used for the final classification. The generated raster was transformed into a vector and manually corrected for classes with inconsistencies in the land use classification. Finally, the area corresponding to each land use and occupation class in the basin was calculated.

2.1.4 Pedology

The pedological data of the basin were obtained from the GeoMetadata portal of the state of Mato Grosso, from the State Secretariat for Planning of Mato Grosso – SEPLAN (Seplan – secretaria de estado de planejamento de mato grosso, 2022). The “shapefile” with the soil information was cropped using the edge of the hydrographic basin as a mask layer to obtain the portions of each soil type present in the basin area. The soils were classified into hydrological groups, ranging from A to D as defined by the (SCS) (1972), based on their characteristics that influence surface runoff. Soil group A is more permeable, whereas soil group D is more impermeable. This study followed the methodology proposed by Sartori, Neto e Genovez (2005) to classify Brazilian soils into the SCS hydrological groups.

2.2 Hydrological study

2.2.1 Telemetry station

A search was conducted for telemetry stations with rainfall and flow data records corresponding to the dates recorded in the FIDE and close to the location of the disaster. This was done to ensure that the delimitation of the basin from this station included the affected region. The search was conducted based on the

stations provided by the National Water Resources Information System (SNIRH) (Agência nacional de Águas, 2022).

2.2.2 *CN-SCS method*

The curve number–soil conservation service (CN-SCS) method developed by the United States Department of Agriculture (USDA), currently called the Natural Resources Conservation Service (NRCS), is an empirical rainfall-runoff model traditionally used in Brazil. It is widely used when hydrological data are not available, as it primarily relies on a single parameter called the curve number (CN). Its widespread use is attributed to its simplicity, minimal parameter requirement, and credibility of its institution of origin (Ponce; Hawkins, 1996).

It was developed to estimate direct surface runoff in a river basin based on rain events. Its use depends on the definition of the CN, influenced by factors such as soil type, land use and occupation, and initial moisture levels.

This method works analogously to the water balance equation, where direct surface runoff is the difference between the volume of precipitation and the sum of the portions of precipitation that infiltrate before the occurrence of runoff and those retained on the surface after runoff (Service, 1999). Evapotranspiration is part of the portion to be subtracted from the precipitation volume; however, it is often negligible and typically disregarded.

Based on the hydrographs generated, this method was used to assess the relative contribution of urban areas to the total volume drained from the basin. The volume drained by the urban plot was used as a reference value for comparison with the values obtained from hydrological modeling.

2.2.2.1 Calculation of CN

The CN of each analyzed plot was determined based on the identification of the hydrological groups of the soils present in the study area, area corresponding to each type of land use and occupation, and considering various soil moisture conditions. A weighted average was then calculated by considering the sum of the products between the areas of land use and occupation plots and their respective CNs. This operation returned the CN value for the entire analyzed area under antecedent moisture condition II. The antecedent moisture condition, or soil saturation, was determined based on the accumulated precipitation over the previous five days. Using the SCS method, three antecedent moisture conditions were defined: I – dry soils – accumulated precipitation in the last five days was less than 15 mm; II – soils with moisture content close to field capacity – precipitation in the last five days was between 15 mm and 40 mm; and III – soil close to saturation – precipitation in the last five days exceeded 40 mm. From the definition of the saturation condition, the definitive CN can be inferred by converting the CN to reflect different soil moisture conditions, as outlined in the conversion

table provided the (SCS) (1972).

2.2.2.2 Calculation of direct surface runoff

Excess precipitation, or direct surface runoff (Equation (1)), is the portion of the total precipitation contributing to surface runoff. This runoff occurs initially in the form of flash floods and later through larger and better-defined watercourses (Porto, 1995).

$$V_{esd} = AD \cdot h_{exc} \quad (1)$$

where V_{esd} is the volume of direct surface runoff, AD is the drainage area, and h_{exc} is the excess precipitation. Using the obtained CN, the other parameters necessary for calculating the excess precipitation (Equation (2)) were determined: potential soil retention (S) and initial abstraction (I_a). The initial abstraction value (I_a) is typically considered to be 20% of the S value.

$$h_{exc} = \frac{(P - 0.2S)^2}{P + 0.8S}, \quad P > 0.2S \quad (2)$$

where P is the precipitation. The value of S (Equation (3)) depends on the land type, use, and occupation and is obtained as a function of the CN.

$$S = \frac{24500}{CN} - 254 \quad (3)$$

where CN ranges from 0 to 100.

3 SWMM

The SWMM is a dynamic rainfall-runoff modeling software that simulates the quantity and quality of surface runoff for continuous precipitation events (long-term precipitation) and discrete events (isolated events). It also models the hydrodynamic processes of the hydrographic network. It was developed in 1971 by the United States Environmental Protection Agency (USEPA) and is open source and freely distributed. It is widely used for hydrological and hydraulic simulations of urban basins and has many applications in nonurban areas (Rossman, 2010).

According to Barco, Wong e Stenstrom (2008) and Rossman (2010), the SWMM can represent a series of aspects of the urban hydrological cycle and water quality, including snow accumulation and melting, rainfall variability over time, water evaporation, surface runoff, infiltration, transport through the drainage network, storage, and treatment. Starting with the SWMM5, simulations with SCT implementation became possible, making the model a valuable tool for simulating future scenarios using sustainable drainage systems. This study analyzed two SCTs: cisterns and permeable pavements.

This study used the SWMM to perform hydraulic-hydrological modeling of a residential area located within the urban region of the study area to simulate the performance of the SCT selected for the analysis scenarios. The following parameters were set to run the simulations: physical process model, rain/flow, flow propagation, infiltration model, curve number CN-SCS, flow propagation model, kinematic wave, and flow propagation time step of 30s.

The CN-SCS model was used to estimate infiltration owing to its simplicity and reliance on a single parameter (CN). Furthermore, this decision was influenced by the lack of field data that would allow for a more precise characterization of the parameters present in the Green-Ampt and Horton models.

The parameters adopted for the sub-basins were defined according to the characteristics of each sub-basin and are detailed and explained in the SWMM manual (Rossman, 2010). The outlet nodes of the sub-basins and their rain conduits were defined. The precipitation time series to be used in the modeling was entered and associated with one or more rain gauges. The rain gauges were directly associated with each sub-basin and inferred the amount of precipitation that they would receive according to the time series entered. In this study, two precipitation events related to two disaster events recorded in the FIDE were used to characterize the time series adopted in the rain gauges. For each sub-basin, the compensatory technique to be implemented was specified based on the scenario to be analyzed. Two types of models were used: cistern sand porous pavements. The parameters used in characterizing the porous pavements were adopted according to those used by Tominaga (2013). The cisterns were designed to function as storage containers, enabling water reuse.

3.1 Analysis scenarios

To evaluate the performance of the SCTs, eight different scenarios were simulated:

Scenario 1: Residential area without SCTs under a rain event recorded in 2014;

Scenario 2: Residential area with cisterns under a rain event recorded in 2014;

Scenario 3: Residential area with porous pavements under a rain event recorded in 2014;

Scenario 4: Residential area with porous pavements and cisterns under a rain event recorded in 2014;

Scenario 5: Residential area without SCTs under a rain event recorded in 2016;

Scenario 6: Residential area with cisterns under a rain event recorded in 2016;

Scenario 7: Residential area with porous pavements under a rain event recorded in 2016;

Scenario 8: Residential area with porous pavements and cisterns under a rain event recorded in 2016.

4 STRUCTURAL COMPENSATORY TECHNIQUES

4.1 Permeable pavements

Traditionally, asphalt and concrete are the most commonly used materials for paving densely populated areas, whether for vehicle and pedestrian traffic routes or parking lots, owing to their waterproofing capabilities. These areas typically occupy large portions of the drainage basin and generate large amounts of surface runoff. According to Abustan, Hamzah e Rashid (2012), permeable pavements are an alternative to these types of pavements.

According to U.S. Environmental Protection Agency (USEPA) (2000) and Bean, Hunt e Bidelspach (2007), these pavements differ from traditional pavements in that they reduce surface runoff through temporarily storage, allowing water to infiltrate into the subsoil. Permeable pavements (PPs) help urbanized basins restore their peak flow rates, drained volumes, and concentration times to pre-urbanization values (Baptista; Nascimento; Barraud, 2015). PPs also control diffuse pollution, promote groundwater recharge (Paraná (estado), 2002), and enable the reuse of stored water (Pratt; Newman; Bond, 1999). PPs can be used for permeable, partially permeable, and nonpermeable soils, with a drainage system used to drain excess water once the storage capacity of the structure is reached (Drake; Bradford; Seters, 2014). Several types of PPs exist, with their applicability varying based on the specific characteristics of the location in which they will be used. According to Abustan, Hamzah e Rashid (2012), the most common types of PPs are permeable concrete, permeable asphalt, and hollow blocks. According to Lima *et al.* (2022), several types of permeable pavements can be used for infiltration purposes, including interlocking blocks, concrete pavements, asphalt pavements, and blocks, typically used on public roads, parking lots, and sidewalks.

4.2 Cisterns

Cisterns are storage elements designed to collect rainwater runoff from the roofs of houses or buildings, allowing for later use. They are typically positioned outside the buildings, downstream of the gutters originating from the roofs.

Water storage in cisterns can be permanent or temporary, depending on their application purpose. These elements help mitigate flood peaks by slowing the propagation of flows downstream, relieving the drainage system. In addition to relieving the drainage system, a key advantage of using cisterns is the financial return achieved through water conservation because the stored water can be reused for various purposes (Lima *et al.*, 2022).

5 RESULTS AND DISCUSSION

5.1 Selection of the study area

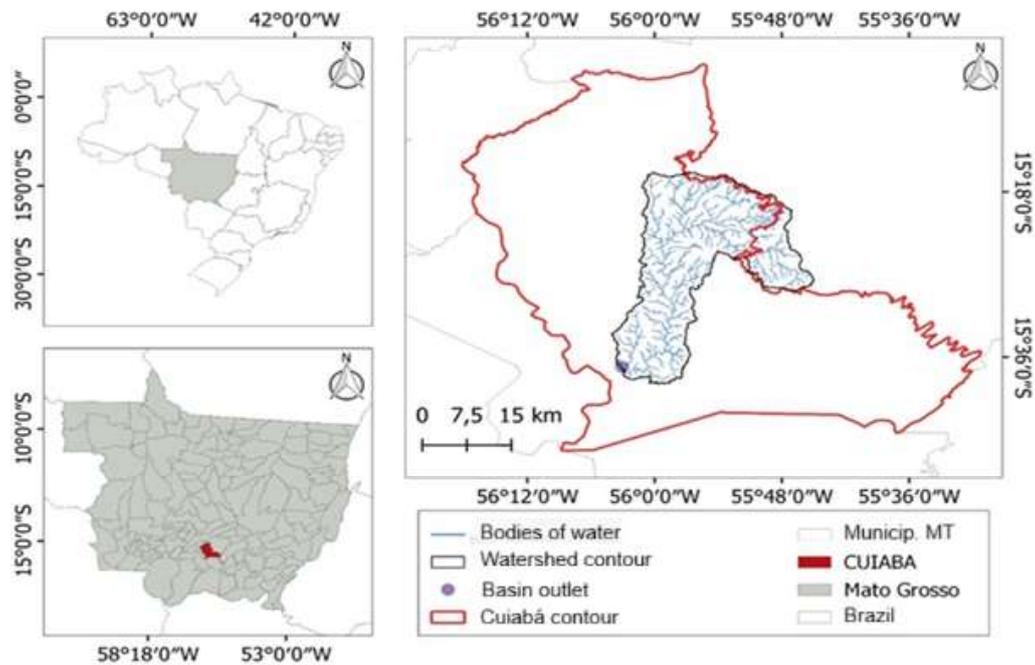
The selection of the study area began with a sample of 51 municipalities. The initial sample was reduced to four municipalities based on the criteria defined in the methodology. Cities located in regions where the drainage system could be influenced by tidal effects were excluded, reducing the sample size to three municipalities. The availability of flow and precipitation data corresponding to the dates of disaster occurrence was then verified, reducing the sample size to one municipality. The selected municipality was Cuiabá, located in the Brazilian state of Mato Grosso. Two FIDE documents with records of flooding disasters caused by heavy precipitation dating from 2014 to 2016 were selected.

According to the FIDE report, the disaster recorded on 04/03/2014 was caused by a precipitation event of approximately 60 mm, which occurred at approximately 5:30 pm. Reports indicated that owing to insufficient drainage of rainwater and heavy rainfall, several neighborhoods suffered from flooding, including an overflow in the Machado Stream, which inundated homes and caused significant damage to residents. Approximately 350 homes were affected, with 100 sustaining damage such as cracked or compromised walls, problems with roofs and coverings, damaged floors, and widespread loss of clothing, food, furniture, appliances, equipment, and utensils. Approximately 1,050 people were affected, with 360 displaced and 690 suffering the loss of their belongings. A power outage lasting approximately 3 h occurred on the date of the event. On 04/01/2016, a 50 mm high-intensity rainfall event was recorded in the FIDE, which caused flooding owing to a lack of or insufficient drainage. According to the record, four homes were affected by flooding. One of these homes was made of wood and was partially destroyed by a flood wave triggered by the fall of a wall retaining a large amount of water on a plot of land. These homes required cleaning, repair, and disinfection. This disaster displaced two people and directly affected another six.

5.1.1 Description of the study area

The selected study area comprises a river basin delimited from the hydrometeorological station 66259650, serving as an outlet, located on the Coxipó River, at coordinates 15°37'03" S and 56°03'04" W (Figure 1). The basin has an area of approximately 686 km² and a thalweg length of 89.15 km. In addition to the municipality of Cuiabá – MT, the basin has a part of its northeastern portion located in the municipality of Chapada dos Guimarães – MT. It is located between longitudes 55°24'00" W and 56°24'00" W and between latitudes 15°00'00" S and 15°54'00" S.

Figure 1 – Location of the study area



5.2 Land use and occupation

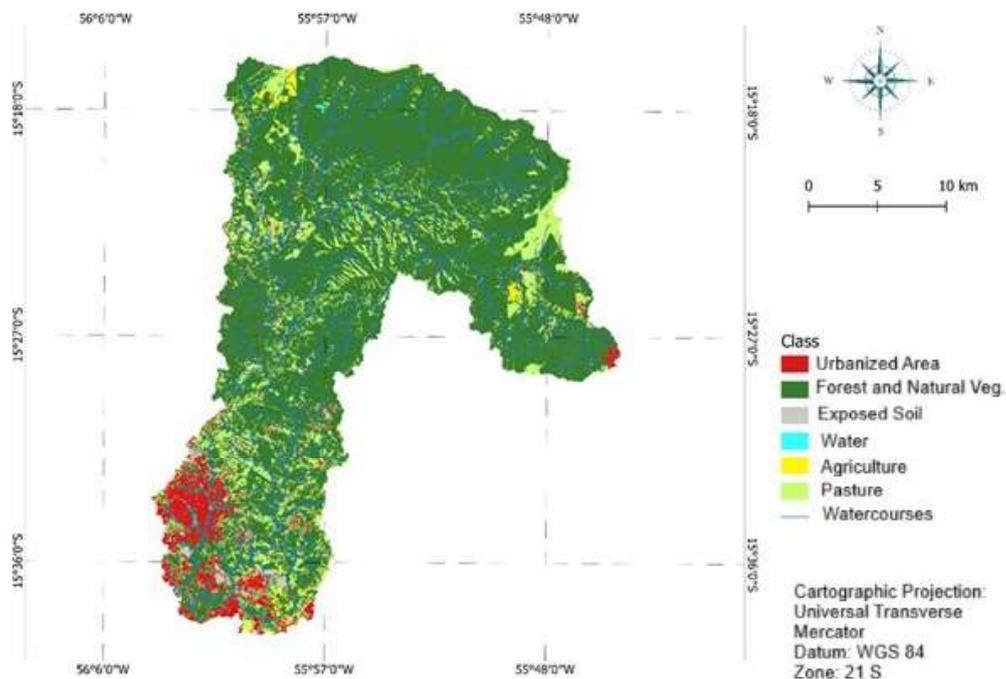
The Landsat-8 images were obtained on July 3, 2014, the date closest to the largest rain event recorded in the FIDE, without the presence of clouds. Based on the analysis and supervised classification, a land use and occupation classification map (Figure 2) and its respective areas (Table 1) were obtained. The selected combination included bands 7, 5 and 3, because the visual contrast in this composition facilitates the visual distinction between different land uses and their subsequent classifications.

Six land use classes were identified: urbanized areas, forest and natural vegetation, exposed soil, water, agriculture, and pastures. These classes were selected to capture the largest possible number of subclasses to facilitate the supervised classification process. This streamlined the process by reducing the number of classes involved.

Table 1 – Land Use and Occupation – Coxipó Basin

Classes	Area (km ²)	(%)
Urbanized area	40.10	5.84
Forest and natural vegetation	534.39	77.83
Exposed soil	6.91	1.01
Water	2.59	0.38
Agriculture	12.76	1.86
Pasture	89.84	13.08
Total	686.59	100.00

Figure 2 – Land use and occupation map of the Coxipó River Basin.



5.3 Pedology

From the “shapefile” obtained from SEPLAN, containing the pedological information of the study region, and after analyzing it in a GIS environment, the plots of each soil type present in the basin were obtained (Table 2). More than half of the soils (58.13%) in the basin were classified as hydrological group D. This indicated that the basin generally has low water infiltration capacity and a high tendency to generate surface runoff, along with high vulnerability to erosion. The other soil plots were classified into groups A, B, and C, totaling 8.78%, 23.93%, and 9.16%, respectively.

5.4 Hydrological study

5.4.1 Measured hydrographs

At station 66259650, a series of precipitation and water level data was obtained, measured at the mouth of the study basin. The flow data were not recorded; thus, they were calculated using the key curve of the station (Equation (4)), according to Junior (2019).

$$Q = 4.33 \times H^{1.85} \quad (4)$$

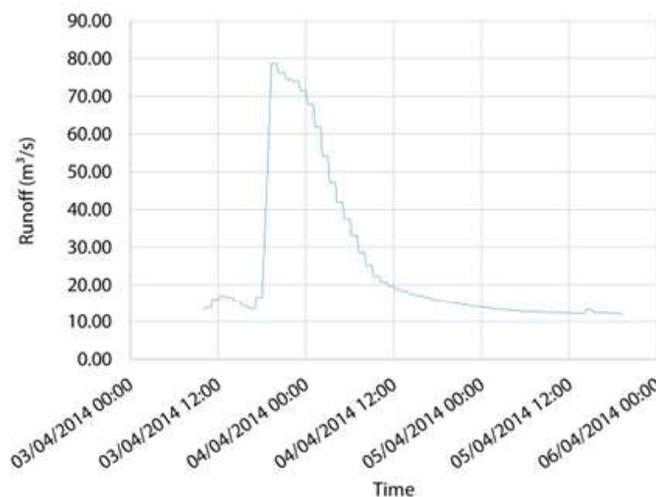
Table 2 – Soil Classes – Coxipó Basin

Soil class	Total area portion (%)
Alic and Dystrophic Quartz Sands (AQa)	12.63
Alic and Dystrophic Cambisol (Ca5)	9.16
Alic and Dystrophic Cambisol (Ca6)	0.00
Dystrophic Cambisol (Cd2)	18.28
Dystrophic Dark Red Latosol (LEd1)	2.67
Dystrophic Red-Yellow Latosol (LVd3)	0.65
Dystrophic Red-Yellow Latosol (LVd5)	7.36
Dystrophic Plinthosol (PTd1)	0.46
Red-Yellow Podzolic Soils (PVe2)	3.19
Alic Litholic Soils (Ra1)	7.90
Dystrophic Litholic Soils (Rd1)	5.86
Alic and Dystrophic Cambic Concretionary Soils (SCCa1)	0.82
Alic and Dystrophic Cambic Concretionary Soils (SCCa2)	21.61
Dystrophic Latosolic Concretionary Soils (SCLd2)	5.63
Dystrophic Latosolic Concretionary Soils (SCLd3)	3.29
Dystrophic Podzolic Concretionary Soils (SCPd)	0.48
Total area	100.00

where Q is the flow rate [m^3/s], and H is the water level [m].

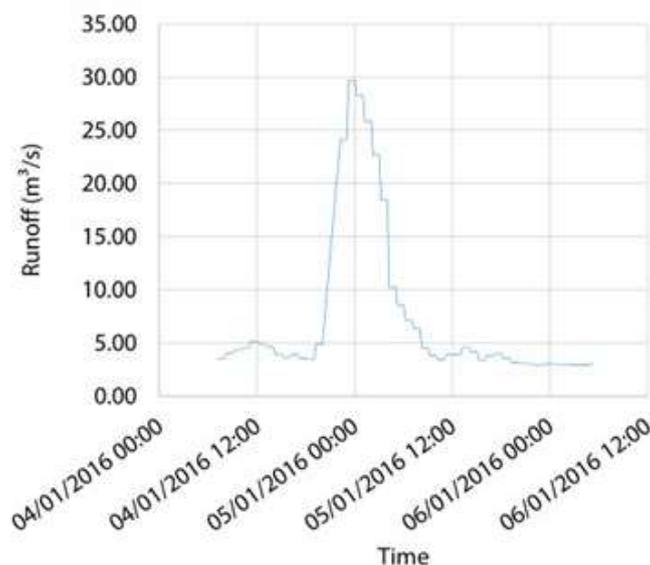
Hydrographs of the precipitation events corresponding to the disaster dates recorded in the FIDE were plotted (Figures 3 and 4).

Figure 3 – Hydrograph for the precipitation event measured at station 66259650 on 04/03/2014.



On 04/03/2014, the date of a disaster recorded in the FIDE with 60 mm of rainfall, station 66259650 recorded a rainfall event of 53.4 mm. On 01/04/2016, corresponding to the second disaster event recorded in the FIDE, the station recorded a total of 33.2 mm, a value well below the 50 mm recorded in the FIDE. This discrepancy can be attributed to a measurement error. In particular, nine consecutive records of precipitation

Figure 4 – Hydrograph for the precipitation event measured at station 66259650 on 01/04/2016.



volume were missing during the rainfall event, totaling 2 h of unmeasured data. From the graphical analysis of the hydrographs, the total volume drained for the two events measured in the field was determined, disregarding the base flow (Table 3).

Table 3 – Total volume of surface runoff for data from station 66259650

Event	Separation equation	Surface runoff volume (L)
2014	$y = 0.0685x - 2846.4$	1 772 900 000.00
2016	$y = 0.5504x - 23321$	493 340 000.00

5.4.2 SCS - CN

The area of each land use type and occupation in each hydrological group were calculated (Table 4) to obtain the CN. For the Coxipó River basin, a CN of 72.63 was calculated for the 2016 precipitation event (soil in humidity condition II – 18.2 mm of rain in the previous five days) and 89 for the 2014 precipitation event (soil in humidity condition III – 60.6 mm of rain in the previous five days).

With the CN defined, the other parameters necessary to calculate the volume of direct surface runoff for the 2014 and 2016 rain events were determined (Table 5). The excess precipitation was calculated using these values, and the total volume of surface runoff generated for the events recorded in the FIDE and hydrometeorological station for the same dates was obtained. The portion corresponding to urban areas was extracted from this volume (Tables 6 and 7). Values of 9.1% and 9.6% were obtained for the 2014 rainfall event for the FIDE measurements and telemetric station data, respectively. For the 2016 rainfall event, values of 15.7% and 25.6% were obtained for the FIDE measurements and telemetric station data, respectively. These results indicate that

Table 4 – Plot, by type of use and occupation, present in each type of hydrological group in the Coxipó River basin

Land Use and Occupation	Area (km ²)				
	Group A	Group B	Group C	Group D	Total
Urbanized area	16.01	2.27	0.21	21.61	40.10
Forest and natural vegetation	33.36	138.42	57.26	305.34	534.39
Exposed soil	1.51	0.24	0.04	5.12	6.91
Water	0.55	0.09	0.08	1.88	2.59
Agriculture	0.86	4.03	1.03	6.84	12.76
Pasture	8.02	19.24	4.29	58.28	89.84
Total	60.307	164.292	62.91	399.08	686.59

urban contributions were significantly higher for the 2016 event. This was because the soil was drier during the 2016 event, implying higher infiltration potential. This highlights the impact of soil waterproofing on runoff volumes, particularly when the soil moisture in the basin is low.

Table 5 – Parameters obtained from the CN calculation

Event	CN	S (mm)	$I_a (0.20 \times S)$ (mm)
2014	89.00	31.39	6.28
2016	72.63	95.73	19.15

Table 6 – Runoff volumes and runoff shares from the urban area for precipitation events recorded in the FIDE, calculated using the CN-SCS method

Event	Rainfall depth (mm)	Surface runoff volume (L)	Urban parcel (%)
2014	60.0	22 280 293 448.57	9.1
2016	50.0	5 163 207 912.42	15.7

Table 7 – Runoff volumes and runoff shares from the urban area for precipitation events recorded at the hydrometeorological station

Event	Rainfall depth (mm)	Surface runoff volume (L)	Urban parcel (%)
2014	53.4	19 417 070 009.39	9.6
2016	33.2	1 235 140 796.18	25.6

The total runoff volume using the CN-SCS model was significantly higher than that obtained from the measured hydrographs. This discrepancy can be attributed to the spatial distribution of the analyzed rainfall. According to Ponce e Hawkins (1996), caution is necessary when applying this method to basins larger than 250 km², and it is advisable to divide the basin into other sub-basins. As the CN-SCS is a grouped model, rainfall is considered uniform for the entire basin. Larger areas typically require more rain gauge stations to ensure the accuracy of the model input parameters, resulting in outputs that more match observed data. The precipitation values adopted for 2014 and 2016 were defined based solely on the telemetric station present within or near

the study area. This resulted in an overestimated value of the total volume drained because the precipitation in the regions upstream of the basin could not be determined; thus, the rainfall was considered homogeneous for the entire area. According to Filho e Marcellini (1995), the precipitation values recorded at a single rain gauge station represent areas of 1 km² to 25 km². Because the basin analyzed in this study covers 600 km², the representativeness of the precipitation distribution throughout the study area and its implications for the results are known. Recent studies have discussed the problem of reduced monitoring points in Brazil for simulating climate variable models (Guarienti *et al.*, 2020), water quality (Costa *et al.*, 2022), and rainfall-runoff (Almeida *et al.*, 2023; Melo; Almeida; Almeida, 2023; Finck *et al.*, 2024). The precipitation values recorded in the FIDE for 2014 and 2016 were higher than those measured by the telemetry station. For 2014, this can be explained by a probable approximation made by the observer responsible for completing the document. For 2016, the discrepancy likely resulted from the non recording of precipitation from 8:15 p.m. to 10:15 p.m., during which the rainfall event had already started but not captured by the telemetry station.

5.4.3 SWMM - SCT performance

The selected area for evaluating the performance of the SCTs consists of a condominium of single-story houses of approximately uniform sizes, distributed in blocks. It covers approximately 22.14 ha, with 9.92 ha and 12.22 ha classified as permeable and impermeable areas, respectively. The impermeable area includes asphalt surfaces, sidewalks, and roofs. The permeable area includes grassy areas. This area was selected considering the spatial layout of the buildings to facilitate the determination of the number of SCTs to be implemented according to the number of residences and street layout. The area is close to the outlet of the study basin (approximately 3.5 km in a straight line), increasing the likelihood of being affected by rainfall recorded at the telemetric station. The area is located on soil classified as hydrological group D. This study aimed to analyze the behavior of the techniques within this region rather than propose a solution for a specific location. Therefore, the exact address of the area and costs associated with implementing the SCTs were irrelevant to this analysis. The selected area was divided into 23 sub-basins (Table 8), which were tested under the analysis scenarios described in the methodology.

Each house was assigned a 5000 L storage tank type cistern. Permeable pavements were distributed to replace the entire asphalt area in the sub-basins. Tables 9 and 10 present the results of the reductions in volume and peak flow for each scenario.

Table 11 presents the two precipitation time series (2014 and 2016) used in the analysis. Immediately thereafter, hydrographs were obtained from the SWMM (Figures 5–12).

The cisterns assigned as the only SCT in scenarios 2 and 6 (Figures 6 and 10) performed well for the 2014 and 2016 rainfall events in terms of the reduction in discharged volumes. For peak flow reductions, the cisterns performed better in the 2014 rainfall event, whereas the PPs performed better in the 2016 event. These results contrast with those found by Abdelkebir *et al.* (2021) in a study conducted in Algeria. In their study, the cisterns performed the worst in terms of reductions in peak flow and discharged volumes for a

Table 8 – Sub-basins modeled in SWMM

Sub-Basin	Number of houses	Area (ha)			
		Roof	Grass	Sidewalk	Asphalt
S1	32	0.4100	0.3573	0.1039	0.1261
S2	32	0.4100	0.3573	0.1039	0.1261
S3	32	0.4100	0.3573	0.1039	0.1261
S4	32	0.4100	0.3573	0.1039	0.1261
S5	26	0.3528	0.3059	0.0602	0.1484
S6	31	0.4335	0.3485	0.1129	0.1224
S7	46	0.5177	0.6341	0.0803	0.2131
S8	3	0.0304	0.5150	0.1305	0.0716
S9	107	1.2747	1.3726	0.2594	0.3868
S10	14	0.1812	0.2275	0.0740	0.0846
S11	16	0.1609	0.3066	0.0835	0.0765
S12	20	0.2284	0.3205	0.0464	0.1213
S13	20	0.2186	0.3232	0.0464	0.1186
S14	20	0.2186	0.3232	0.0464	0.1186
S15	20	0.2186	0.3232	0.0464	0.1186
S16	20	0.2186	0.3232	0.0464	0.1186
S17	18	0.2100	0.3005	0.0416	0.1224
S18	18	0.2100	0.3005	0.0416	0.1224
S19	23	0.2455	0.3357	0.0489	0.1017
S20	19	0.2110	0.2587	0.0487	0.1198
S21	46	0.5177	0.7418	0.1020	0.1603
S22	11	0.1181	0.2340	0.0198	0.0497
S23	5	0.0331	1.0003	0.1573	0.1963

Table 9 – SWMM modeling results for a 53.4 mm rainfall event – 2014

Scenario	Rainfall (mm)	Porous pavement	Storage tank (cistern)	Surface runoff volume (L)	Volume reduction (%)	Peak flow (L/s)	Flow reduction (%)
1	53.4	N	N	10 802 000	-	3965.19	-
2	53.4	N	Y	7 906 000	27	2317.82	42
3	53.4	Y	N	10 646 000	1	3715.79	6
4	53.4	Y	Y	7 637 000	29	2289.89	42

Legend: N – no SCT | Y – with SCT

Table 10 – SWMM modeling results for a 33.2 mm rainfall event – 2016

Scenario	Rainfall (mm)	Porous pavement	Storage tank (cistern)	Surface runoff volume (L)	Volume reduction (%)	Peak flow (L/s)	Flow reduction (%)
5	33.2	N	N	5 245 000	-	2214.14	-
6	33.2	N	Y	2 821 000	46	950.62	57
7	33.2	Y	N	4 800 000	8	1655.83	25
8	33.2	Y	Y	2 713 000	48	647.19	71

Legend: N – no SCT | Y – with SCT

rainfall event with a 10-year recurrence interval. These results highlight the importance of simulating the SCT implementation according to the physical and climatic characteristics of the region of interest. A study by Qin, Li e Fu (2013) conducted in China supports this significance. Their results revealed that SCT implementation yielded different results according to the temporal arrangement of the peak of the analyzed precipitation and

Table 11 – Time series referring to the rainfall events of 2016 and 2014, respectively. Source: Hidroweb Portal - ANA (2022)

2016 event	Volume (mm)	2014 event	Volume (mm)
01/04/2016 18:30	0	04/03/2014 17:30	0
01/04/2016 18:45	0.2	04/03/2014 17:45	5
01/04/2016 19:00	1.2	04/03/2014 18:00	24.8
01/04/2016 19:15	0.2	04/03/2014 18:15	15.2
01/04/2016 19:30	0.2	04/03/2014 18:30	7.2
01/04/2016 19:45	0	04/03/2014 18:45	1.2
01/04/2016 20:00	0	04/03/2014 19:00	0
01/04/2016 20:15	NR		
01/04/2016 20:30	NR		
01/04/2016 20:45	NR		
01/04/2016 21:00	NR		
01/04/2016 21:15	NR		
01/04/2016 21:30	NR		
01/04/2016 21:45	NR		
01/04/2016 22:00	NR		
01/04/2016 22:15	NR		
01/04/2016 22:30	17.6		
01/04/2016 22:45	7.6		
01/04/2016 23:00	3.8		
01/04/2016 23:15	1		
01/04/2016 23:30	0.2		
01/04/2016 23:45	0.6		
01/05/2016 00:00	0.6		
01/05/2016 00:15	0		

Legend: NR – no data

the adopted recurrence time.

The combined use of PPs and cisterns in scenarios 4 and 8 (Figures 8 and 12) yielded reductions in peak flow and drained volume. It should be noted that all scenarios showed improved performance for rainfall events with lower volume and intensity. This is consistent with the findings of Eckart, McPhee e Bolisetti (2017), who stated that SCTs employed at the source tend to perform better for rain events with a shorter recurrence period. They also noted that for more intense and voluminous rainfall events, the combined application of SCTs employed at the source with detention basins yields better results.

Figure 5 – Hydrograph of scenario 1.

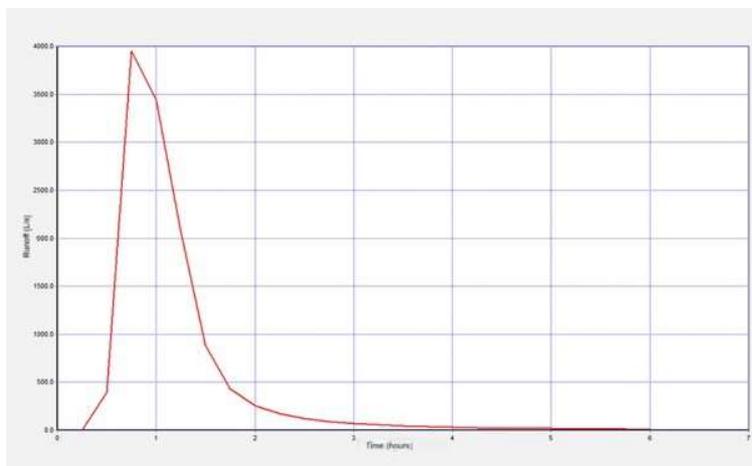


Figure 6 – Hydrograph of scenario 2.

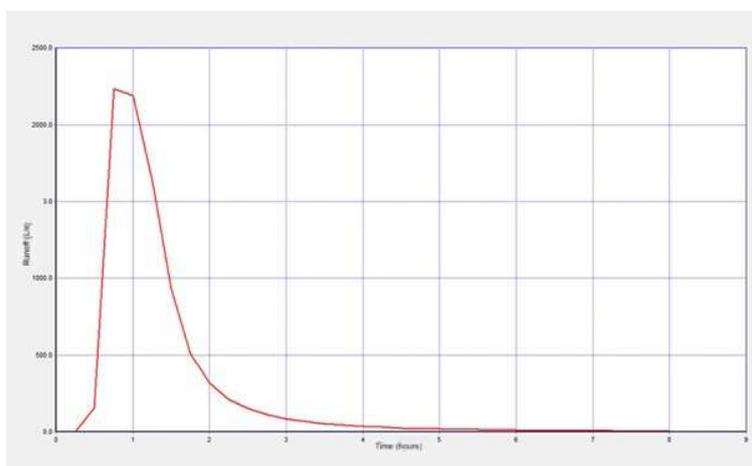


Figure 7 – Hydrograph of scenario 3.

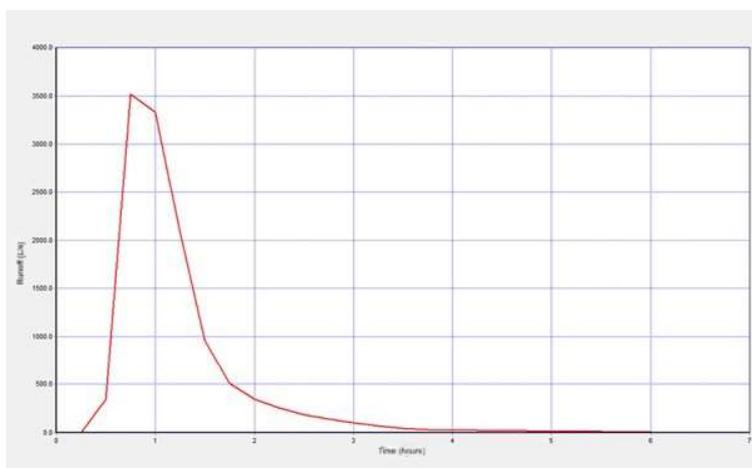


Figure 8 – Hydrograph of scenario 4.

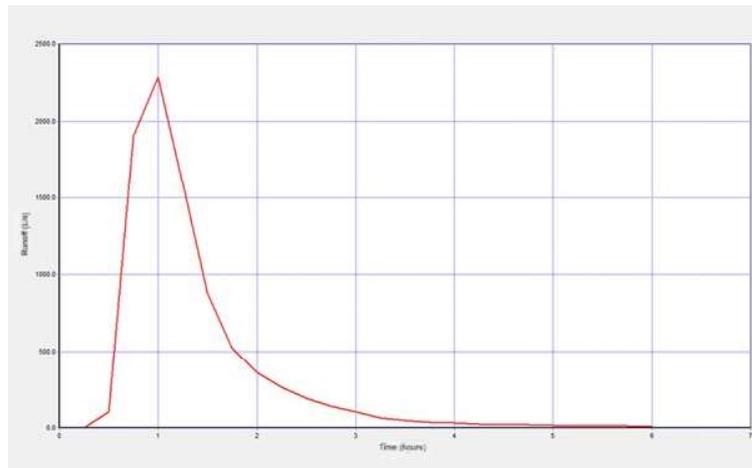


Figure 9 – Hydrograph of scenario 5.

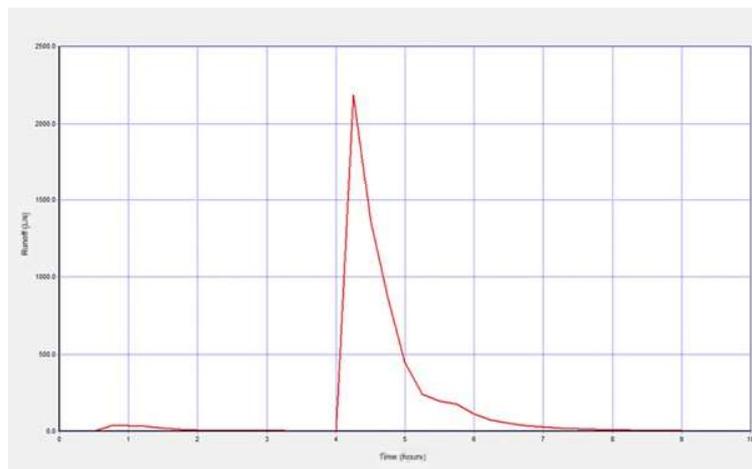


Figure 10 – Hydrograph of scenario 6.

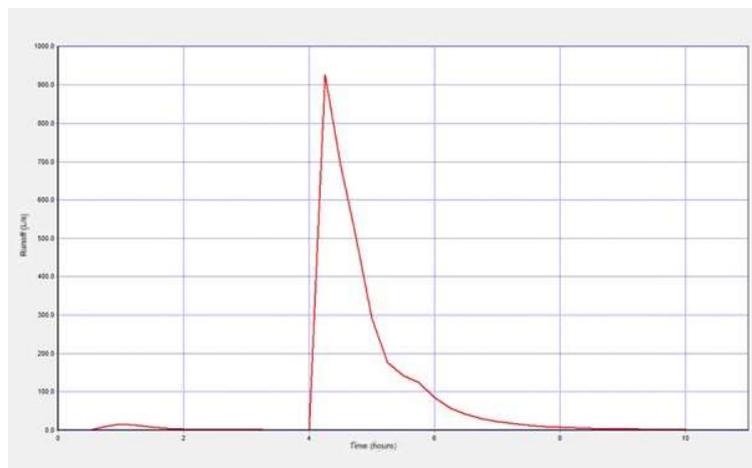


Figure 11 – Hydrograph of scenario 7.

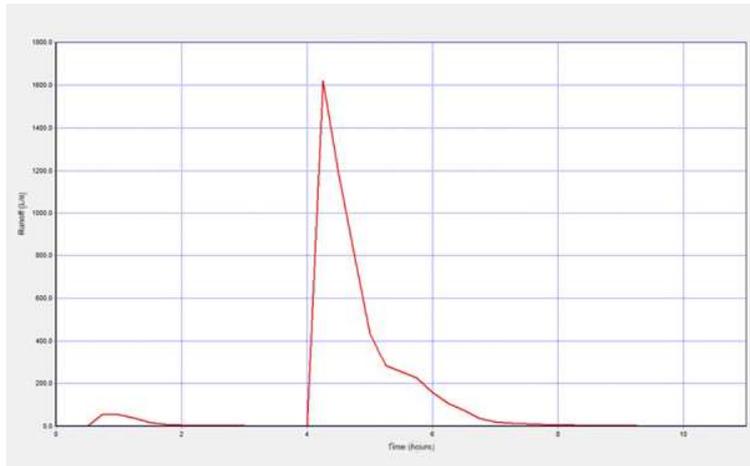
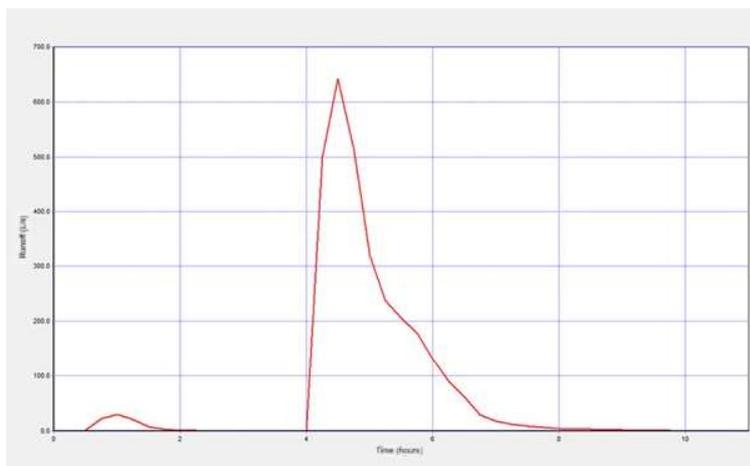


Figure 12 – Hydrograph of scenario 8.



6 CONCLUSION

The SCS method yielded runoff volume values significantly higher than those recorded in the field. This highlights the need for caution when using it for large basins, particularly during heavy rainfall, because it assumes a homogeneous rainfall distribution across the entire drainage area. It was also observed that drier soil conditions led to a greater contribution from urban areas to the flood hydrograph.

The compensatory techniques used in this study demonstrated good performance for the scenarios analyzed. Satisfactory results were achieved in terms of runoff volume and peak flow reductions, with some cases showing nearly a fifty percent reduction in volume. The analyzed techniques proved to be more efficient for rainfall scenarios with lower intensity and volume, yielding substantially better results than when subjected to more intense and voluminous rainfall. Cisterns outperformed porous pavements in the scenarios analyzed in this study.

Given the favorable results obtained with the use of compensatory techniques, it is crucial for urban planning to consider the use of such measures in conjunction with traditional drainage systems.

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