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Geosciences

Use of hydrologic and hydraulic modeling for optimizing an existing detention pond

Uso de modelagem hidráulico-hidrológica para otimização de um reservatório de detenção

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ABSTRACT

In Brasilia, the local regulations limit the maximum flow rate per unit area discharged in rivers by drainage systems. The purpose of this work is to analyze the possibility of optimizing the use of an existing detention pond, known to be oversized, by directing to it the stormwaters of adjacent areas not attended by any urban drainage system. SWMM (Storm Water Management Model) is a hydrologic and hydraulic model that was used to design a new urban drainage system for this added area and to analyze the basin with the detention pond at the outlet. As a result, the new system designed complies with all local regulations including maximum flood peak for the design critical rainfall. However, the original drainage system for the area needs improvements considering that there were flooded manholes for all rainfall events tested - clearly seen with the 2D modelling. If adapted, the existing detention pond is sufficient for the proposed adjacent area. This study showed the importance of hydrological and hydraulic modelling in urban drainage to manage this system and to propose sustainable measures – such as ponds. It was also revealed that the benefits of these ponds are related to the damping of the peak flow and if located at the end of the drainage system, floodings on the area may still occur.

Keywords: Flooding; Hydrological modelling; Sustainable urban drainage

RESUMO

Em Brasília, a legislação local limita a vazão máxima por unidade de área, lançada em algum corpo receptor por sistemas de drenagem urbana. O propósito desse trabalho é analisar a possibilidade de otimização do uso dessa lagoa de detenção, atualmente superdimensionada, direcionando as águas de áreas adjacentes que não possuem sistema de drenagem urbana. O SWMM (“Storm Water Management Model.”) é um modelo hidrológico-hidráulico e foi utilizado para projetar um novo sistema de drenagem e analisar a bacia com a lagoa de detenção em seu exutório. Como resultado, o sistema proposto segue todas as recomendações legais locais, incluindo o pico de vazão para uma chuva crítica. Porém, o sistema de drenagem original para a área necessita de melhoria, considerando que houve poços de visitas inundados para todos os eventos de chuva testados - vistas claramente na modelagem 2D. Se adaptada, a lagoa de detenção é capaz de atender a área adjacente proposta. Esse trabalho mostrou a importância do uso da modelagem hidráulica e hidrológica em drenagem urbana para planejar e propor medidas sustentáveis – como lagoas. Também foi mostrado que os benefícios de tais estruturas (lagoas) estão relacionados a diminuição do pico de vazão e, se localizada ao final da rede de drenagem, os pontos de alagamentos na área ainda irão ocorrer.

Palavras-chave: Drenagem urbana sustentável; Modelagem hidrológica; Inundações

1 INTRODUCTION

Urban drainage systems are necessary for management of stormwater and are needed to evolve harmoniously with the cities dynamic (Oliveira et al., 2019; Conserva et al., 2019). Solutions only composed of conduits and manholes are outdated and solve the problem locally (Qiao et al., 2019; Batista et Boldrin, 2018; Righetto, 2009), creating an increasing volume and velocity of surface runoff with the increase of urbanization (Castro et al., 2019; Berndtsson et al., 2019; Targa et al., 2012; Du et al., 2012; Luk, 1999).

New and creative technologies must be added to the projects, as Low Impact Development (LID) structures which can promote storage and infiltration (Zanandrea et al., Silveira, 2019; Jia et al., 2013; Baptista et al., 2011; Chocat et al., 2001). Ponds are a good example of these structures, having a potential of stormwater detention facilities to decrease diffuse pollution in stormwater by decreasing the velocity and allowing suspended sediments and associated pollutants to settle and accumulate within the basin (Luk, 1999; Souza et al., 2019; Campana et al., 2007; Grung et al., 2016; Sun et al., 2019), they permit a temporal redistribution and the attenuation of high floodwaters up to a pre-specified storm design limit (Nascimento et al., 1999).

Optimizing the use of existing pond can thus minimize some stormwater impacts. Gomes (2015) highlighted the number of ponds existing in Brasília-DF, Brazil, including a specific regimentation to stormwaters encouraging the use of ponds to damping peak flows. In Brasília–DF, a detention pond constructed, that replaced an old wastewater treatment pond, was identified as oversized by (Volken, 2018; De Paula, 2019). Volken (2018) modelled that the volumetric capacity of the pond is enough to retain a rainfall with return time values of 290 years. De Paula (2019), who monitored the pond during 2018 and 2019, found a damping of peak flow capacity by over 90% and a short circuit inside that can cause a reduction of efficiency in damping of diffuse pollution loads.

One way to improve the performance of the pond is using modeling hydraulic and hydrologic with model as SWMM (Storm Water Management Model). SWMM is a well-documented, comprehensive computer model for analysis of quantity and quality problems associated with urban runoff widely used in Brazil urban watersheds (Silva et al., Silva, 2020; Tsuji et al., 2019; Garcia et al., Paiva, 2006). All aspects of the urban hydrologic and quality processes, including rainfall, surface and subsurface runoff, flow routing through drainage network, storage and treatment, may be simulated. It is particularly useful as a planning tool to obtain an overall assessment of different sustainable device options.

In Brasilia–DF, ADASA (Regulatory Agency for Water, Energy and Sanitation of the Federal District) established the maximum stormwater flow per unit area that can be discharged to any water stream (24.4 L s^{-1} ha^{-1}). As consequence of this urban drainage management measure, the use of detention ponds was expanded even though alternative use of LIDs near runoff sources are still recommended.

The present paper analyses one area in Brasília, Guará, not attended by urban drainage system. It is located adjacent to an oversized detention pond. The aim of this work is to propose a drainage system to this area including the adaptation of the existing detention pond to dampen the peak flows, using the SWMM model, instead of building a new pond in another area.

With the SWMM model it was verified that that the existing detention pond can be adapted to absorb very effectively the runoff produced by the new added area if it were adapted. The 2D modelling made it possible to identify that part of the flooding occurring in the area is generated by the upstream area already provided with drainage system that can't cope with the amount of runoff generated.

2 MATERIAL AND METHODS

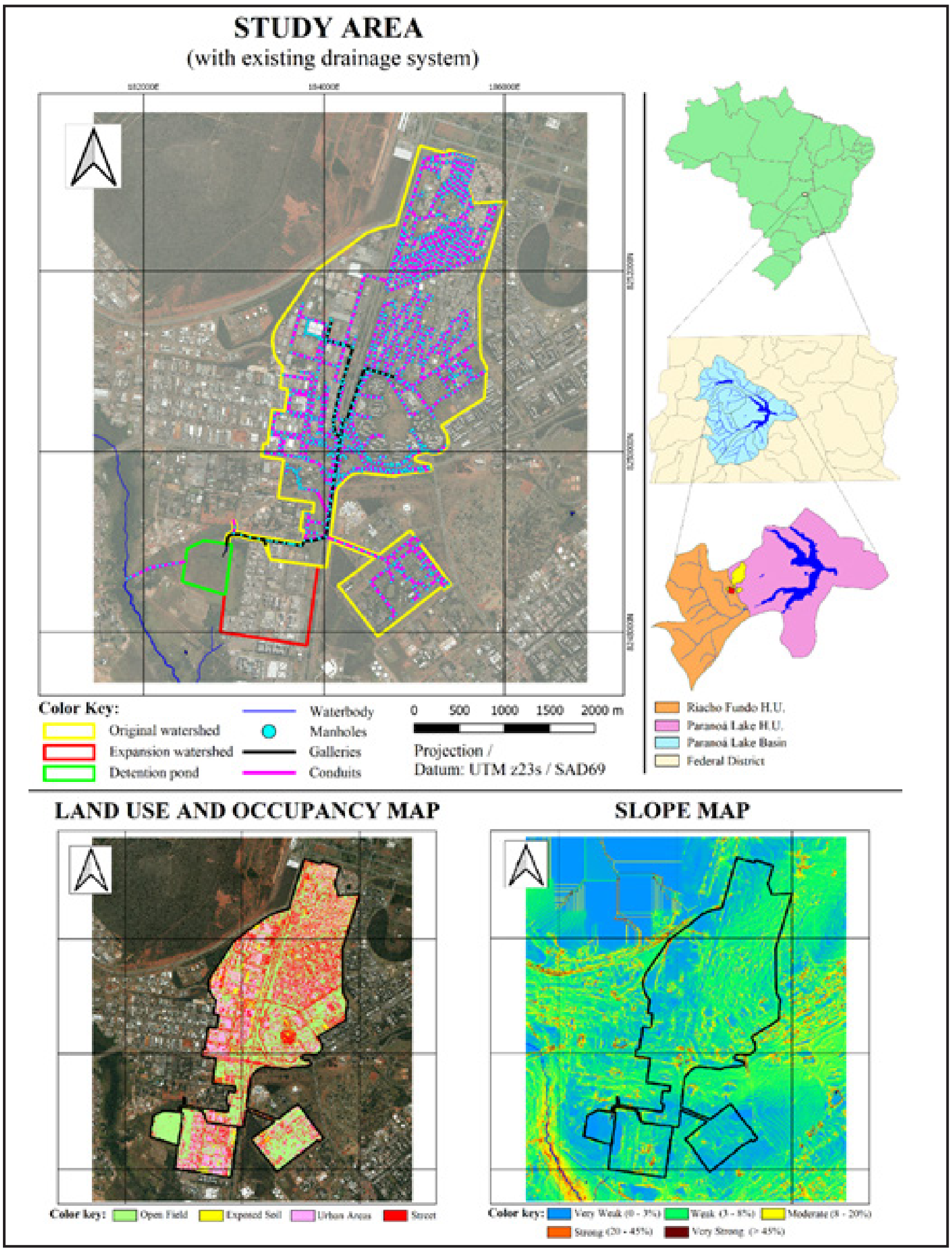
2.1. Study Area

In 2009 a detention pond with 24 ha of area was set up in the location of a decommissioned wastewater treatment pond in the city of Guará, near Brasilia (ArKIS, 2005). The size of the detention pond was consequently pre-defined and studies have shown that its capacity is currently oversized considering the catchment area and the local regulations (Volken, 2018; De Paula, 2019). It is located in the Paranoá Lake Basin as shown in Figure 1.

As shown in Figure 1, the study area is divided into two watersheds. One, called in this work as original watershed (with 767 ha), is the area that currently discharge the surface runoff to the existing detention pond for dumping the stormwater peak flow. The other one, called here as expansion watershed (with 97 ha), does not have any drainage system and this study is proposing a drainage network discharging into the existing detention pond.

This study analyzes if the existing and the proposed systems are capable of avoiding flooding when considering a ten-year design storm and if it is possible do adapt the existing detention pond considering that the expansion watershed is approximately at the same elevation as the existing detention pond.

Figure 1 – Study area, land use and occupancy and slope map with both area



Source: Authors (2023)

The soil in the whole area is a latosol (EMBRAPA, 2004) and it can be classified as A type according to SCS-CN Method. The type of soil as well as its use resulted in a table containing the percentage area of each class (for each basin) with their respective Curve-Number, shown in the table 1. The corresponding CN was weighted for each sub catchment.

Table 1 – CN classes, values and percentages for each land use occupancy

CN classes	CN Values	Total area percentage (Original watershed)	Total area percentage (Expansion watershed)
Field	35	32 %	44 %
Exposed Soil	55	6 %	3 %
Urban Areas	85	30 %	34 %
Streets	98	32 %	19 %

Source: Authors (2023)

2.2. Drainage System Modeling

The existing drainage system of the original watershed was simulated using SWMM under PCSWMM (Personal Computer Storm Water Management Model), from CHI Water, considering a 10-year design rainfall and the existing detention pond showed a damping of roughly 98% of the peak flow (De Paula, 2019).

The surface runoff was estimated using the SCS Method, widely used with good results in the region (Tsuji et al., 2019; Aguiar et al., 2007; Costa et al., Koide, 2014). In this study, four classes were adopted: “open field”, “exposed soil”, “urban areas” and “streets”. Their CN were, respectively, 35, 55, 85 and 98 showed in Table 1.

Information of elevation and slope of the watershed were assembled using GIS with the software QGIS 3.8.3. Using data from a 2016 LiDAR (Light Detection and Ranging) survey, made available from TERRACAP, a Digital Terrain Model (DTM) was created as well as a slope map (Figure 1). The spatial resolution of this DTM based on LiDAR data is 0.2 m (Barbosa, 2021). The concentration time of the watershed was estimated by using the Carter method (equation 1), recommended for urban areas with areas up to 1,100 ha (Silveira, 2005).

$$t_c = 5.862\frac{L^{0.6}}{S^{0.3}} \tag{1}$$

With: t_c = concentration time (min);

L = Length of main stream (km);

S = Medium slope (m/m).

According to local regulations (ADASA, 2018; NOVACAP, 2019) two rainfalls must be used for drainage system design, called design and critical storms, both assembled using the local IDF (Intensity-Duration-Frequency) curve (equation 2). The design storm (also called project storm) is a 24h duration alternating block rainfall with 10-year return period with time interval blocks with maximum of 20% the concentration time of the basin. The critical storm is a constant intensity rainfall with duration equivalent to the concentration time of the watershed being analyzed and 10-year return period.

$$i = \frac{1574.70 * T_R^{0.207}}{(t+11)^{0.884}} \tag{2}$$

With: i = Intensity of the rain (mm/h);

T_R = Return time (year);

t = Duration of the rain (min).

For the expansion area, a drainage network was designed following local authorities recommended restrictions and parameters, such as minimum pipe diameters, maximum distance between manholes and maximum relative flow depths (NOVACAP, 2019).

To calculate wave propagation in SWMM, dynamic wave was used. This is enough to create a 1D model with PCSWMM that can describe where in the drainage system there is an overload, but it can’t show where this surface water will go to (preferred paths), where the flooding will occur or it’s volume. For this, a 2D analysis is needed.

PCSWMM Pro can integrate 1D-2D models (Fileni et al., 2019). It couples the 1D drainage system already described prior with a 2D mesh created using a DTM. First there is a need to describe the boundary for where the mesh will exist, the chosen was the outer limits of both watersheds together so that one may influence the other. The geometry of the mesh chosen was the hexagonal – as recommended for urban areas (CHI, 2020a). The spatial resolution of the mesh adopted was 5 m

(CHI, 2020b). PCSWMM then creates a virtual manhole on the center of this hexagon and integrates the model by connecting each real existing manhole to the closer virtual one – this is the method chosen and is recommended for urban areas (CHI, 2020c).

3 RESULTS AND DISCUSSION

Both watersheds are urbanized and although exists a considerable vegetated area, which implies a considerable infiltration for the modeling, the sum of “streets” and “urban areas” cover over 50% of the total area. There is a separation between streets and urban areas classes due to the noticeable difference between their CN value.

The design storm (with 24h duration) was assembled using the alternate blocks method and based on the IDF curve for the region (ADASA, 2018) discretized into 5 min intervals. The peak rainfall depth is 18.2 mm. There are two critical rains (constant intensity rainfall with duration equivalent to the concentration time of the watershed), one for each basin. The concentration time (by the Carter method) for the original and expansion watersheds are, respectively, 62 min and 24 min. For the original watershed, the rain intensity equals 57.2 mm/h and for the expansion watershed, the rain intensity is equal to 109.5 mm/h.

The proposed drainage system for the expansion watershed, does not have enough elevation to discharge the outflow into the existing detention pond. Therefore, it is proposed to excavate part of the existing detention pond to lower its elevation, creating a new and smaller detention pond with the purpose of receiving only the surface runoff from the expansion watershed. This new detention pond (named on this study as expansion pond) would consequently diminish the area of the existing pond by 15,000 m^2 (6% of its total area). The expansion pond was designed with a depth of 1.5 m, leading to a volume of 22.500 m^3.

3.1. PCSWMM 1D results

The PCSWMM results obtained were divided into two groups, the 1D and 2D. The 1D results shows the efficiency and the peak flow at the entrance and exit for both detention ponds (existing and the proposed) as well as the locations of the flooded manholes and for how long they stayed in this situation. Two scenarios were studied for both ponds (Table 2) and for both watersheds (Table 3), the design storm and the critical storm. The original detention pond (Table 2), although called on this study as “original”, has its dimensions resized to encompass the expansion pond.

Both ponds can dampen the peak flow to levels required by local legislation, independently of the rainfall event, showing efficiency (ratio between the entrance and exit flow) of up to 3%. The design, or project, storm has a much higher rainfall peak than the critical storm (18.2 mm and 4.8 mm respectively). The design storm peak flow is higher for both ponds. Even with the reduced dimension the original pond still showed a good efficiency when compared to other local studies made with its existing size (Paranayba et al., 2019), as consequence of its oversized dimensions.

Table 2 – Urban drainage system modeling surrounding the detention ponds

	Rainfall			
	Project Rain		**Critical Rain**	
Which Detention Pond	**Original**	**Expansion**	**Original**	**Expansion**
Peak Entrance Flow	26.1 m^3/s	17.2 m^3/s	19.6 m^3/s	12.8 m^3/s
Peak Exit Flow	1.3 m^3/s	2.2 m^3/s	0.6 m^3/s	1.4 m^3/s
Efficiency	5 %	13 %	3 %	11 %

Source: Authors (2023)

For the flooding analysis (Table 3), the expansion watershed with the designed stormwater network, has no points of overload – as expected considering that the system was designed adequately. For the original watershed, there is a noticeable difference between what happens with both rains. Although the design storm results in more problems (due to its higher peak rainfall), with the critical storm the manholes that are flooded, remain flooded for a higher time (0.3 hours on average).

Table 3 – Results of urban drainage system modeling surrounding flooding

Which Watershed	**Rainfall**			
	Project Rain		**Critical Rain**	
	Original	**Expansion**	**Original**	**Expansion**
Total Rain Volume	158,278 m^3	22,360 m^3	61,120 m^3	15,040 m^3
Volume flooded	63,618 m^3	0	5,276 m^3	0
N° manholes flooded	511	0	194	0
% manholes flooded	42%	0	16%	0
Maximum time a manhole was flooded for	12.4 h	0	1.1 h	0
Average time a manhole was flooded for	0.06 h	0	0.04 h	0
Average time a manhole was flooded given that it was flooded	0.15 h	0	0.30 h	0

Source: Authors (2023)

Evaluating the original watershed and design storm, 40% of the total stormwater volume was spilled, which means that the current drainage system is highly inefficient: 42% of the manholes were flooded and one of them remained flooded for 12.4 hours.

Note that the existence of a detention pond at the downstream end of a drainage system will not improve these problems, because its purpose is to reduce the flow peak released downstream to comply with local legislations. Similar results are found in the literature (Souza et al., 2019; Fileni et al., 2019; Araújo et al., 2019). To reduce then flooded area, LID devices are usually recommended as a solution (Araújo et al., 2019; Bezerra et al., 2020).

3.2 PCSWMM 2D results

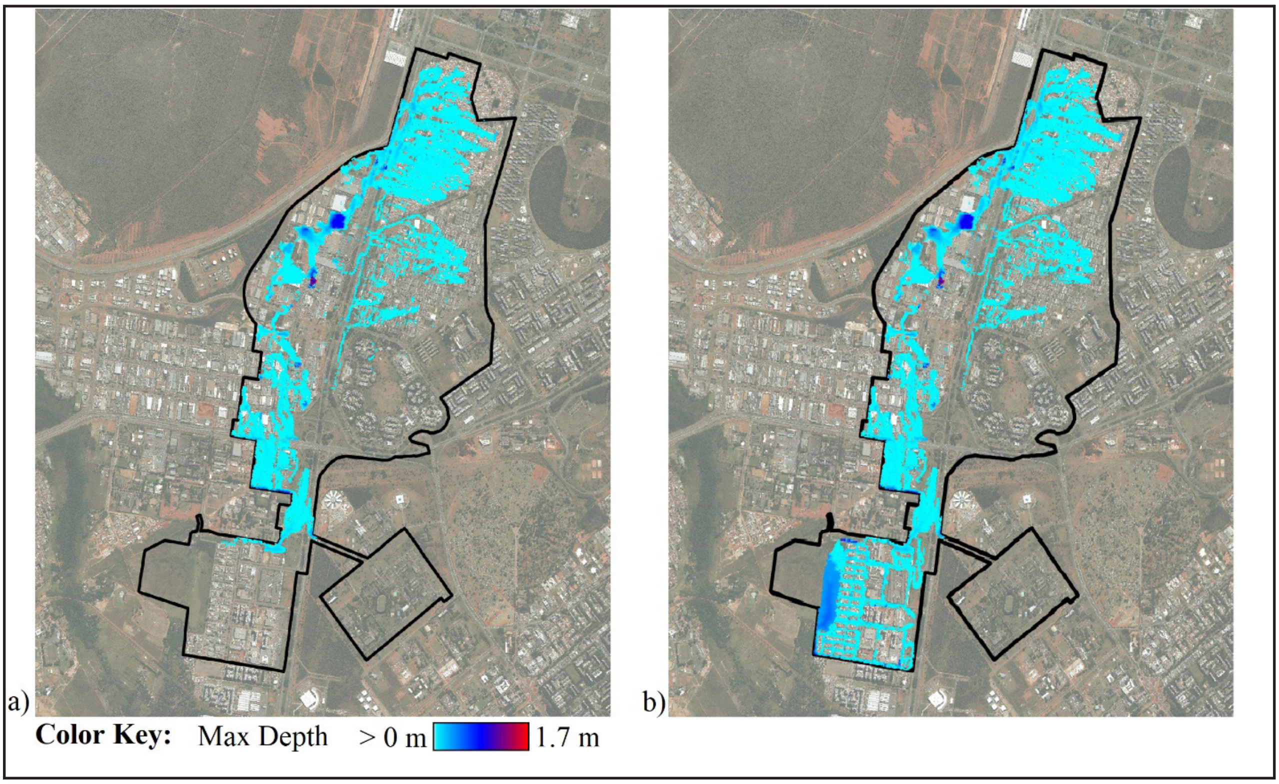
The 2D analysis using PCSWMM allows computing the volume of water flooded, and flow paths based on the DTM created. Regarding the obstruction option in PCSWMM, it is important to recognize that the buildings are only part of the possible obstacles to the flow, therefore there may exist different pathways for the water. Hence one must either define each building individually or consider the whole allotment as obstructions. For the expansion area, the buildings were individually considered as obstructions.

There are two computed scenarios shown in Figure 2 that represents the maximum depth that occurred during the simulated period using the design storm. The scenario "a" was carried out including the drainage system created for the expansion watershed and thus with both detention ponds, the original one with its area reduced and the expansion pond. It shows little flooding in the expansion area, only on the northern part due to the flooding coming from the original watershed. However, for the original watershed there are many flooded areas due to its undersized existing drainage system. The total flooding volume is shown in table 3.

Scenario "b" shows the same areas without the designed drainage system for the expansion watershed and only the original detention pond with its actual size. This is a representation of the current situation in the expansion area that does not have any drainage system. The total volume of flooding in the expansion area was approximately 43 % of the project rain, resulting in 9,588 m^3 of flooding in the expansion watershed only. The remaining water was drained during the simulation (that lasted 36 h).

The 2D analysis from the PCSWMM show where the flooding occurs and the path of water, emphasizing as well the locations with higher water accumulation – these being more exposed to risk. This can be used to plot the most vulnerable areas and hence the best places for LIDs implementation (Fileni et al., 2019; Araújo et al., 2019).

Figure 2 – 2D Model identifying the flooding for two scenarios with the project rain



Source: Authors (2023)

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4 CONCLUSIONS

It is important to have a hydrologic and hydraulic model capable of representing the studied area and simulating critical events as well as running different scenarios. This provides information to make the better decision about the alternatives that can be applied in a watershed to promote a sustainable environment as well as reducing impacts such as flooding and diffuse pollution.

Although the drainage system designed for one of the watersheds showed no flooding in the 1D analysis, there is a flood occurrence on the 2D simulation caused by the surface runoff from the upstream watershed. This is important for decision making and urban planning showing that the new system must consider the whole watershed and impacts of upstream water.The main results were incredibly significant as it shows where there is flooding, for how long they happen (up to 12.4 hours) and its total volume (up to 63,618 m^3). The detention ponds were able to reduce the stormwater up to 3% of its original value and ended up respecting local legislation. A properly designed drainage system with the help of models, as used in the expansion watershed, can absorb up to 9,588 m^3 of the surface runoff, preventing flooding for many scenarios.

Besides that, the modelling ratified that the exiting pond worked to dampen the peak flow, however it does not solve any flood related problems along the watershed. Although, the modelling helped to plan a new detention pond inside the existing oversized pond to optimize the structure and mitigate the impact caused due to impermeabilization in the new neighboring areas.

For future work it is recommended to analyze if there are other surrounding urban areas that can also make use of this detention pond, as it is still working below it is maximum capacity. Moreover, it is important to model the LID usage along the watershed to reduce the flooding points. It is also very important to analyze the water quality at inflow and outflow of the detention pond to check if it enhances the water quality and to propose new internal layout to improve its efficiency in this aspect.

5 DATA AVAILABILITY STATEMENT

All data and models generated or used during the study area available from the corresponding author upon reasonable request.

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