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FUZZY LOGIC CONTROL APPLICATION ON ON-LINE RESERVOIRS UNDER NON-STATIONARY IDF CONDITIONS

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Abstract: Increasing climate change impacts, along with the densification and vertical expansion of flood-prone urban areas, heighten flood vulnerability by amplifying rainfall frequency and expanding impervious surfaces. This intensifies peak runoff and places greater pressure on urban drainage systems. To address these challenges, real-time control of stormwater infrastructure, equipping systems with sensors and controllable gates, can dynamically manage watersheds during rainfall events, reducing downstream flooding. In this study, we implement independent real-time controls for stormwater detention reservoirs using Fuzzy Logic Control (FLC) within a 100 km² poorly gauged urban catchment, aiming to decrease flood vulnerability. A calibrated and validated coupled hydrological-hydraulic model was employed to apply FLC in upstream reservoirs and evaluate its effectiveness in mitigating flood impacts. Results show that the total affected population (TAP) in the Aricanduva basin decreased by 3.86%, 2.56%, 3.14%, 3.20%, 2.76%, and 1.91% under non-stationary intensity-duration-frequency (IDF) curves with return periods of 2-, 5-, 10-, 25-, 50-, and 100-years, respectively. Additional flood impact indicator further confirms the efficacy of the FLC-based approach as a flood mitigation strategy. These findings demonstrate the potential of this methodology as a practical framework for flood risk management, especially in poorly gauged urban areas. The study supports the Sustainable Development Goals (SDGs) 6, 9, 11, and 13 related to water resilience, smart infrastructure, climate adaptation, and urban sustainability.

Keywords: Fuzzy Logic Control (FLC); Disaster Risk Reduction (DRR); Urban flooding.

Resumo: Os impactos das mudanças climáticas, juntamente com a densificação e a expansão vertical das áreas urbanas propensas a inundações, aumentam a vulnerabilidade às enchentes ao amplificar a frequência de chuvas e expandir as superfícies impermeáveis. Isso intensifica o pico de escoamento e coloca maior pressão sobre os sistemas de drenagem urbana. Para enfrentar esses desafios, o controle em tempo real da infraestrutura de águas pluviais, equipando os sistemas com sensores e comportas controláveis, pode gerenciar dinamicamente as bacias durante eventos de chuva, reduzindo as inundações. Neste estudo, implementamos controles independentes em tempo real para reservatórios de retenção de águas pluviais utilizando Controle por Lógica Fuzzy (FLC) em uma bacia urbana de 100 km² pouco monitorada, visando diminuir a vulnerabilidade às inundações. Um modelo hidrológico-hidráulico acoplado, calibrado e validado, foi utilizado para aplicar o controlador FLC. Os resultados evidenciam que a população total afetada (TPA) na bacia do Aricanduva diminuiu em 3,86%, 2,56%, 3,14%, 3,20%, 2,76% e 1,91% sob curvas de intensidade-duração-frequência (IDF) não estacionárias, com períodos de retorno de 2, 5, 10, 25, 50 e 100 anos, respectivamente. Outro indicador de impacto de inundação também confirma a eficácia

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da abordagem baseada em FLC como uma estratégia de mitigação. Essas descobertas demonstram o potencial desta metodologia como um framework prático para gestão de risco de inundação, especialmente em áreas urbanas pouco monitoradas. O estudo apoia os Objetivos de Desenvolvimento Sustentável (ODS) 6, 9, 11 e 13, relacionados à resiliência hídrica, infraestrutura inteligente, adaptação às mudanças climáticas e sustentabilidade urbana.

Palavras-chave: Controle por Lógica Fuzzy (CLF); Redução de Risco de Desastres (RRD); Inundações Urbanas.

1. INTRODUCTION

The rapid growth of megacities, its densification and verticalization, coupled with aging infrastructure and the increasing frequency and intensity of extreme weather events, presents significant challenges to become cities resilient to urban floods. Urban flood risk management focuses on developing strategies to mitigate the impacts of climate change, particularly the damages resulting from flooding caused by the overflow of urban rivers and canals. Building a resilient city entails the capacity to adapt to such hazards, thereby reducing human and economic losses while leveraging natural advantages for sustainable urban development (Nkwunonwo *et al.*, 2020).

There are various modeling approaches to simulate the complex non-linear dynamics of urban floods to assess their impact or the effectiveness of the measures against them. These models can predict flow propagation in rivers, channels, and floodplains, serving as essential tools for designing effective flood mitigation strategies and minimizing adverse effects (Vermuyten *et al.*, 2020; Qi *et al.*, 2021). Others models are focus on the optimal operational management for detention and retention in urban reservoirs, by Real-time control (RTC) operations, that can manage the reservoir's outlets (e.g., pump systems, orifices, gates) in accordance with predefined operating rules (Qi *et al.*, 2021; Li, 2020).

Despite its significant potential benefits, the implementation of RTC strategies in urban drainage systems remains limited to only a few cities worldwide (Lund *et al.*, 2018). Additionally, there have been relatively few studies focused on simulating and assessing the collective impact of multiple reservoirs on flood management (Fleischmann *et al.*, 2019; Sánchez, 2025). Existing research has largely been conducted in catchments characterized by high-quality, detailed data on urban drainage networks, including high-resolution flow and water level time series (Mounce *et al.*, 2020; Li, 2020). Such data availability is relatively rare in urban basins of less developed countries, highlighting a critical gap in knowledge and practice (Sánchez, 2025).

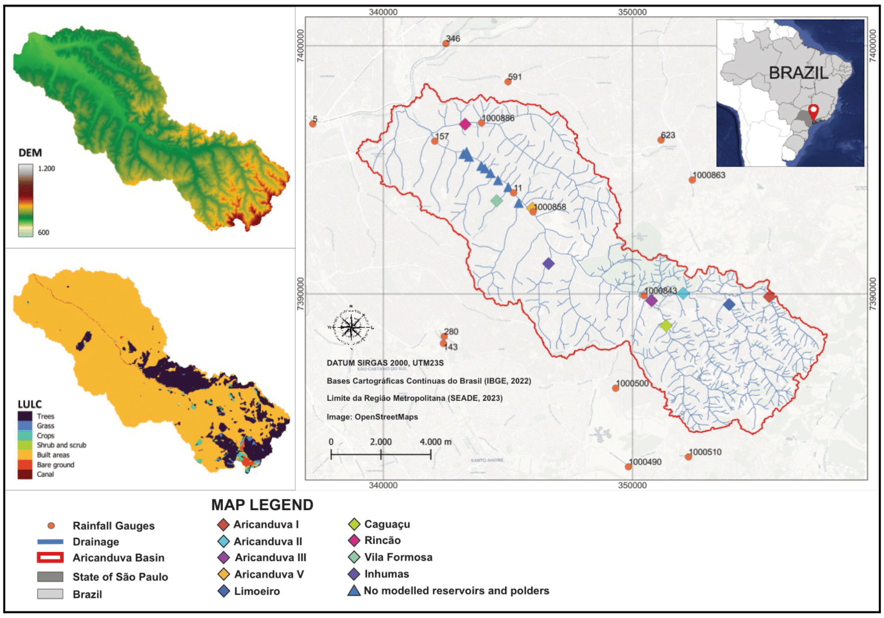
This study aims to reduce a crucial knowledge gap by examining the effectiveness of fuzzy logic control (FLC) as an RTC flood risk reduction measure. Specifically, it investigates whether control strategy for multiple reservoirs can effectively mitigate flood risk in large urban watersheds with limited gauging data. This is achieved by simulation of non-satationary intensity-duration-frequency (IDF) curves for 2-, 5-, 10-, 25-, 50-, 100-year return periods. The control approach is tailored to the characteristics of a poorly gauged urban basin, serving as a proof of concept for the practical application of a fuzzy real-time control in basins with monitoring limitations. Overall, this analysis represents an initial step toward evaluating the potential of multi-reservoir reactive control strategies and contributes to the broader discussion on urban flood risk management in less developed countries.

2. METHODOLOGY

2.1. STUDY AREA

The Aricanduva Basin, covering around 100 km² in eastern São Paulo Metropolitan Area (SPMA), faces frequent flooding along its main river, particularly during intense rainfall events due to heavy urbanization, reduced soil permeability, and high slope areas (Simas *et al.*, 2017). The basin is monitored and managed through the São Paulo Flood Warning System (SAISP), which includes multiple reservoirs and a main flow-control channel. This study focuses specifically on four of the five online reservoirs, located in the upstream basin, where fuzzy logic control will be implemented (i.e., Limoeiro, Caguaçu, Aricanduva I, and Aricanduva III). The study area is illustrated in Figure 1.

Figure 1 – Aricanduva River Basin, São Paulo - Brazil. Taken from Sánchez (2025).



2.2. FUZZY LOGIC CONTROL IMPLEMENTATION

The stormwater reservoirs in the upstream basin zone have culverts and spillways as outlet devices. These structures are modeled through rating curves as a function of the water level (Gomes Jr *et al.*, 2024). However, if the culvert and the spillway are retrofitted with a vertically controllable device that modifies the cross-sectional area, the sluice fate equation with discharge to the atmosphere, can be applied (Sánchez, 2025). Thus, the discharge behavior of the outlet devices will depend on the relationship between the upstream energy head and the gate opening, having the dual functionality of culvert /spillway or gated culvert/gated spillway (Sánchez, 2025).

The development of a fuzzy controller involves the establishing of controller membership function parameters (CMFPs) and fuzzy control rules (FCRs) (Li, 2020). With these components are built a Fuzzy Inference System (FIS).

The CMPs implemented for controlling the gated culvert of the reservoirs are defined for two input variables and one output variable. The first input variable is the water level (WL) at the current time, which has three membership functions (MFs) called low (L), medium (M), and high (H). The second input variable is the water level variation (WLV) between control intervals and has five MFs called negative high (NH), negative low (NL), zero (Z), positive low (PL), and positive high (PH). Lastly, the output variable is the Gate Opening (GO), selected to characterize gate openness, defined with five MFs ranging from 0% to 100% in increments of 25%. The input and output membership functions described above are presented in Figures 2a and 3a, respectively.

The CMPs implemented for the case of gated spillways of the reservoirs are defined with the same inputs and output variables as the gated culvert case. However, the WL variable has four MFs called low (L), medium low (ML), medium high (MH), and high (H); and the WLV variable has two MFs, called negative (N) and positive (P). Lastly, although GO has the same quantity of MFs, their functions are different. The input and output MFs described for gated spillways are presented in Figures 2b and 3b respectively.

The FCRs are based on CMFP values and establish an effective IF-THEN statement by defining the degree of relationship between the input and output variables. Table 1 summarizes a total of fifteen FCRs for the gated culvert case, and Table 2 summarizes eight FCRs for the gated spillway case. The established rules can generate an output surface, which describes all possible combinations of WL and WLV across the range, as well as their relation with GO. These output surfaces are shown in Figures 3a and 3b for gated culvert and gates spillways respectively, and describing graphically the FIS used in Aricanduva I, Limoeiro, Caguaçu, and Aricanduva III reservoirs.

This study used a coupled hydrological-hydrodynamic model, called HydroPol2D (Gomes Jr *et al.*, 2023), of the Aricanduva river Basin previously calibrated (Sánchez, 2025). The model is an open code source based on MATLAB programming language, providing the possibility to modify their modules and the implementation of the FLC by creating .fis files. Therefore, for our approach the process begins with HydroPol2D's hydrological-hydraulic solver, followed by the FIS evaluation using the current state conditions of WL and WLV. Then, the output generated by the FIS is defuzzified into gate openness and will be adjusted. This evaluation is applied every five minutes throughout the simulation time, that is the control interval established in this study, showing that the concept of this implementation involves a looping mechanism to represent an RTC simulation.

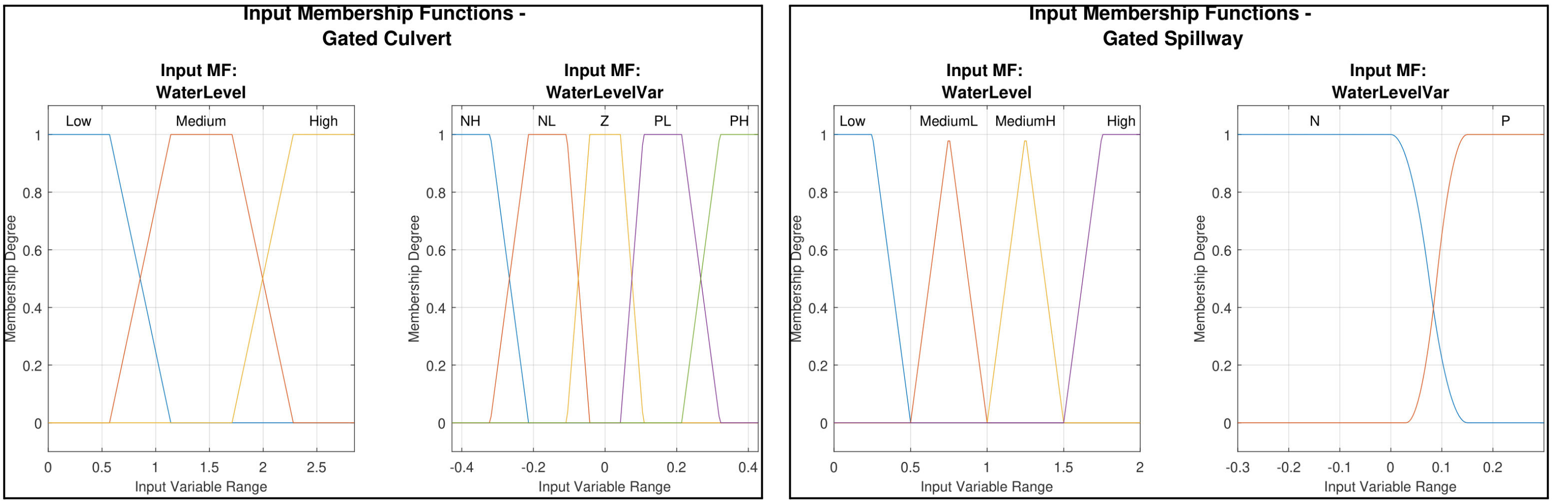
Table 1 – FCRs used for reservoir gated culverts.

Water Level (WL)	Water Level Variation (WLV)				
	N. High (NH)	N. Low (NL)	Zero (Z)	P. Low (PL)	P. High (PH)
Low (L)	Open 25	Open 25	Open 100	Open 50	Open 50
Medium (M)	Open 25	Open 25	Open 100	Open 50	Open 75
High (H)	Open 75	Open 75	Open 100	Open 100	Open 100

Table 2 – FCRs used for reservoir gated spillways.

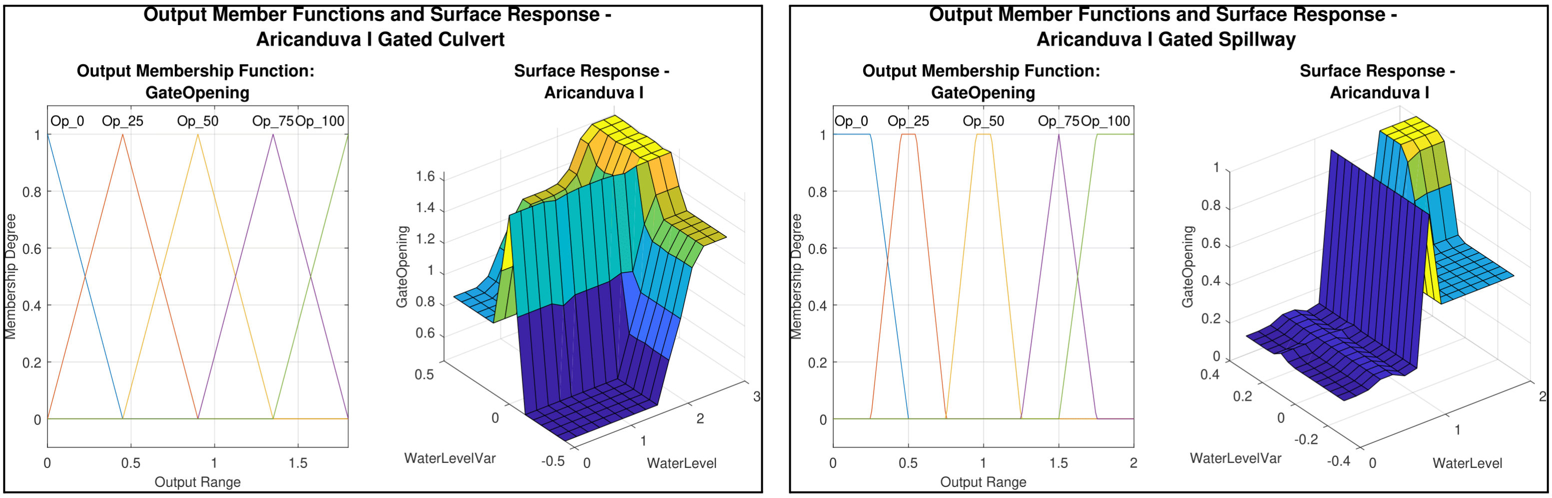
Water Level Variation (WLV)	Water Level (WL)			
	Low (NH)	M. Low (ML)	M. High (MH)	High (H)
Negative (N)	Open 0	Open 0	Open 25	Open 25
High (H)	Open 0	Open 0	Open 25	Open 50

Figure 2 – MFs for input variables WL and WLV in gated culverts (2a) and gated Spillways (2b). Taken from Sánchez (2025).



(a) (b)

Figure 3 – MFs for output variables GO and surface response in gated culverts (3a) and gated spillways (3b). Taken from Sánchez (2025).



(a) (b)

2.3. MODELLED SCENARIOS

This study evaluates the efficiency of FCL controllers in the Aricanduva basin under current conditions. Therefore, we generated inundation maps by using IDF parameters from Silva (2022). We represented design rainfall for return periods of 2-, 5-, 10-, 20-, 50-, and 100-years applying Huff method with a rainfall duration of 360 minutes. This approach generates hyetographs that capture the natural variability of storms, including multi-peak and high-intensity short-duration events, essential for assessing urban hydraulic infrastructure (Moon *et al.*, 2023). Silva (2022) established IDF parameters for São Paulo based on historical rainfall data (1933–2018). These projections consider the non-stationarity of rainfall patterns, reflecting significant changes associated with intense rainfall events, as documented in prior studies (Lima *et al.*, 2014). The intensity calculations and scenario parameters are summarized in Equation 1.

$$I = \frac{K.RP^{a}}{(td+b)^{c}}, \quad (1)$$

where I is the maximum intensity of precipitation (mm/h), td is the duration time (minutes), RP is the return periods (years), and K, a, b, c are adjusted equation's coefficients with values of 1801.42; 0.170; 21.843; and 0.823 respectively.

For current population density features, we used spatialized information in Shapefile from Brazilian Institute of Geography and Statistics census (IBGE, 2022), available at GeoSampa platform (Perfeitura de São Paulo, 2016). Since our analysis was based on flood maps generated by the hydrological-hydraulic model, we rasterized the Shapefile with a 10-meter resolution.

2.4. FLOOD IMPACT FACTORS

In assessing flood impacts in the Aricanduva Basin, we adopt Castro's (1999) definition of a disaster as "the result of adverse events, whether natural or human-induced, affecting a vulnerable ecosystem and causing human, material, and environmental damage." Accordingly, our evaluation encompasses socio-environmental impacts, with the premise that any flood depth exceeding 0.5 meters can adversely affect the inhabitants of the inundated area. The impacts are categorized into three factors: Total Affected Population (TAP) and Affected Population During the Event (APDE) (Sánchez, 2025). These factors are quantified using inundation maps generated from hydrological-hydrodynamic simulations conducted via HydroPol2D, combined with census data from the IBGE. We calculated these impact factors in both base and fuzzy logic controller application scenarios, labeled as Baseline and FLC implementation, respectively.

2.4.1. Total Affected Population

For this impact factor, we overlapped the total inundation map, that shows all flooded areas that had at least a water depth greater than 0.5 meters at some point during the simulation, with the population density map (Sánchez, 2025).

2.4.2. Affected Population During the Event

The second spatiotemporal analysis involves a graph that explicitly illustrates the relationship between water depths at multiple reference points and the overall flood impact over time. On the Y-axis, it plots the affected population at each time interval (*Xi*), calculated by overlaying basin-wide inundation maps with population density data. Conversely, the inverted Y-axis displays water depths at various reference points, such as every 5 kilometers along the basin's main river, extracted at each *Xi* during the simulation. The X-axis represents elapsed simulation time, capturing the development of inundation impacts. The primary objective of this visualization is to facilitate a comparative assessment of the effectiveness of structural and non-structural strategies in minimizing flood vulnerability in different basin's points. A time interval of 10 minutes was employed, covering the entire rainfall event duration of 360 minutes (Sánchez, 2025). To address the effectiveness of the FLC-based approach, this analysis was focused on the location of the gauge station 1000843, because the station is the nearest rainfall gauge to the upstream reservoirs, showing a clearer demonstration of the controller's influence. Accordingly, these graphs are referred to as "Affected Population and 1000843 Gauge Depth versus Time".

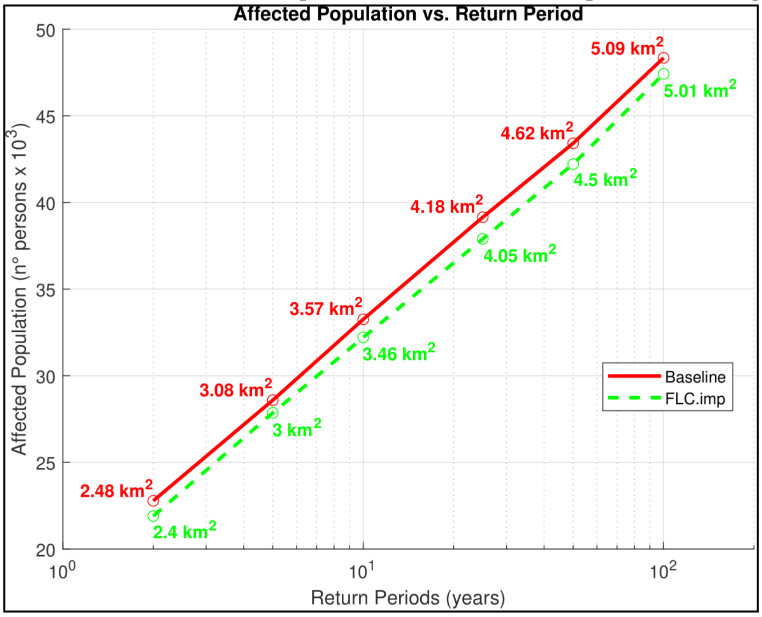
3. RESULTS

The flood impact analysis with TAP and APDE factors was conducted for both controlled and uncontrolled systems. We compared these factors under scenarios with design storm events of 2-, 5-, 10-, 25-, 50-, 100-year return periods, in order to assess the FLC implementation in Aricanduva I, Limoeiro, Caguaçu and Aricanduva III reservoirs.

3.1. Total Affected Population

Figure 4 illustrates the total affected population corresponding to the flood area in each simulated Baseline (red line) and FLC implementation (green line) scenarios from design rainfall events with 2-, 5-, 10-, 25-, 50-, and 100-year return periods. X-axis represents the return period in a logarithm scale, and Y-axis represents the total affected population in thousands of people. Each marker represents the total inundated area in each simulation in square kilometers.

Figure 4 – Total affected population against 2-, 5-, 10-, 25-, 50-, and 100-year return periods. Baseline scenario is represented with red line and FLC implementation scenario is represented with green line.



In general, the TAP in scenarios with FLC implementation in stormwater reservoirs was lower than the observed in Baseline scenarios. For the design storms with 2-, 5-, 10-, 25-, 50-, and 100-year return periods TAP decreased in the FLC implementation scenario by 3.86%, 2.56%, 3.14%, 3.20%, 2.76%, and 1.91% respectively. This indicates that 879, 733, 1044, 1253, 1199, and 925 people, respectively of each return period, likely not to be impacted due to the implementation of FLC in the upstream reservoirs.

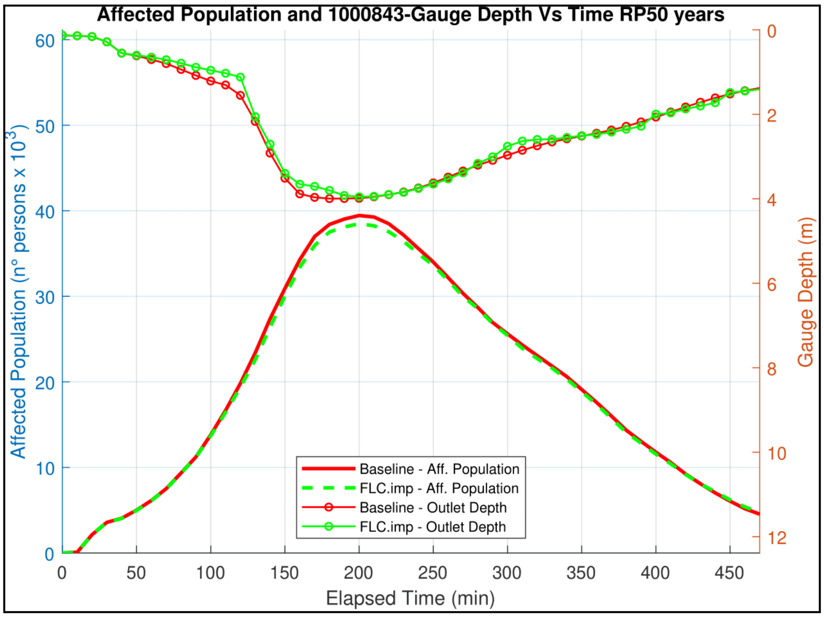
3.2. Affected Population During the Event

Figure 5 illustrate the relationship between the affected population, water depth at the rainfall gauge 1000843 (Figure 1), and elapsed time of the simulation with a 50-year return period design rainfall. This figure is an example of the analysis comparing the simulations across all the analyzed return periods based on non-sationary IDF curves. Red line represents the Baseline conditions and the green line represents the simulation with the FLC implementation.

Overall, for all the return period floods, the FLC implementation scenarios showed lower water depths and impacts. For 2- and 5-year recurrence intervals, the controllers decreased the water depth peaks at the gauge station by 5.88% and 5.03%, respectively, which is reflected in an impact peak reduction of 4.71% and 3.87%, respectively, in the FLC implementation scenario. For the interval recurrence of 10- and 25-years, the influence of the controllers was evidenced in the inundation's rising phase, reducing and maintaining constant the water depth peak in the FLC implementation scenario. The water depth peaks at the gauge station decreased by 4.67% and 2.55% , and have a lag in the peak by 30 and 20 minutes, resulting in an impact peak reduction of 4.27% and 3.27%, respectively. Nevertheless, the flood impacts in FLC implementation scenario started to be similar to Baseline scenario in the 25-year return period simulation.

Lastly, for low recurrence periods (i.e., 50- and 100-year), the influence of the controllers was presented in the rising and in some parts of the decreasing phases of the inundation (Figure 6). The water depth peak at the gauge station, in the 50-year return period simulation, decreased by 1.05% and occurs 20 minutes later, resulting in an impact peak reduction of 2.42% under the FLC implementation scenario. In the 100-year return period simulation, the water depth peak decreased by 0.1%, with no delay to the peak under the FLC implementation scenario. However, the impact peak decreased by 1.66%.

Figure 5 – Affected Population During the Event with design rainfalls of 50-year return period in the gauge 1000843. Baseline scenario is represented by the red line and FLC implementation scenario is represented by the green line.



4. DISCUSSION

In this study, we observed that the implementation of the FLC in the upstream retention reservoirs as sluice gates in the culverts and spillways is effective in the reduction of flood impacts. The implemented impact assessment framework provides a foundation for addressing the development of the impact during the event and estimating the total flood impact, to better support urban resilience planning. Overall, the performance of the FLC implementation is good until the design precipitation of 25-year return period, showing the best and worst yield in a storm event of 2- and 100-year, respectively.

This study highlights the potential of Tunable Fuzzy Logic Control (FLC) for stormwater reservoir management, emphasizing that various tuning methods could optimize performance across different reservoirs and rainfall regimes (Li, 2020; Mounce *et al.*, 2020). Future research should explore data-driven, stochastic, and heuristic tuning approaches, as well as develop hydrodynamic models to improve FLC responses under diverse precipitation scenarios, including climate change (Chou e Wu, 2015).

The study case demonstrates that FLC has a proactive potential to reduce flood vulnerability, particularly in upstream regions experiencing high-intensity events, although it is less effective in midstream and downstream areas. The findings also suggest that controlling multiple smaller catchments or reservoirs in a coordinated, segmented approach offers significant benefits over single-objective control strategies, especially in complex urban basins like Aricanduva. Besides, this study recommends that future studies should analyze the integration of the other stormwater reservoirs located at the downstream and middle zone of the basin to the FLC implementation strategy, for enhancing the resilience of the study area.

Extending this framework to other cities with different climatic conditions could broaden its applicability, especially in data-scarce regions. Overall, this research underscores the importance of adaptive, integrated control strategies and paves the way for future developments in urban flood management using fuzzy logic models.

5. CONCLUSION

This study address the effectiveness of the implementation of FLC tool applied individually to stormwater reservoirs, aiming to reduce downstream flooding volume in a poorly gauged urban catchment, by simulating non-satationary IDF curves across different return periods. The results show that stormwater reservoirs, located at the upstream basin area, can be controlled by FLC in order to reduce the flood impacts in the downstream zone. The main contributions of this study are: (i) The simulation of a RTC strategy incorporating FLC into rainfall-runoff simulations. (ii) The development of a framework to establish a FIS using a manually rule based method. (iii) The combined effect of FLC implementation in upstream reservoirs can reduce the flood impact under non-satationary IDF curves across different return periods.

This study demonstrates the potential benefits of implementing FLC into urban drainage systems, especially in stormwater reservoirs with data scarcity. However, several uncertainties and limitations remain, including model assumptions, the data limitations, and the sensitivity of FLC input inaccuracies. Future research should focus on integrating advanced optimization algorithms and robust filtering methods into the established framework to enhance system reliability and performance. Besides, the integration of other reservoirs located on the downstream and middle basin's area to the FLC implementation with other outlet devices could be tested.

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