SENSITIVITY OF THE FLOOD EXTENT TO THE INITIAL ABSTRACTION RATIO OF THE NRCS-CN METHOD IN AN URBAN WATERSHED

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ABSTRACT– The initial abstraction ratio (λ) in the Natural Resources Conservation Service Curve Number (NRCS-CN) method directly influences the estimation of effective rainfall, but its effects on spatially explicit hydraulic outputs are still rarely discussed in urban watersheds. This study evaluated the sensitivity of water depth and flood extent simulated in the Hydrologic Engineering Center's River Analysis System (HEC-RAS) to changes in λ, comparing the classical value of λ = 0.20 with the reduced value of λ = 0.05 in the urban Aricanduva River watershed, São Paulo, Brazil. To maintain consistency with the NRCS-CN formulation, the tabulated Curve Number (CN) was reinterpreted, reducing the representative watershed value from 85 to 76. The results indicated that reducing λ, together with CN conversion, decreased effective rainfall by 13,7% and produced spatially heterogeneous differences in water depth, mainly concentrated along the drainage network and in areas near reservoirs. Although the overall flood extent remained similar between scenarios, local differences greater than 0.50 m indicate that the choice of λ can affect the hydraulic representation of critical areas. These results reinforce the importance of evaluating λ in hydrologic-hydraulic modeling, especially in urban watersheds, where its selection may locally alter simulated water depths.

Key-words – hydrodynamic modeling, surface runoff, Aricanduva River.

RESUMO – A relação de abstração inicial (λ) do método *Natural Resources Conservation Service - Curve Number* (NRCS-CN) influencia diretamente a estimativa da precipitação efetiva, mas seus efeitos sobre produtos hidráulicos espacialmente explícitos ainda são pouco discutidos em bacias urbanas. Este estudo avaliou a sensibilidade da lâmina d'água e da mancha de inundação simuladas no *Hydrologic Engineering Center - River Analysis System* (HEC-RAS) à alteração de λ, comparando o valor clássico λ = 0,20 com o valor reduzido λ = 0,05, na bacia urbana do rio Aricanduva, em São Paulo. Para manter consistência com a formulação do NRCS-CN, o CN tabelado foi reinterpretado, reduzindo o valor representativo da bacia de 85 para 76. Os resultados indicaram que a redução de λ, acompanhada da conversão do CN, diminuiu a precipitação efetiva em 13,7% e produziu diferenças espacialmente heterogêneas na lâmina d'água, concentradas principalmente ao longo da rede de drenagem e em áreas próximas a reservatórios. Embora a extensão geral da inundação tenha permanecido semelhante entre os cenários, diferenças locais superiores a 0,50 m indicam que a escolha de λ pode afetar a representação hidráulica de áreas críticas. Esses resultados reforçam a

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importância de avaliar λ em modelagens hidrológico-hidráulicas, sobretudo em bacias urbanas, onde sua escolha pode alterar localmente a lâmina d'água simulada.

Palavras-Chave – modelagem hidrodinâmica, escoamento superficial, rio Aricanduva

INTRODUCTION

Urban flooding has intensified as a drainage planning and management problem, especially in cities where urban expansion has increased soil impermeabilization, reduced natural storage areas, and concentrated economic assets in regions susceptible to these events. Over the last decade, the state of São Paulo recorded an annual average of 73 events, and projections indicate increases of 9% to 43% in design flows, along with additional costs exceeding 10% in up to 46% of municipalities in the immediate future (Brandão *et al*., 2026). In the state capital, a flood with an impact radius of 100 m can generate R$ 43.54 million in direct losses and R$ 218.19 million in total losses to the national economy (Haddad and Teixeira, 2015), demonstrating that urban risk is not limited to the directly flooded area. Thus, improving the hydrological and hydraulic representation of these events is essential to reduce uncertainties in delineating exposed areas and evaluating mitigation measures.

Integrated hydrological and hydrodynamic models have been widely used for this purpose, with a focus on workflows combining the U.S. Army Corps of Engineers' Hydrologic Engineering Center (HEC) tools, particularly HEC-HMS (Hydrologic Modeling System) and HEC-RAS (River Analysis System), for generating hydrographs, inundation maps, and hazard maps. Recent studies have applied this approach to simulate floods in various contexts, including urban watersheds, using rainfall-runoff transformation methods such as the Natural Resources Conservation Service - Curve Number (NRCS-CN) and subsequent hydraulic routing in HEC-RAS 2D (Ferreira and Rocha, 2023, 2026). Concurrently, the Rain-on-Grid approach has gained ground by applying precipitation directly onto the 2D mesh, allowing runoff generation and routing to be resolved entirely within the hydraulic domain (Costabile *et al.*, 2021; Ennouini *et al.*, 2024). HEC-RAS itself incorporates infiltration loss formulations, including the NRCS-CN method, in which the user defines the Curve Number and the initial abstraction ratio, generally set between 0.05 and 0.20 (USACE, 2026).

Despite these advancements, a significant gap remains in linking the hydrological parameterization of the NRCS-CN method to its effects on spatially explicit hydraulic results. The NRCS-CN literature shows that the classic value λ = 0.20 has been questioned, and several studies indicate that lower values, especially λ = 0.05, can improve surface runoff estimation under different hydrological conditions (Brandão *et al.*, 2025; Hawkins *et al.*, 2009). Although there has been progress in evaluating the NRCS-CN method in urban watersheds, this body of evidence remains limited and generally does not directly address densely urbanized and highly impermeable basins (Galbetti *et al.*, 2022; Simpson *et al.*, 2023). Furthermore, most of these investigations assess performance in terms of runoff depth, hydrographs, or CN calibration, without directly examining how altering λ propagates to hydraulic modeling outputs, such as water depth, flood extent, and potentially affected areas. This point is relevant because recent HEC-RAS Rain-on-Grid studies highlight that loss formulation, roughness, and topographic representation are core parameters in flood simulation; however, there is still little specific discussion regarding the sensitivity of the flood extent to the choice of λ in the NRCS-CN method.

Given the above, this study aims to evaluate the sensitivity of the flood extent and water depth simulated by HEC-RAS to the alteration of the initial abstraction ratio of the NRCS-CN method, comparing the classic value $\lambda = 0.20$ with a reduced value $\lambda = 0.05$. The analysis is applied to the Aricanduva River basin in São Paulo, a densely occupied area historically affected by floods. Through this, the study seeks to verify whether a choice typically treated as a standard hydrological input parameter can significantly alter the spatial representation of flooding, contributing to the debate on uncertainties in hydrological-hydraulic modeling applied to urban drainage.

MATERIALS AND METHODS

Study area and datasets

The Aricanduva River basin is in the eastern zone of the municipality of São Paulo, Brazil (Figure 1), constituting an important urban sub-basin tributary of the Tietê River. It has an area of 103.9 km², with elevations ranging from 993 m to 707 m, and longitudinal slopes between 0.025 $m.m^{-1}$ and 0.05 $m.m^{-1}$ (Ferreira and Rocha, 2026; Caderno da Bacia Hidrográfica: bacia do córrego Aricanduva, 2022). The basin is located in a humid subtropical region, with a climate classification between the *Cfa* and *Cwa* types, characterized mainly by strong precipitation seasonality, with high monthly totals in summer, approaching 211 mm in February, and reduced values in winter, around 38 mm in August (Alvares *et al.*, 2013). This concentration of rainfall during the wet season, associated with consolidated urbanization, favors rapid hydrological responses during intense events.

The Aricanduva River has a recurrent history of urban flooding, with 96 episodes recorded between 1995 and 2020. Its susceptibility is related to the dense occupation of riparian areas, the suppression of floodplains, the channelization of the stream and its tributaries, and the increase in peak flows (Santos, 2025). In response, the basin underwent structural macro-drainage interventions, including a flood control system composed of nine storage reservoirs and six polders, highlighting the importance of these structures for surface runoff management in this urban watershed (Caderno da Bacia Hidrográfica: bacia do córrego Aricanduva, 2022).

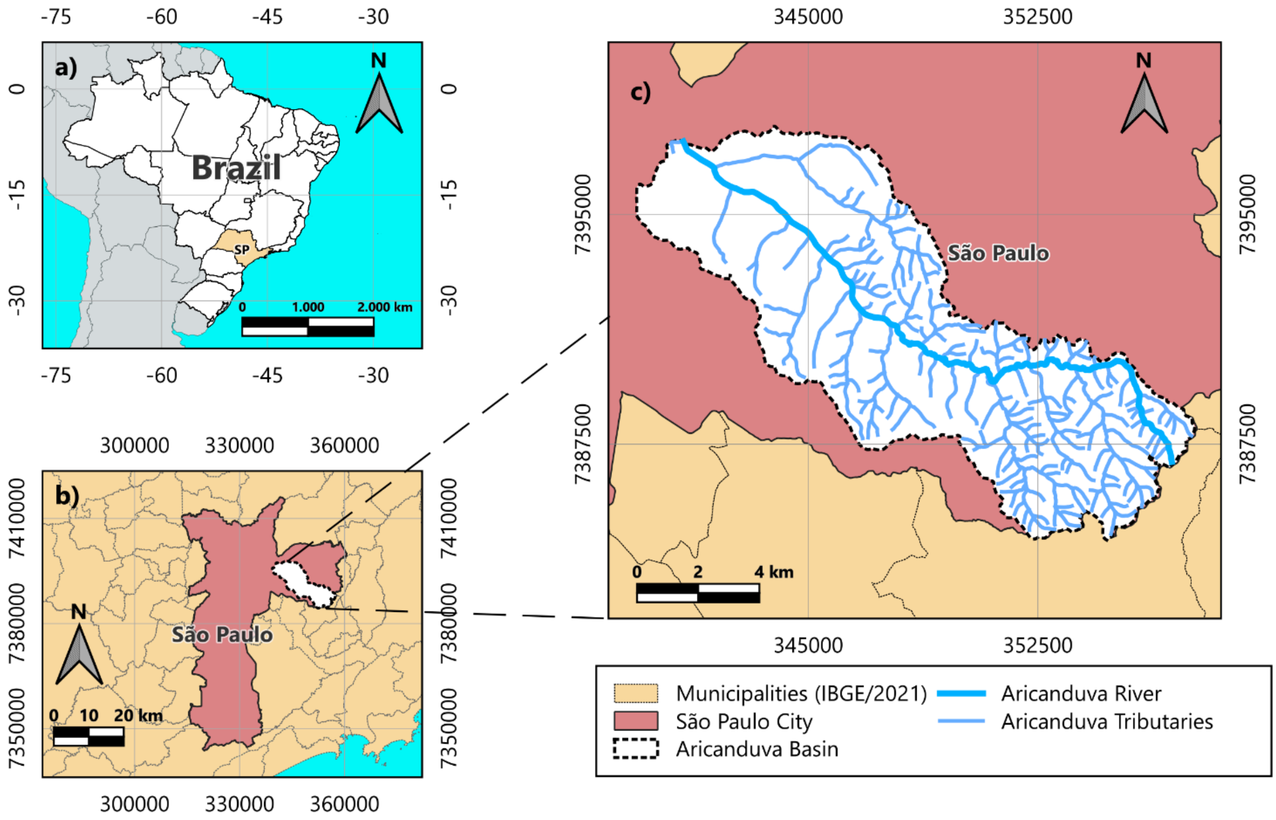

Figure 1 – Location and hydrographic context of the Aricanduva River Basin, São Paulo, Brazil. (a) State of São Paulo in Brazil. (b) Municipalities highlighting São Paulo City and the Aricanduva River Basin limit. (c) Aricanduva River Basin and its tributaries. Data sources: GeoSampa (2020) and ANA (2021).

Hydrological configuration

Effective rainfall was estimated using the NRCS-CN method, considering two scenarios for the initial abstraction ratio: the classic value $\lambda = 0.20$ and a reduced value $\lambda = 0.05$. For each scenario, the maximum potential retention of the soil was calculated from the Curve Number, according to equations (1), (2) e (3).

$$P_e = \begin{cases} 0, & P \leq \lambda S_\lambda \\ \dfrac{(P - I_a)^2}{P - I_a + S}, & otherwise \end{cases} \tag{1}$$

$$I_a = \lambda \cdot S \tag{2}$$

$$S = \frac{25400}{CN} - 254 \tag{3}$$

Where Pe represents the effective precipitation (mm), P is the total precipitation (mm), λ is the initial abstraction ratio (dimensionless), Ia is the initial abstraction (mm), S is the maximum potential retention (mm), and the corresponding CN is the Curve Number (dimensionless).

The IDF (Intensity-Duration-Frequency) curve (mm/h), equation (4), and its coefficients, were obtained from (Caderno da Bacia Hidrográfica: bacia do córrego Aricanduva, 2022).

$$I_{Aricanduva} = A \cdot (t_d + B)^C + D \cdot (t_d + E)^F \left\{G + H \cdot ln\left[ln\left(\frac{TR}{TR-1}\right)\right]\right\} \tag{4}$$

Where A = 32.77; B = 20.00; C = - 0.878; D = 16.10; E = 30.00; F = - 0.9306; G = - 0.4692 and H = - 0.8474; all dimensionless. A duration (t_d) of 5 hours and a return period (TR) of 25 years were considered.

The tabulated CN values for the basin were obtained from ANA (2021). Subsequently, a representative value for the basin was calculated using the area-weighted average of each land use and land cover class. Since the traditional CN values were developed considering the classic formulation of the NRCS-CN method, i.e., λ = 0.20, altering the initial abstraction ratio requires the reinterpretation of the applied CN values. Thus, for the scenario with λ = 0.05, the corresponding $S_{0.05}$ value was estimated based on the equation proposed by (Brandão *et al*., 2025), presented in equation (5).

$$S_{0.05} = 0.9191 \cdot S_{0.20}^{1.174} \quad 0 \leq S_{0.05} \leq \infty \tag{5}$$

Hydraulic modeling

Hydraulic simulations were performed in HEC-RAS 6.6, using a two-dimensional approach to represent runoff propagation and flood extent formation in the Aricanduva basin. The hydraulic domain was derived from the digital elevation model (DEM) of the study area, obtained from the GeoSampa (2020), platform, with a computational mesh of 30 m × 30 m. To improve the representation of the main channel, linear structures, and relevant terrain changes, break lines were inserted with 10 m spacing and a 10 m offset. Hydraulic roughness was spatially distributed based on land use and land cover classes, as described in the previous step.

HEC-RAS allows solving two-dimensional flow using the diffusive wave equations or the Shallow Water Equations; generally, these formulations are solved on an unstructured polygonal mesh, combining finite difference and finite volume methods with subgrid bathymetry technology.

The diffusive wave formulation simplifies the momentum equation by assuming that flow movement is controlled by the balance between the water surface gradient and bottom resistance. This approximation can be expressed by equations (6) and (7).

$$\frac{n^2}{R^{4/3}} = |V| \cdot V = -\nabla Z_S \tag{6}$$

$$V = -\frac{R^{2/3}}{n}\frac{\nabla Z_S}{\sqrt{|\nabla Z_x|}} \tag{7}$$

Two hydraulic plans were simulated, differing only in the parameterization of the initial abstraction ratio in the NRCS-CN method. Plan 3 adopted λ = 0.20, while Plan 4 adopted λ = 0.05. In both cases, the hydraulic parameters were maintained, including the 30 m × 30 m mesh, break lines, Manning's roughness coefficients, the 1 s computational interval, and the 1 s mapping output interval.

RESULTS AND DISCUSSIONS

The adoption of λ = 0.05, associated with the reinterpretation of the tabulated CN, reduced the representative value for the basin from CN = 85 to CN = 76, which corresponds to a 10.6% reduction compared to the classic scenario. This alteration reduced the total effective precipitation by 13.7%, evidencing that the change in λ does not act merely as a conceptual adjustment of λ, but also directly alters the volume of excess rainfall available for hydraulic routing, as demonstrated in Figure 2. This result is consistent with studies that question the universal adoption of the classic value and indicate that lower values may better represent the rainfall-runoff response in urban watersheds (Galbetti *et al*., 2022; Simpson *et al*., 2023; Brandão *et al*., 2025).

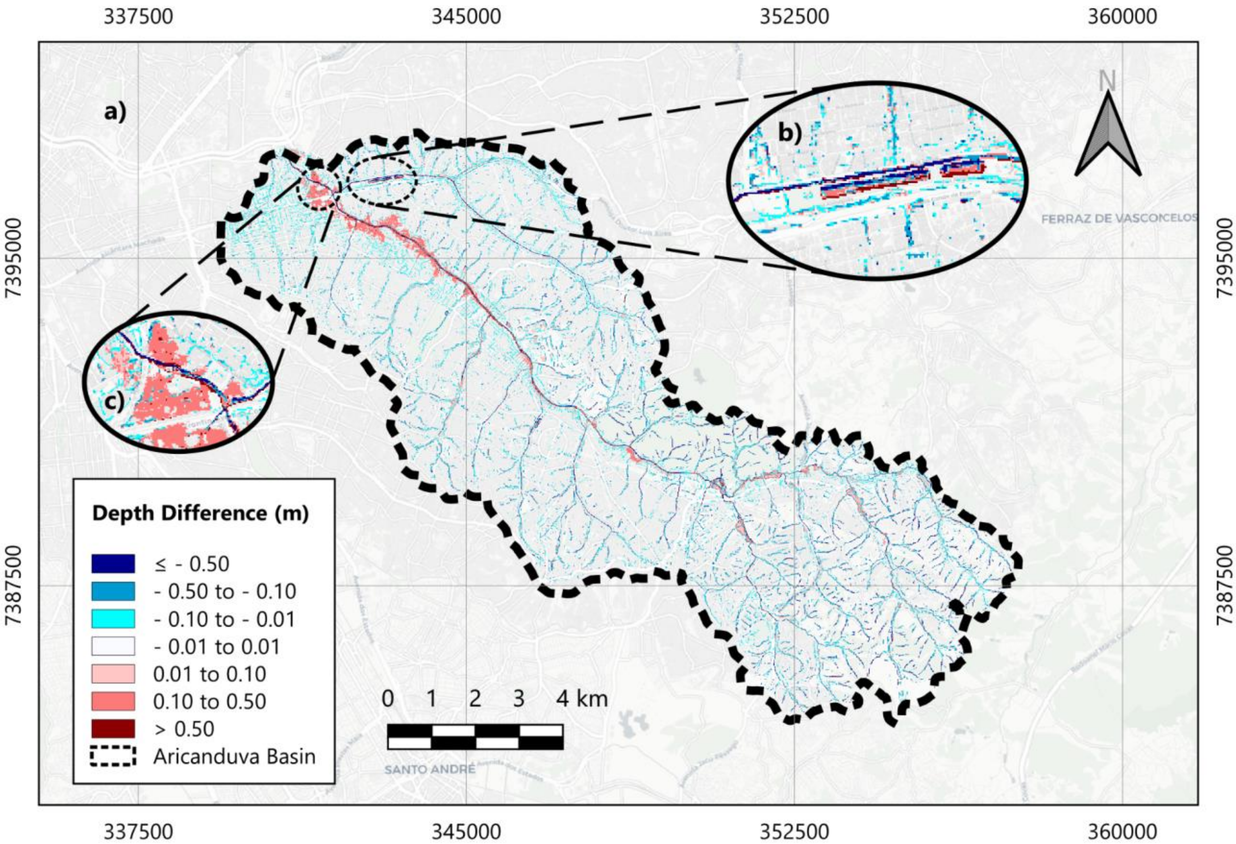

Figure 2 – Spatial difference in water depth between 2D HEC-RAS simulations $(\Delta h = h_{\lambda=0,020} - h_{\lambda=0,05})$ for the Aricanduva Basin, considering uniform rainfall distribution over the entire mesh. (a) Overview of the entire mesh. (b) Detailed view of the Rincão Reservoir, which exhibited the highest depth difference in the basin. (c) Enlarged view at the junction of the Rincão Stream and Aricanduva River.

The differences are mainly concentrated along the drainage network and in areas close to the channels, where the scenario with λ = 0.20 generated water depths higher by approximately 0.10 to 0.50 m. In contrast, sectors further away from the main channel presented predominantly small differences, generally between - 0.10 m and 0.10 m, indicating low spatial sensitivity outside the preferential flow routes. The enlarged panels show, however, that this limited average response can hide relevant localized alterations, especially in reaches close to the reservoirs, where depth differences exceeded 0.50 m.

Figure 3 compares the simulated flood extent for the two values of the initial abstraction ratio. Generally, both scenarios reproduce the flooding along the main drainage routes of the basin, indicating that the overall spatial structure of the flood extent is strongly conditioned by the topography and the channel network. However, the scenario with λ = 0.20 presented greater spreading in some sectors, consistent with the higher effective precipitation available for hydraulic routing. This result shows that the difference between the scenarios is not restricted to the runoff depth calculated by the NRCS-CN, but can be reflected in spatially explicit hydraulic products, such as flood depth and extent. This point is particularly relevant because, although there are applications of the NRCS-CN method in urban drainage studies (Galbetti *et al.*, 2022; Simpson *et al.*, 2023), analyses that critically investigate its parameters in highly impermeable urban watersheds and, above all, that evaluate how these choices propagate to final hydraulic results are still scarce. Thus, the present study contributes by showing that substituting the classic value of λ can locally alter the simulated water depth in a complex urban basin with high impermeabilization, a channelized drainage network, and flood control structures.

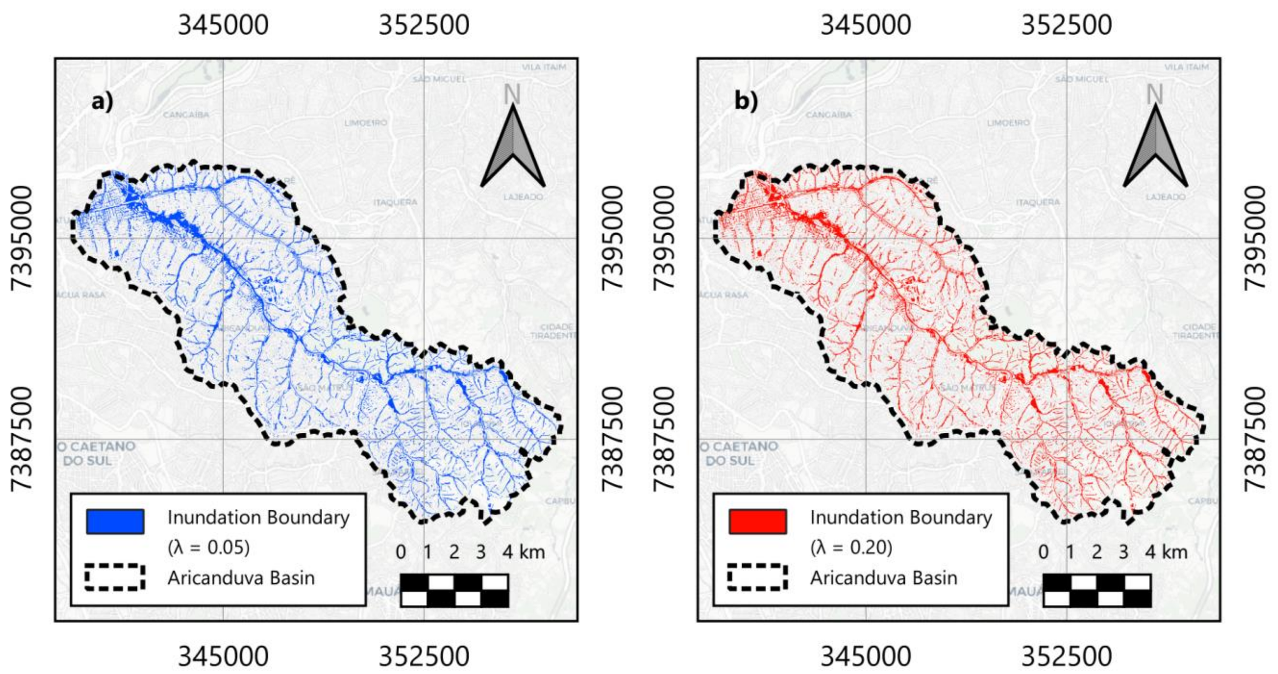

Figure 3 – Sensitivity of HEC-RAS 2D simulation spreading to the initial abstraction ratio (λ) in the Aricanduva basin under uniform rainfall for (a) λ = 0.20. (b) λ = 0.05.

Besides its use in modeling workflows with HEC-HMS and HEC-RAS, the NRCS-CN method is also incorporated into widely used models, such as the Soil and Water Assessment Tool (SWAT) and the Storm Water Management Model (SWMM), with applications in flood control, water quality, sediment yield, and drainage projects. This reinforces the importance of critically evaluating its parameters. Since the hydraulic model has not yet been calibrated and validated with observed flood extents in the Aricanduva basin, the results do not allow defining which scenario best reproduces the real inundation. Nevertheless, this limitation does not compromise the study's objective, which is focused on analyzing the sensitivity of the hydraulic response to the hydrological parameterization of the NRCS-CN. With other hydraulic conditions kept constant, the results show that altering λ and the corresponding CN can locally modify the simulated water depth. Thus, the results should be interpreted as a controlled sensitivity analysis, indicating that the initial abstraction ratio can propagate to final hydraulic products and should be considered in future calibration and validation stages.

CONCLUSIONS

This study evaluated the sensitivity of the water depth and flood extent simulated in HEC-RAS 2D to the alteration of the initial abstraction ratio of the NRCS-CN method in a highly impermeable urban watershed. The substitution of the classic value $\lambda = 0.20$ with $\lambda = 0.05$, associated with the reinterpretation of the tabulated CN, reduced the representative value for the basin from 85 to 76 and decreased the effective precipitation by 13.7%. The results indicated that this alteration produced spatially heterogeneous differences in water depth, concentrated mainly along the drainage network, in areas close to the channels, and in reaches influenced by flood control reservoirs. Although the flood extent maintained a similar overall structure between the scenarios, local differences exceeding 0.50 m demonstrate that the choice of λ can significantly affect the hydraulic representation of critical areas. Therefore, parameters usually treated as hydrological can propagate to spatially explicit hydraulic results. Thus, in urban flood studies, it is recommended to rigorously evaluate the consistency among λ, the adopted CN, and the hydraulic products used in drainage planning.

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