Modeling urbanization impact on surface runoff in a West African city: A case study of Dakar's suburbs (Senegal)

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Abstract

Urbanization profoundly modifies hydrological processes by altering natural drainage pathways, reducing infiltration, and increasing surface runoff volumes. In rapidly expanding cities such as Dakar, these changes are exacerbated by unplanned development and limited stormwater infrastructure. This study aims to assess the hydrological impacts of urbanization by implementing a rainfall–runoff model adapted to data-scarce environments. The model was calibrated using the limited hydrological and meteorological observations available, along with integrated spatial indicators representing both urbanization density and the modification of natural drainage directions. Simulations were carried out for identical rainfall events under two contrasting land-use scenarios, corresponding to the years 1983 and 2018. The results reveal a marked increase in runoff levels and discharges at the watershed outlets, with amplification factors of 1.75 for watershed 1 and 2.75 for watershed 2. These results clearly demonstrate the intensification of surface runoff resulting from increased imperviousness and the densification of the urban fabric. Beyond the quantitative findings, this study highlights the strong relationship between urban growth, flood risk, and urban planning in African cities, where land pressure and informal development are particularly pronounced. The acquisition of additional rainfall–runoff measurements would help refine model calibration, reduce uncertainties, and strengthen the robustness and relevance of the proposed approach.

1. Introduction

In West African cities, rapid and predominantly unplanned urbanization (Forget et al. 2021; Yuan et al. 2023), driven by population growth and the concentration of economic activities (Tabutin, Schoumaker 2020), accentuates hydrological risks, particularly flooding (Ramiaramanana, Teller 2021). In Dakar, this dynamic has led to extensive land artificialization, including in former natural drainage areas, often disregarding hydro-morphological constraints (Ndiaye 2015; Diop et al. 2018). In the absence of adequate drainage infrastructure, these urban transformations have contributed to recurrent flood events in 2005, 2009, 2012, and 2020 (Diedhiou et al. 2024a; 2024b; Diémé et al. 2024). The floods were further exacerbated by the intensification of extreme rainfall in the Sahelian zone (Taylor et al. 2017; Chagnaud et al. 2022).

The link between changes in urban dynamics, alterations in hydrological response, and the increasing frequency of flooding has been the subject of various studies. Several recent studies provide empirical evidence to characterize these interactions. Among the major references, Tang et al. (2025) examine the respective contributions of urbanization and population growth to changes in urban flood exposure in a

large Chinese city over the last decade (2010-2020). To this end, they apply the InfoWorks Integrated Catchment Modeling (ICM) tool, developed by Innovyze (Autodesk), to translate the physical evolution of the city (urbanization) into measured hydrological impacts (water levels, flooded areas), and then assess the consequences for residents by integrating census data. Their results show that in areas of rapid urban expansion, urbanization accounts for more than 97% of the increase in risk, while in already densely populated urban centers, it is mainly population growth that increases exposure. Another study in China highlights a significant increase in flow rates during the 2002-2013 urbanization period (Bian et al. 2020). The authors indicate that the flood magnitudes were higher than during the reference period (1986-2001), even for identical return periods. Using the HEC-HMS hydrological model coupled with GIS to analyze two land-cover states in Poland, corresponding to 1990 (before significant urbanization) and 2018 (period of rapid urbanization), Janicka and Kanclerz (2022) confirm the direct effect of impervious surfaces on hydrological responses and flood peaks. Finally, at the global scale, Cao et al. (2022) point out that urban exposure to flooding has been increasing steadily for more than three decades, and that this trend poses a major challenge for sustainable risk management in the context of rapid urbanization, regardless of climate variability. In a more recent study, Zhang et al. (2025) indicate that, according to projections, the North-South gap in urban exposure to rainwater is likely to widen over the course of the century.

In West Africa, studies on the quantitative assessment of the impact of urbanization on hydrological response remain scarce (Ongaga et al. 2024). Moreover, the absence or discontinuity of urban rainfall and hydrometric records is a major constraint for hydrological modeling (Djibo et al. 2023; Koch et al. 2025). In this context, semi-empirical approaches are particularly interesting for analyzing and managing urban runoff. They offer a relevant compromise between simplicity of implementation, parsimony of parameters, and robustness of results, while enabling the assessment of urbanization impacts on the hydrological response (Chahinian et al. 2023; Diémé et al. 2025). In addition, the growing availability of remote sensing data, combined with cadastral databases, now facilitates the spatialization of hydrological parameters (Ali et al. 2023), thereby improving the representativeness of simulations, even in environments characterized by strong spatial heterogeneity. From this perspective, the ATHYS modeling platform (L'ATelier HYdrologique Spatialisé, https://www.athys-soft.org/, last access 30 September 2025), designed for hydrological analysis in both data-rich and data-poor contexts, was used to implement simple approaches based on conceptual models and also more detailed schemes relying on a distributed representation of parameters. The SCS (Soil Conservation Service) production model, applied to estimate surface runoff, was combined with the Lag and Route (LR) hydrological transfer model (Tramblay et al. 2011). The study compares two contrasting land-cover conditions (1983 and 2018), subjected to the same rainfall forcing, to isolate the effect of urbanization on runoff dynamics and the spatial redistribution of flows. Two representative catchment areas in the city of Dakar were modeled using detailed cadastral, topographical, and rainfall data, providing a basis for analyzing the hydrological changes induced by urban expansion.

This work is structured in four parts. The first describes the study area and its main characteristics. The second presents the data used and their processing. The third part details the hydrological model selected and its calibration, while the fourth is dedicated to the presentation and discussion of the results, before concluding.

2. Study area

The study area is located on the outskirts of Dakar, within a context of rapid and dense urbanization over the past several decades (Sané 2013), which has significantly disrupted local hydrological functioning (Diop et al. 2018). The annual rainfall ranges from 400 to 600 mm (Mendy 2023) over predominantly sandy soils, with hydromorphic characteristics around low-lying areas linked to a shallow groundwater table (Faye et al. 2019). The flat topography, combined with predominantly sandy and highly permeable soils, naturally limits surface runoff; however, increasing imperviousness and the limited efficiency of drainage systems amplify runoff volumes (Schaer et al. 2018). Two small urban catchment areas (50-107 ha) were selected to illustrate contrasting urbanization trajectories around the area. Catchment 1 (Djidah Thiaroye Kaw) is characterized by dense urbanization that began in 1983 with the gradual occupation of former runoff channels and natural depressions. Catchment 2 (Mbede Fass) illustrates rapid informal urbanization since the 1990s and shows mixed urbanization (planned and unplanned) leading to the disappearance of wetlands (Fig. 1).
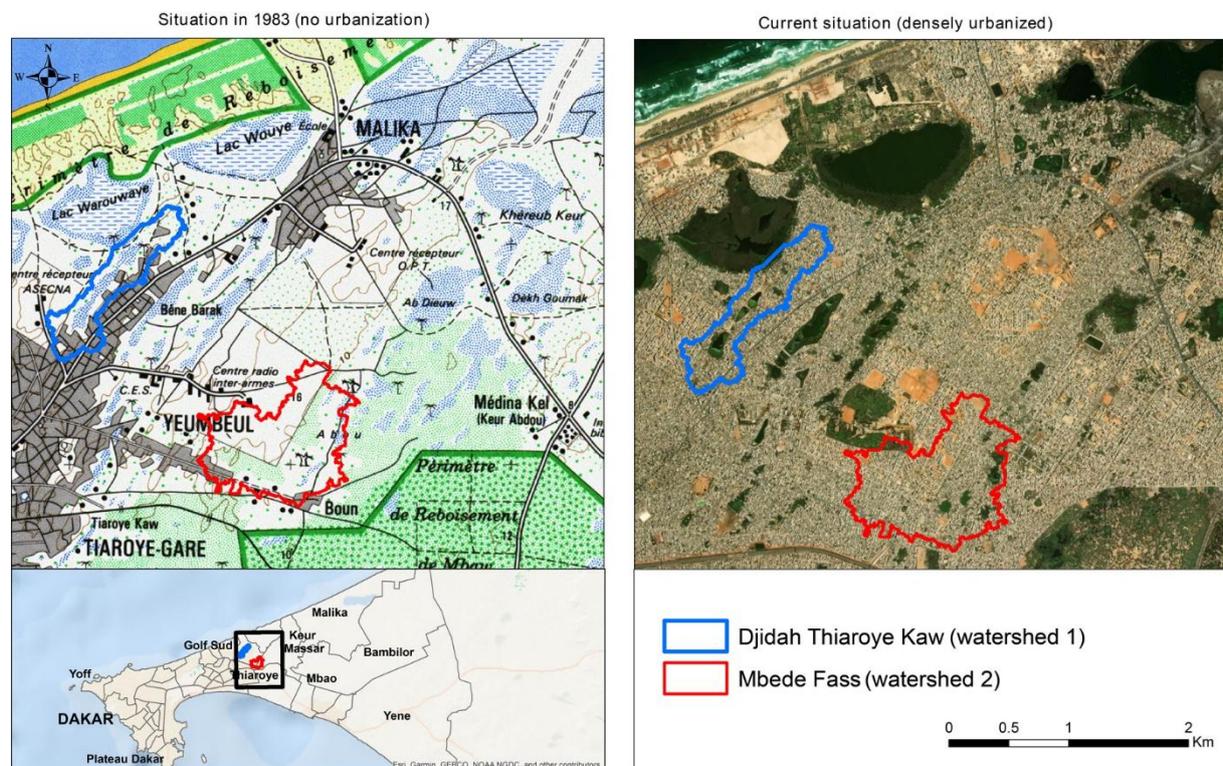

Fig. 1. Location and urban context of the studied catchments.

3. Data

Three categories of data are used: (i) topographic data, (ii) land use data, which are used to define surface conditions and associated runoff coefficients, and (iii) rainfall data.

3.1. Topographic data

The topography of the catchments was characterized using a high-resolution Digital Elevation Model (DEM) with 1 m² spatial resolution (Fig. 2), derived from high-density airborne LiDAR surveys over Dakar. This DEM, acquired within the framework of the Integrated Flood Management Project in Senegal (PGIIS) and provided by the Directorate for Flood Prevention and Management (DPGI), offers a detailed representation of micro-relief features. It was used for extracting drainage directions, whether natural or altered by urban developments (Diémé et al. 2022) and as a basis for implementing the surface runoff simulation model.
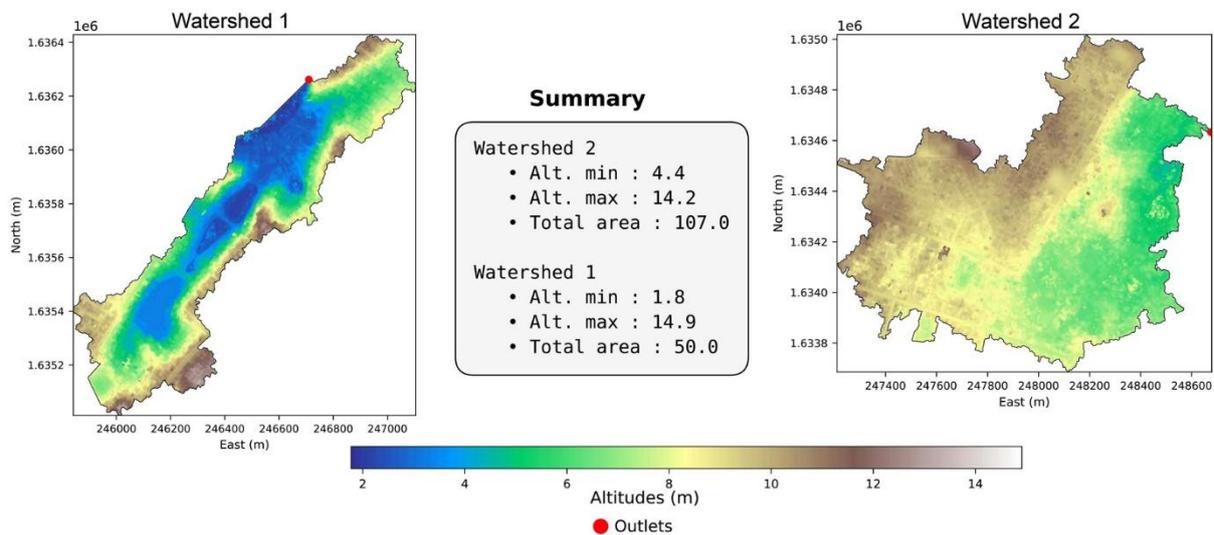

Fig. 2. Altitude distribution within the two catchments.

3.2. Land use data

Urban development was analyzed using land-use data from 1983 and 2018. For the 1983 reference state, the urbanization rates of the two catchments were estimated from city topographic maps (IGN, scale 1:25,000) and available aerial photographs, using visual interpretation and digitization of built-up areas. Although these historical maps do not allow a detailed characterization of urban density, they provide a sufficiently reliable representation of the spatial extent of urbanized areas, estimated at less than 20% in watershed 1 and less than 10% in watershed 2. For the 2018 situation, the analysis relied on cadastral data from the Dakar urban database provided by the DPGI. These building-level data were aggregated to the urban block scale to quantify built-up density within the urban blocks of each catchment. Density rates, defined as the ratio of built-up area to total block area, averaged 58% in watershed 1 and 55.2% in watershed 2 (Fig. 3).
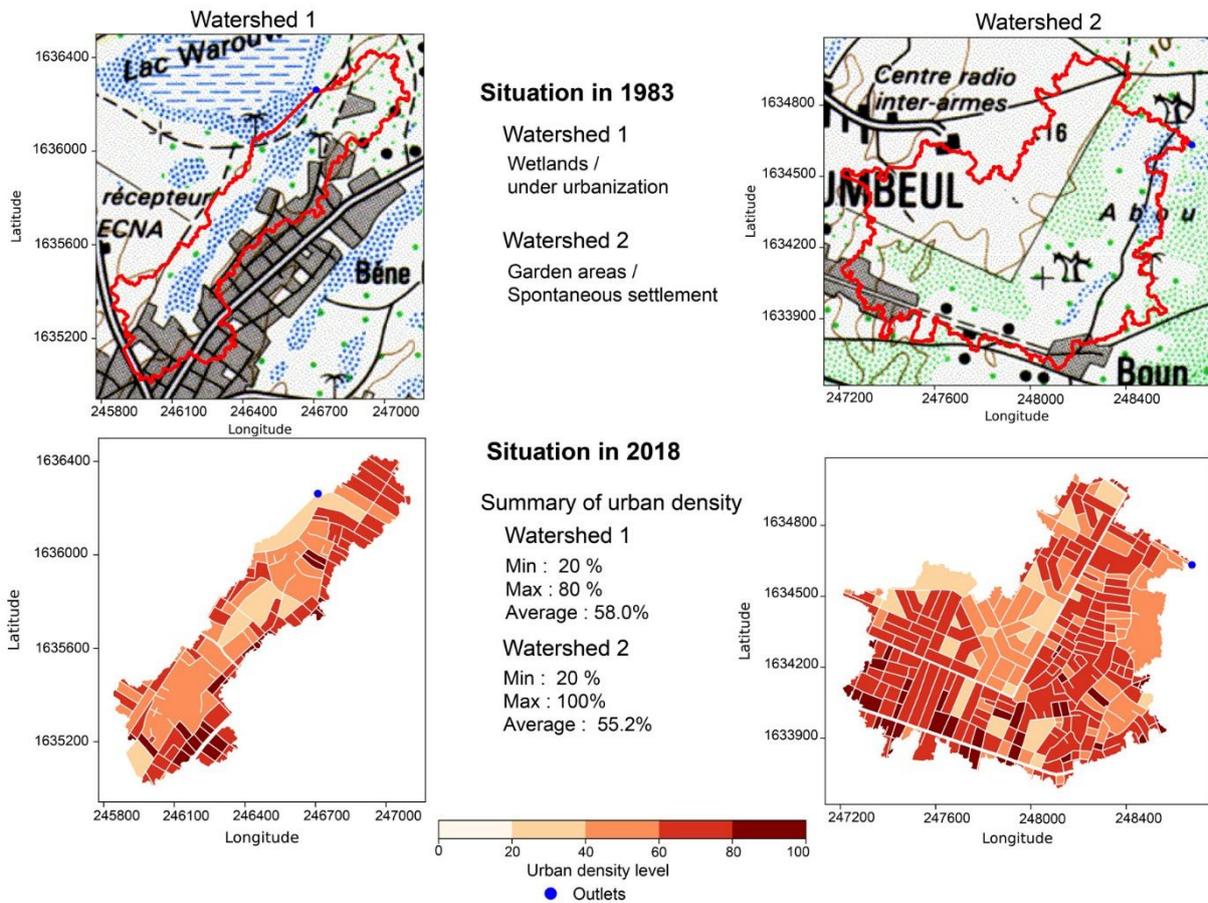
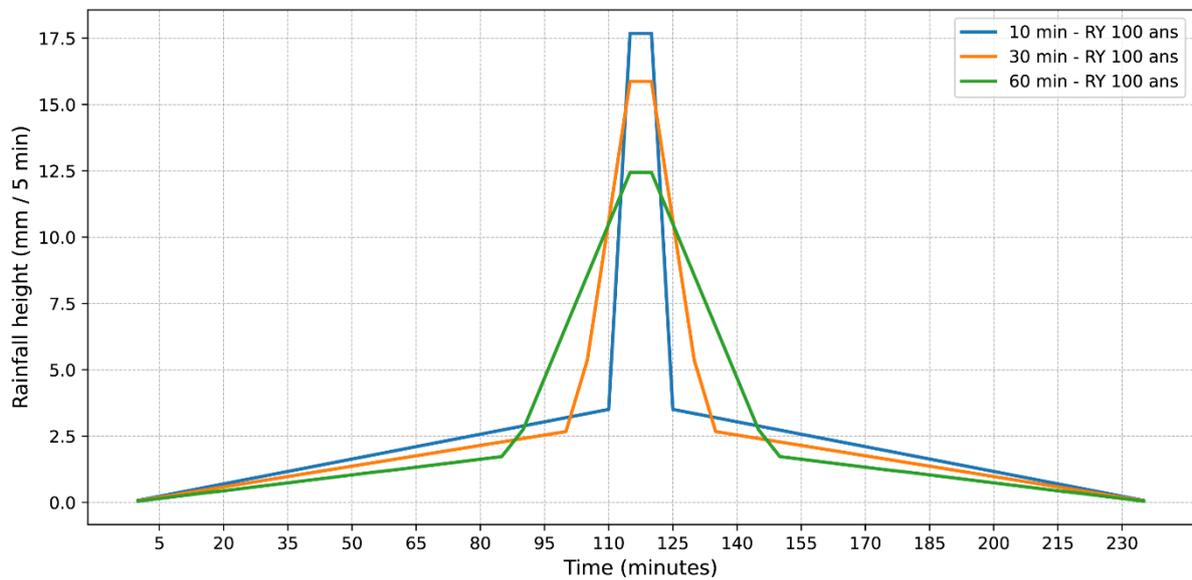Fig. 3. Land use in 1983 and current urban density.

Fig. 4. Double-triangular hyetograms derived from Dakar IDF curves.

3.3. Rainfall data

Rainfall data were derived from Intensity–Duration–Frequency (IDF) curves established for Senegal by Diedhiou et al. (2024a), based on sub-hourly (5-minute) rainfall series spanning several decades. These

new curves provide a finer resolution than the hourly curves previously produced by Sane et al. (2018), allowing for a more accurate characterization of extreme rainfall variability in Dakar. In this study, a 100-year return period was selected, representing a rare but hydrologically plausible event, relevant for both long-term planning and in the context of increasing extreme precipitation frequency. Using this basis, 4-hour double-triangular 4-hour storms were generated following the Desbordes method (Desbordes, Raous 1980), consistent with the total duration of regional convective rainfall events (Tadesse, Anagnostou 2010). Three characteristic durations of maximum intensity – 10 min, 30 min, and 1 h – were generated (Fig. 4) to cover a relevant range of temporal scales for urban hydrological modeling.

4. Method

A distributed hydrological model (SCS-LR) was applied that integrates runoff production and transfer processes within natural and urban units and is then calibrated using available observations to estimate flows.

4.1. Model overview

4.1.1. Runoff production model

The SCS model (equation 1), widely applied in urban contexts (Meng et al. 2019; Nguyen, Bouvier 2019; Nielsen et al. 2025), is used to simulate the rainfall–runoff transformation process (Bouadila et al. 2023) at a high-resolution grid scale of 1m². For each grid cell in the catchment, infiltration and runoff capacities were assigned based on soil type and urban density. The model relies on two parameters: the initial abstraction Ia (mm) and the maximum retention capacity S (mm). Ia is considered equal to $0.2S$, which allows runoff Q (mm) for each grid cell to be computed as follows:

$$Q = \frac{(P-0,2.S)^2}{P+0,8.S} \qquad P > 0,2.S \; ; \; if \; not \; Q = 0 \tag{1}$$

where Q is the runoff (mm), and P is the net rainfall (mm).

To account for the temporal evolution of rainfall intensity, a dynamic formulation (equation 2) (Gaume et al. 2004), was applied to each grid cell with a time step of 5 minutes, considering the spatial variability of S in relation to urban conditions:

$$Pe(t) = Pb(t).\left(2 - \frac{(P(t)-0,2.S)}{P(t)+0,8.S}\right)\left(\frac{P(t)-0,2.S}{P(t)+0,8.S}\right) \tag{2}$$

where $Pe(t)$ represents the runoff produced at time step t (mm/h), $Pb(t)$ is the intensity of the rain at time t (mm/h), and $P(t)$ is the cumulative rainfall at time t, since the start of the storm (mm). S is the only model adjustment parameter.

4.1.2. Runoff transfer using the Lag and Route (LR) model

Runoff computed by the SCS model was routed to the catchment outlet using the LR model (Tramblay et al. 2011; Nguyen, Bouvier 2019). Each grid cell produces an elementary hydrograph, and the sum of these hydrographs constitutes the total catchment at the outlet. The transfer time (equation 3) is defined as:

$$Tm = Lm/Vo \tag{3}$$

where *Lm* is the distance to the outlet and *Vo* is the average velocity, while wave diffusion (equation 4) is given by:

$$Km = Ko.Tm \tag{4}$$

with *Ko* as the proportionality coefficient. The hydrograph (equation 5) produced by the grid mesh m and the effective rainfall *Pe(to)* at each time is expressed as:

$$Q(t) = \frac{Pe(t_0)}{K_m} \, exp\left(\frac{t-(t_0+T_m)}{K_m}\right) A \qquad \text{if } t > t_0 + T_m \text{ and } Q(t) = 0 \text{ if not} \tag{5}$$

where A is the grid cell area. The LR model has the advantage of being numerically stable with respect to grid size and time step. It was applied at a resolution of 1 m² with a 5-minute time step. The calibrated parameters of both the SCS and LR models allow for the assessment of urbanization impacts on surface runoff height and outlet flow hydrographs.

4.1.3. Simulation scenarios

Two contrasting land-use scenarios were simulated:

- Scenario 1 (1983): Land use based on IGN mapping, representing predominantly permeable soils with low built-up coverage.
- Scenario 2: Land use based on 2018 cadastral data, characterized by high urban density, increased impervious surfaces, and encroachment of former wetland areas.

Both scenarios were subjected to the same rainfall event – a rare, 100-year return period storm – to directly compare the hydrological impacts of urban development.

4.2. Model calibration

4.2.1. Calibration of the runoff production model

The calibration of the hydrological model was carried out in two steps: (1) Direct measurements of soil moisture (Diémé 2023) were used to estimate infiltration rates of Dakar's sandy soils through inverse soil moisture modeling (Le Bourgeois et al. 2016) and Hydrus 1D simulations (Šimůnek et al. 2016). These analyses confirmed their high permeability, as previously highlighted by (Diémé 2023); (2) runoff coefficients (CR) were then evaluated for different rainfall events using data from the only available experimental catchment in Dakar, Fann Mermoz (Bassel et al. 1994; Bassel, Pépin 1995), which is 20%

urbanized. According to (Diémé et al. 2025), these coefficients are 10%, 20%, and 30% for rainfall of 40, 78, and 150 mm, respectively, confirming that non-paved, highly permeable soils generate very little runoff. Consequently, the built-up coefficient for the watershed was equated to the runoff coefficient associated with a 78 mm rainfall, corresponding to a decennial event in Dakar (Sane et al. 2018; Diedhiou et al. 2024a). Adjusting the SCS model parameter S to 117 mm allowed reproducing the observed behavior in the reference watershed (Diémé et al. 2025). Subsequently, S values were computed for different built-up density classes using the following equation (Equation 6):

$$CR = \frac{Q}{P} = \frac{(P-0.2S)^2}{P.(P+0.8S)} \qquad (6)$$

Where P is the 4-hour ten-year rainfall height, i.e., 78 mm. At the scale of the studied catchments, these S values were generalized and assigned according to urban density classes in both scenarios (Table 1).

Table 1. The S values obtained after adjusting the SCS model

Urban density classes (%)	Runoff coefficient (ten-yearly)	S values
20	20	117
40	40	67
60	60	35
80	80	15
100	100	0

4.2.2. Calibration of the routing model

Because of the dependency between the Vo and Ko parameters, the parameter Ko was set to 0.7, a commonly used empirical value (Bouvier et al. 2017). The parameter Vo was determined from historical data from the Fann Mermoz experimental catchment (Bassel 1996). The lag time (Tr, between the center of gravity of runoff and that of rainfall) was estimated at 30 minutes, corresponding to the centroid grid cell of the urbanized area, located 1.2 km from the outlet (Diémé et al. 2025). The velocity Vo (Equation 7) is then calculated as:

$$Vo = 1.7\frac{Lm}{Tr} = 1.1 \, \text{m/s} \qquad (7)$$

This value, obtained for the reference catchment, was applied to the studied catchments, considering that the slight variation in slopes makes this approximation representative for all rainfall events.

5. Results and discussion

Both land-use scenarios were subjected to the same rare-event rainfall hyetogram (100-year return period) to isolate the effect of urbanization changes on the two catchments. Model outputs include simulated water depths for each natural or urban grid cell (Fig. 5) as well as flow hydrographs computed at the catchment outlets (Figs. 6 and 7).

The results highlight a significant increase in surface water level per urban density block. The magnitude of this increase, which varies according to urban density, can be explained mainly by the increase in impervious surfaces, which reduces infiltration capacity and amplifies surface runoff.
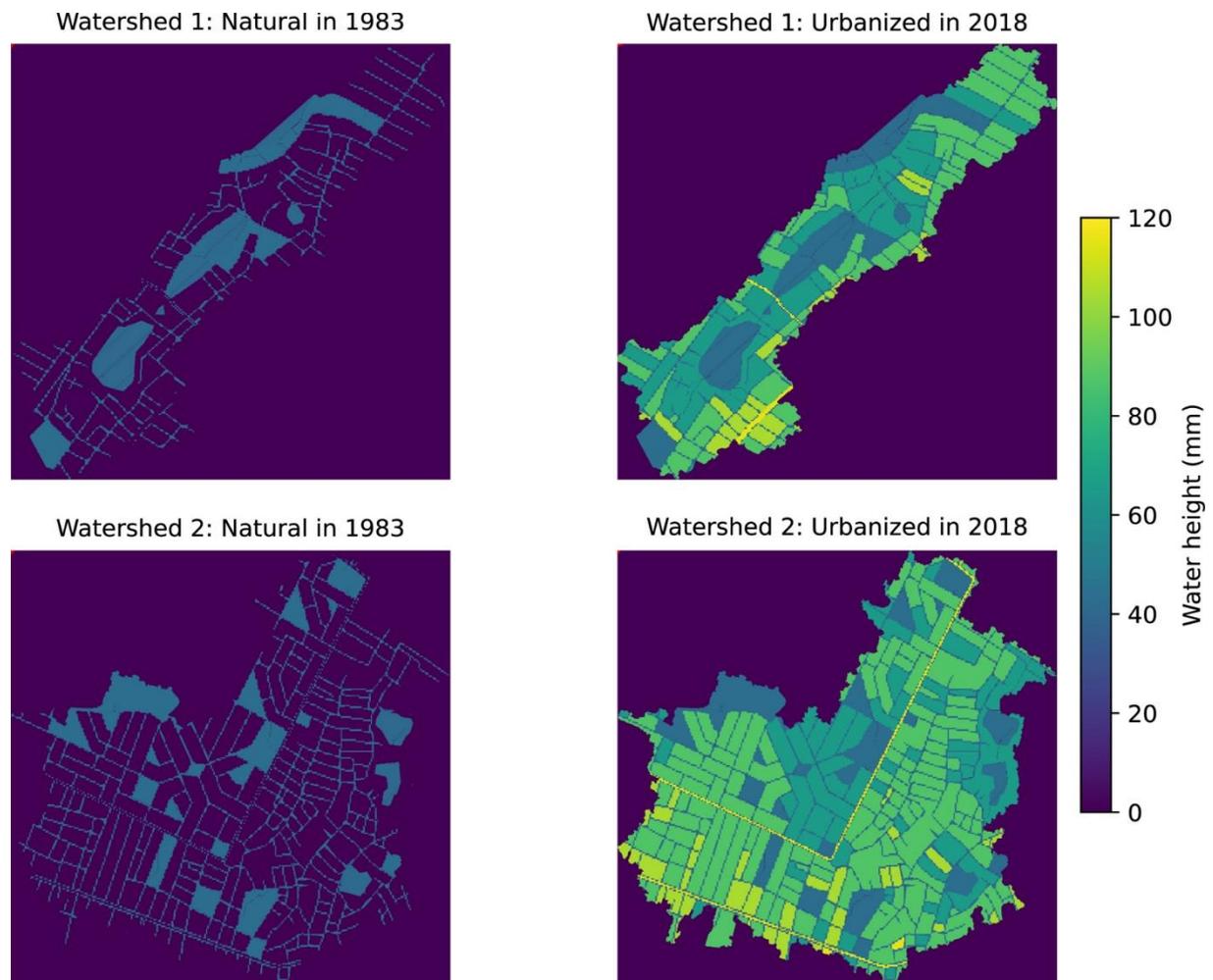

Fig. 5. Spatial distribution of runoff water levels before and after urbanization for a 100-year return period rainfall event (54.4 mm), with a total duration of 4 hours and peak intensity concentrated over 30 minutes.

In both catchments, peak flows in the hydrographs increased significantly between the two land-cover states of 1983 and 2018 (Figs. 6 and 7). For a 4-hour rainfall event with a 30-minute peak intensity, catchment 1 exhibits a peak flow rising from 3.29 to 5.75 $m^3 s^{-1}$, an increase of approximately +75%, corresponding to a factor of 1.75. The larger catchment 2 shows an even more pronounced rise, with peak flow increasing from 7.97 to 21.9 $m^3 s^{-1}$, or nearly 175% (factor 2.75), almost three times the flow of the natural scenario. This amplification is directly linked to urban development: the urbanization rate in catchment 2, below 10% in 1983, reached 55% in 2018, demonstrating that urban expansion has strongly intensified flows, accelerated surface runoff, and contributed to increased flood risk.

The results indicate that urban growth substantially amplifies flood risk in Dakar's urban watersheds. They provide a quantitative framework for evaluating the influence of urbanization on flood vulnerability,

underscoring the importance of incorporating stormwater management in urban planning, conserving natural retention zones, and deploying suitable drainage systems, including nature-based solutions.
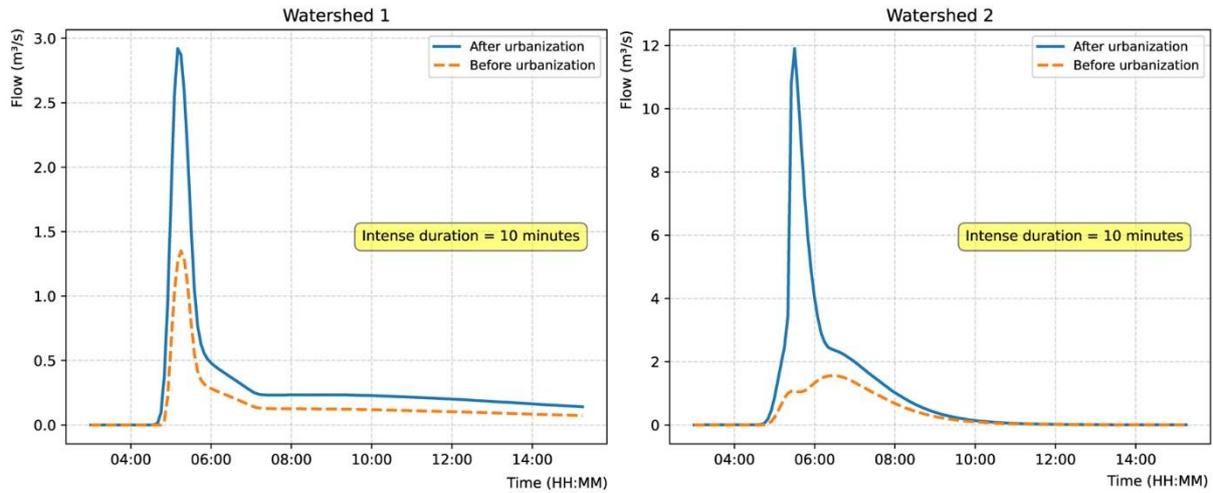

Fig. 6. Comparison of hydrographs for a 10-minute peak intensity of a 100-year return period rainfall event (29.5 mm).
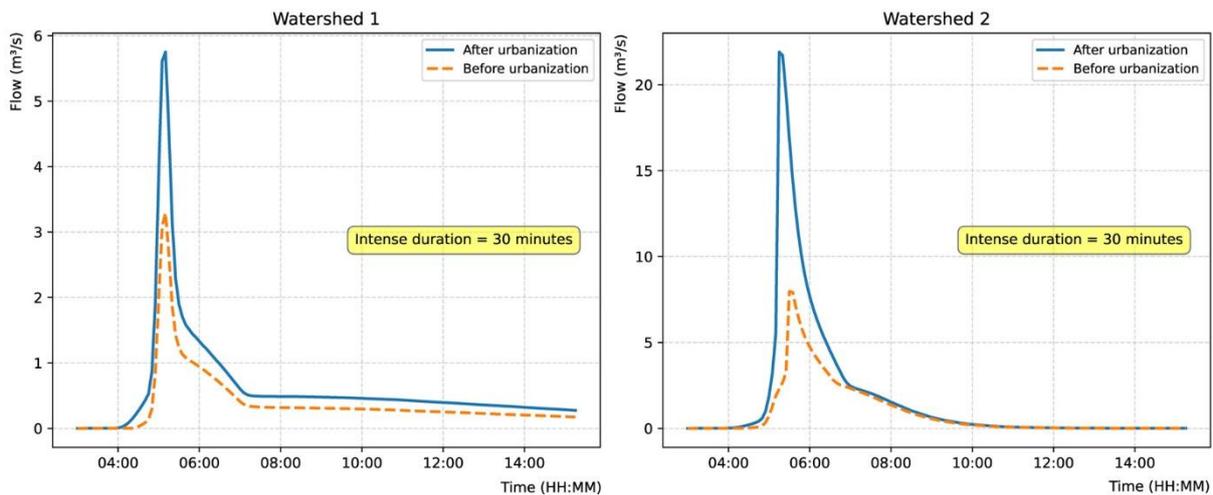

Fig. 7. Comparison of hydrographs for a 30-minute peak intensity of a 100-year return period rainfall event.

5.1. Validity of the approach and limitations

The use of reconstructed historical data (1983) allows visual representation of past land-use states, though their reliability is limited by the precision of surveying techniques of that period. Nevertheless, the 1983 map of Dakar used here provides sufficient resolution and accuracy, supporting its use alongside current cadastral data. Extending this approach to the entire city could enable the spatial delineation of runoff-generating areas, identification of zones with the highest surface water levels, and assessment of outlet flows across catchments. Such a spatial analysis could be used to identify the distribution of impervious and pervious areas, and the resulting hydrological variability associated with land use (Ongaga et al. 2024; Dell'Aira, Meier 2025), topography, and imperviousness dynamics (Gong et al. 2023). In the context of Dakar, the availability of rainfall data from the meteorological radar recently installed in the city would be an asset for implementing this approach, providing high spatial resolution, improving the representation

of intra-urban precipitation and runoff variability. Furthermore, instrumenting and regularly monitoring selected urban catchments would provide essential field data for calibrating and validating the applied hydrological models (Chahinian et al. 2023) and for capturing local processes not resolved by spatial data alone. This approach would enhance the reliability of results and facilitate the development of predictive tools, such as future climate scenarios and prospective analyses, tailored for urban stormwater management. Specifically, this proposed approach provides a relevant framework for quantifying the impact of urbanization on runoff generation, especially modifications of drainage directions induced by anthropogenic alterations (Diémé et al. 2022) and the spatial distribution of imperviousness surfaces. These capabilities represent a notable advantage over other modeling approaches commonly applied in urban contexts, which tend to simplify or neglect such changes (Ferrans, Temprano 2023; Tamm et al. 2023), making it a relevant tool for evaluating runoff and flood risk in cities.

6. Conclusion

This study aimed to evaluate the impact of urbanization on surface runoff in Dakar's peri-urban areas using comparative hydrological modeling for two distinct land-use periods (1983 and 2018) under identical rainfall conditions. The results indicate that intensified urbanization substantially increases water levels and peak flows, in some cases doubling the values computed under natural conditions. These impacts are closely linked and driven by extensive impervious surfaces, the disappearance of natural infiltration zones, and the unplanned occupation of wetlands. This study provides the first differentiated quantification of urbanization effects on flood exposure at the scale of small catchments, highlighting the need to incorporate hydrological considerations into urban planning in Senegal and other rapidly urbanizing African cities. In many parts of the world (e.g., EU Floods Directive, Low Impact Development in North America, and China's Sponge City policy), hydrological simulations are already used to support urban planning decisions and flood risk management, whereas such tools remain seldom integrated into planning practices in rapidly growing African cities. The fine-scale, scenario-based modeling approach proposed here is valuable for assessing impacts and guiding planning toward sustainable solutions. Overall, the study emphasizes the urgent need to rethink urban development with a focus on hydrological resilience, using accessible simulation tools and locally relevant data. In data-scarce urban contexts such as Senegal, the proposed approach should be viewed as a progressive framework, whose robustness can be strengthened through targeted field measurements, monitoring of selected representative catchments, and regular updating of spatial urban data.

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