Impacts of Changes in Climatic Conditions and Urbanization on Runoff at City Scale

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Abstract−Urbanization and climate change are increasingly recognized as key drivers of hydrological alterations in rapidly growing cities. This study assesses their combined and individual impacts on runoff generation in Algiers, Algeria, over the period 1992–2016 using the Soil Conservation Service Curve Number (SCS-CN) model. Land cover maps from the European Space Agency's Climate Change Initiative and long-term rainfall records were integrated with hydrological soil data to quantify runoff under three scenarios: (i) real conditions combining changes in climatic conditions and urbanization, (ii) fixed urban settings isolating climate effects, and (iii) fixed climatic conditions isolating urbanization impacts. Findings reveal that during the period 1992-2016, the city experienced an expansion of the impervious surfaces (from 19.86% to 41.48%) at the expense of other land covers. Moreover, the results show that although annual precipitation remained close to its baseline (608.25 mm·y^{-1}), runoff displayed a continuing upward shift above its baseline (70.04 mm·y^{-1}) after the early 2000s. Correlation analysis indicates that precipitation highly affects runoff variability (R^2 = 0.695) compared to urbanization impacts. Nevertheless, under the fixed climate conditions scenario, the 2-fold urban area expansion (with an increase of +108.4%) between 1992 and 2016 led to a +11.9% increase in runoff, underscoring its structural role in altering hydrological responses. These findings highlight the dual influence of the climatic conditions and land-use change on urban runoff dynamics and emphasize the need for integrated planning to enhance flood resilience and sustainable water management.

***Keywords*− Change in climatic conditions, Runoff, SCS-CN method, Urbanization, Water management.**

NOMENCLATURE

SCS-CN	Soil Conservation Service–Curve Number.
SWAT	Soil and Water Assessment Tool.
HEC-HMS	Hydrologic Engineering Center's Hydrologic Modeling System.
PRMS	Precipitation-streamflow modeling system.
CN	Curve number.
AMC	Antecedent moisture conditions.
CCI-LC	Climate Change Initiative Land Cover.
LULC	Land use and land cover.
HSG	Hydrological soil group.

I. INTRODUCTION

Cities in the Mediterranean region face growing challenges in managing water resources due to rapid urban expansion and climate change [1]. This dual pressure, where land-use transitions and changing rainfall patterns have affected hydrological responses. Rapid urban development changes land cover by replacing vegetation and permeable soils with impervious surfaces such as roads, rooftops, and pavements. This transformation disrupts the hydrological cycle by increasing surface runoff, modifying infiltration and groundwater recharge, and affecting evapotranspiration and water quality [2], [3], [4]. Consequently, the expansion of impervious areas and loss of vegetation significantly heighten flood risks [5].

In parallel, climate change amplifies these pressures through its direct influence on precipitation regimes. Shifts in rainfall intensity, duration, and frequency can intensify hydrological cycle response [6], particularly surface runoff [7], [8], producing both more severe floods and longer droughts. [9].

Several hydrological models were employed to assess runoff and study how changes in precipitation regimes and expansion of impervious surfaces affect surface runoff response, including SWAT [10], [11], [12], HEC-HMS [13], [14] and PRMS [15], [16]. Among these, the Soil Conservation Service Curve Number (SCS-CN) method has emerged as one of the most widely applied empirical models for runoff estimation, due to its relative simplicity, modest data requirements, and proven applicability across diverse climatic and land use contexts [17], [18], [19]. It has been extensively used to assess hydrological impacts of land-use change and climate variability in both urban and rural watersheds [20], [21].

Despite growing attention to the individual effects of climatic conditions and urbanization on runoff, relatively few studies have explicitly addressed their combined impacts over extended time periods. Understanding how these factors interact is essential for regions experiencing rapid urban expansion while simultaneously facing climate pressures. This study addresses this gap by investigating the long-term (1992–2016) runoff response of Algiers, a rapidly urbanizing Mediterranean city, under the impact of climate change and urbanization. Therefore, this study aims to identify the relative roles of precipitation variability and urban expansion (combined and isolated) in affecting runoff dynamics using the SCS-CN method.

II. STUDY ZONE

The study area is Algiers, the capital of Algeria, located on the Mediterranean coast of North Africa between 36°34′–36°49′N

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latitude and 2°48′–3°23′E longitude (Fig.1). Based on the Köppen climate classification [22], the city experiences a Mediterranean climate, with an average annual temperature of 18 °C and mean precipitation of about 600 mm, most of which occurs during winter. Algiers covers a total area of 774 km², of which 44.1% was classified as urban land in 2020 [23]. The city has undergone rapid demographic growth, with its population increasing from 1.6 million in 1987 to 2.6 million in 1998, and surpassing 3 million by 2008 [24].

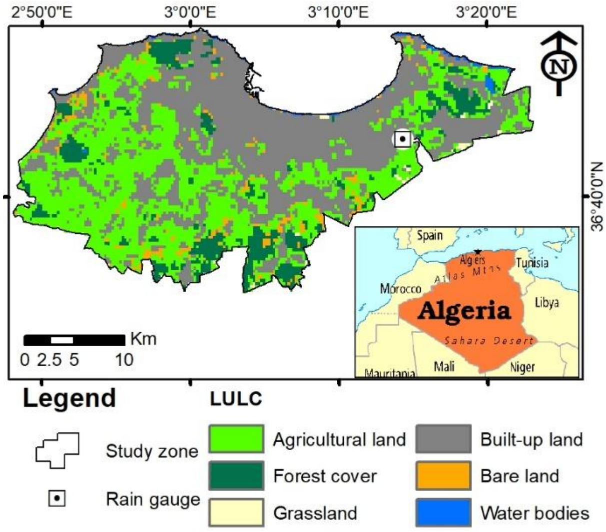

Fig. 1: Study zone location, land use map for 2022 [25] and rain gauge location

III. DATA AND METHODS

To better understand and evaluate how runoff responds to the impacts of climate change and urban development, this study applied the Soil Conservation Service–Curve Number (SCS-CN) model [26]. This method establishes a quantitative relationship between rainfall, land cover, soil type, and antecedent moisture conditions, therefore enabling reliable estimation of direct runoff. It is given by “(1)”.

$$Q = \max\left(0, \frac{(P-I_a)^2}{(P-I_a)+S}\right) \ \wedge \ I_a = \lambda S \ \wedge \ S = \frac{25400}{\mathrm{CN}} - 254 \quad (1)$$

where P [mm/day] denotes the precipitation, I_a [mm/day] refers to the initial abstraction, representing the portion of rainfall lost before the onset of runoff through processes such as vegetation interception, evaporation, depression storage, and initial infiltration. Q [mm/day] indicates the direct runoff. The parameter λ is a dimensionless coefficient typically set to 0.2, and S [mm/day] represents the potential maximum retention. The curve number (CN) is a dimensionless index that reflects the combined influence of soil type (Fig.2), land use/land cover, and hydrological conditions. CN values also vary according to antecedent moisture conditions (AMC), which are determined by the cumulative rainfall over the preceding five days. Three AMC classes are defined: AMC I (dry), AMC II (average), and AMC III (wet), as summarized in Table I.

Table. I
ANTECEDENT MOISTURE CONDITIONS CLASSIFICATION [26]

Class	Condition description	Total 5 days of antecedent rainfall	
		Dormant season	Growing season
AMC I	Dry condition	< 13 mm	< 36 mm
AMC II	Average condition	13 to 28 mm	36 to 53 mm
AMC III	Almost completely wet situation	> 28 mm	53 mm

In this study, two datasets were integrated to generate yearly CN2 maps (corresponding to AMC II) for the period 1992–2016. The first dataset consisted of land cover maps derived from the European Space Agency’s Climate Change Initiative Land Cover (CCI-LC) product [25]. With a spatial resolution of 300 m, the CCI-LC dataset offers a yearly consistent global coverage and is particularly suitable for long-term land use and land cover assessments. For this analysis, the original land cover classes were reclassified into six categories relevant to hydrological modeling: built-up land, agricultural land, forest cover, grassland, water bodies, and bare land (Fig.3). This reclassification enabled the detection of urban expansion and land use transitions over time, thereby facilitating the assessment of their effects on runoff dynamics in combination with climate variability. The second dataset was a hydrological soil group (HSG) map derived from the soil map (Fig.2). Based on these inputs, CN2 values were produced and subsequently used to compute and map CN1 (AMC I) and CN3 (AMC III) through equations “(2)” and “(3)”, respectively producing daily CN maps over the studied period.

$$\mathrm{CN1} = \frac{\mathrm{CN2}}{2.281 - 0.01281 \times \mathrm{CN2}} \quad (2)$$

$$\mathrm{CN3} = \frac{\mathrm{CN2}}{0.427 + 0.00573 \times \mathrm{CN2}} \quad (3)$$

In addition to land cover and soil data, meteorological inputs were incorporated into the analysis. Daily precipitation records were obtained from the Dar El-Beida rain gauge, situated within the study area (Fig.1) and managed by the National Water Resources Agency. The precipitation record used covers the period 1992–2016 and served as the primary climatic input for the quantitative estimation of runoff.

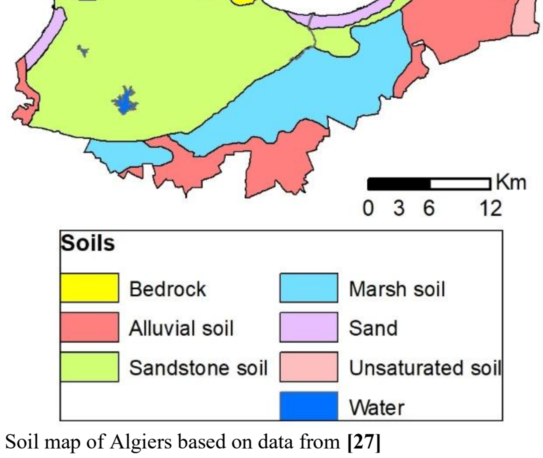

Fig. 2: Soil map of Algiers based on data from **[27]**

To investigate the potential impacts of changes in climatic conditions and urban development on runoff generation, three analytical scenarios were designed:

- Scenario 1: Combined effect (real system analysis). This scenario integrates both changes in climatic conditions and urbanization effects simultaneously, thereby representing the actual evolution of the system and allowing an evaluation of runoff response (Q) under real-world conditions.
- Scenario 2: Climate-only conditions (fixed urban extent). In order to isolate the role of climatic variability, LULC was held constant at its 1992 state, while only precipitation and climatic conditions were allowed to vary. This provides insights into the impact of the change in climatic conditions independently of urban expansion.
- Scenario 3: Urbanization-only settings (fixed climate conditions). Conversely, to assess the influence of urban development, climate conditions were fixed to those of the baseline year 1992, while urban expansion was allowed to vary. This isolates the hydrological impacts of urban growth from those of the climatic conditions.

IV. Results and discussion

The present study investigates the impacts of changes in climatic conditions and urbanization on runoff (combined and separated) at the city scale during the period 1992-2016. The analysis will be presented first in terms of urban development. (examining the spatiotemporal of land use and land cover (LULC) changes and patterns in the areas across the period 1992-2016), while the second analysis relies on the assessment of the precipitation variability during the same period. And finally, the evaluation of runoff quantity and response under three scenarios: (1) the combined effect of urbanization and changes in climatic conditions, (2) climate-only conditions, and (3) urbanization-only settings.

A. LULC spatiotemporal analysis

The spatiotemporal assessment of LULC between 1992 and 2016 (Fig.3-4) highlights pronounced urban expansion across the study area. Built-up areas more than doubled, rising from 19.86% to 41.48%, which corresponds to an average annual growth rate of +0.9%. Agricultural land exhibited the most significant decline, decreasing from 57.32% to 43.53% at a rate of –0.57% per year, indicating a substantial conversion of fertile land into urban surfaces. Grassland showed only a marginal reduction, decreasing from 1.11% to 0.5% (–0.03% annually). In contrast, forest cover registered a slight but steady gain, increasing from 8.66% to 9.77% (0.05% annually), which may reflect localized reforestation or conservation initiatives. Bare land, however, demonstrated considerable changes, dropping from 11.61% to 3.64% over the study period (-0.33% annually), possibly due to urban occupation or conversion into other land uses. Water bodies also declined slightly, from 1.44% to 1.08%.

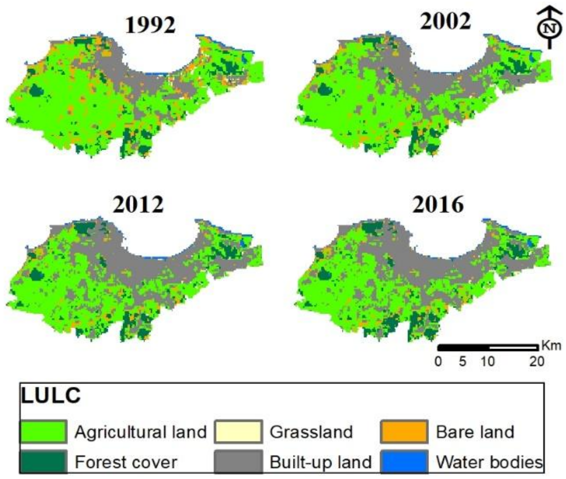

Fig. 3: LULC spatiotemporal evolution in Algiers during 1992-2022

Overall, the observed expansion of built-up areas has come largely at the expense of other vegetated classes, underscoring the intensity of urban growth and its transformative effect on the city fabric. This urban development results in increased pressure on natural resources (e.g., water), while also impacting the natural hydrological cycle by altering infiltration, groundwater recharge, and surface runoff, and elevating flood risks [28], [29], [30], [31], [23].

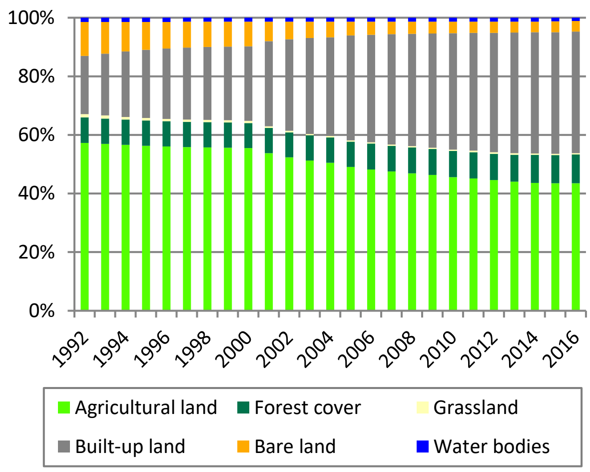

Fig. 4: Trend of LULC changes during 1992-2016.

B. *Temporal variability of precipitation and runoff at the city scale*

The precipitation regime during the studied period reflects a temporal variability (Fig. 5) closely oscillating around the long-term baseline (1992-2016) of 608.25 mm·y^{-1}. Moreover, the long-term polynomial trend remains nearly flat, with values during the mid-2000s that slightly exceed this baseline.

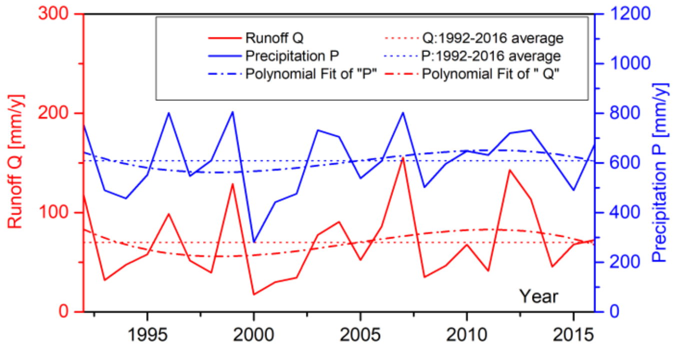

Fig. 5 precipitation variability and runoff patterns under real system scenario for Algiers during the period 1992-2016.

On the other hand, the runoff trend under the combined effects of changes in climatic conditions and urbanization (Fig. 5) exhibits more pronounced variability compared to the long-term baseline (1992-2016) runoff of 70.04 mm·y⁻¹. During the 1990s, the trend generally remained below the multiannual average. However, from the mid-2000s, the runoff values show an upward trajectory, gradually surpassing the long-term baseline. These findings suggest that climate variability (precipitation patterns) modulated the timing of peaks, but the continuing elevation of runoff, even during years of near-average precipitation, points to runoff response to urbanization, where the urban area increased. Similar findings were reported in other urban cities such as Bengaluru, known as the Silicone city of India [32], Robe town, Ethiopia [33], Beijing-Tianjin-Hebei, China [34].

A. Impacts of urbanization and changes in climatic conditions

To identify the dominant factor influencing runoff variability, a comparative analysis was performed under the real system scenario, examining the relationships of runoff with both precipitation and the proportion of urbanized area (Fig.6). The results demonstrate a strong linear relationship between precipitation and runoff (R^2 = 0.695), indicating that approximately 23.8% of rainfall was transformed into runoff during the period 1992–2016. In contrast, the correlation between runoff and urban area percentage was weak (R^2 = 0.023), suggesting that precipitation exerted far greater control on runoff dynamics than urban expansion. This highlights that, during the studied period, climate variability (particularly rainfall fluctuations) was the primary driver of runoff changes in the city.

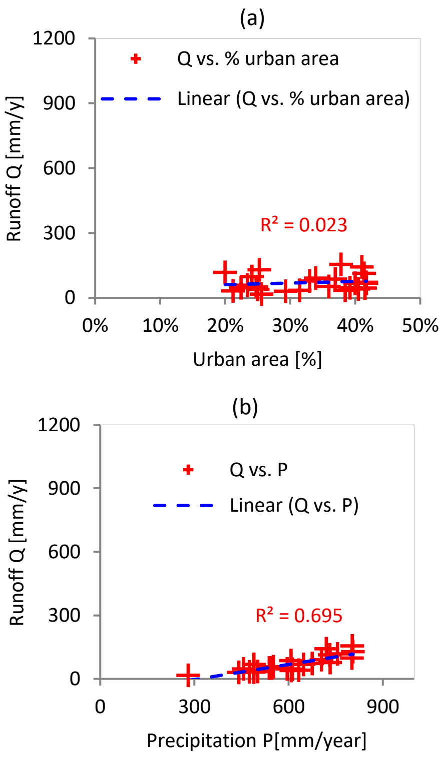

Fig. 6: Correlation between runoff under real system scenario and (a) the percentage of the urban area and (b) the precipitation.

The runoff response under urbanization-only effects (fixed climate conditions) demonstrates a gradual increase relative to the 1992 reference year (Fig.7). From 1992 to around 2000, the increase remained modest, reflecting the relatively slow rate of urban expansion during this period. However, beginning in the early 2000s, the urban-induced runoff effects became more pronounced, with a steady rise observed until 2016. This period coincides with accelerated urban growth in Algiers, which expanded impervious surfaces such as roads and buildings (this aspect was also reported by [35]), resulting in enhanced surface runoff. During 1992-2016, the urban area, with respect to 1992, expanded by +108.4%, which resulted in a +11.9% increase in runoff in 2016. Importantly, this effect persists regardless of precipitation variability, underscoring the structural modification of the city's capacity to regulate runoff. A similar trend was reported by [36], where a 10% increase in impervious surfaces resulted in a 12% rise in runoff.

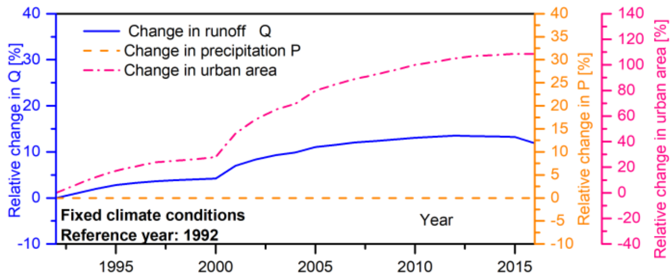

Fig. 7: Relative change (with respect to the year 1992) in precipitation, the urban area percentages and the runoff under a fixed climatic conditions scenario.

On the other hand, when only climatic influences are considered (with fixed urbanization settings at 1992 constants), runoff exhibits pronounced interannual variability that closely follows precipitation patterns (Fig.8). Relative change in precipitation fluctuates between –62.83% in 2000 and +6.55% in 1999, while relative change in the produced runoff ranges from –85.90% in 2000 to +19.63% in 2007. These findings highlight the hydrological system's (particularly runoff) heightened sensitivity to rainfall variability. This aspect was reported in recent studies [37], [38], [39], [40].

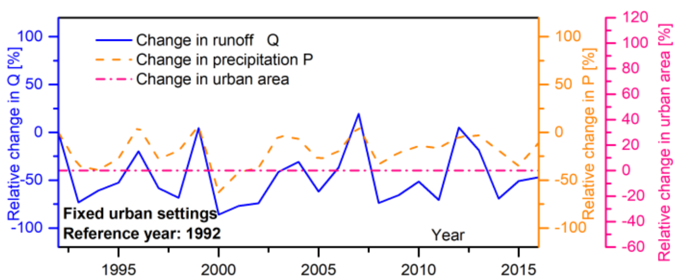

Fig. 8: Relative change (with respect to the year 1992) in precipitation, the urban area percentages and the runoff under a fixed urban settings scenario.

In terms of limitations, the following points summarize the main constraints of this study.

- This study used precipitation data from the Dar El-Beida station which offers the only long, daily, continuous, and quality-controlled rainfall record. However, it may not fully represent spatial rainfall variability across Algiers.
- The absence of continuous discharge records limited the ability to validate simulated runoff directly.
- The study relied on the CCI–LC products with a validated accuracy (approximately 75% globally, as reported by ESA [41]) and applied a standardized reclassification approach. This reclassification could not be verified against ground observations due to the lack of local survey data.

V. Conclusion

This study investigated the combined and individual impacts of changes in climatic conditions and urbanization on runoff generation in Algiers from 1992 to 2016, using the SCS-CN method. The spatiotemporal analysis of LULC during the period 1992-2016 indicates an increase in built-up areas from 19.86% to 41.48%, corresponding to an annual growth rate of +0.9%. This urban development was at the expense of other land cover, particularly the agricultural land (reduced from 57.32% to 43.53% at a yearly rate of –0.57%), leading to intensifying pressure on natural resources, altering hydrological cycles, and contributing to environmental degradation. The findings also reveal that precipitation is the dominant driver of interannual runoff variability, as reflected in the strong correlation ($R^2 = 0.695$) between rainfall and runoff, indicating that 23.8% of precipitation contributes to runoff during the study period. Nevertheless, the continuing upward shift in runoff relative to the long-term baseline, even during periods of near-average precipitation, highlights the role of urban expansion in structurally influencing the city's hydrological response. By 2016, urban areas had increased by +108.4% relative to 1992, resulting in an estimated +11.9% rise in runoff under urbanization-only conditions. The results also underscore that changes in climatic conditions amplify short-term fluctuations in runoff through influences on rainfall intensity, while urbanization contributes to a permanent change in the runoff regime by modifying infiltration and enhancing surface flows. Together, these drivers not only increase annual runoff but also elevate the risks of flooding and impact groundwater recharge, thereby intensifying pressure on urban water management systems.

Overall, this study indirectly demonstrates the importance of integrating land-use planning and climate adaptation strategies to mitigate hydrological risks in rapidly urbanizing Mediterranean cities. The methodology and findings provide a transferable framework for other regions facing similar challenges of balancing urban growth with climate adaptation. Future research should aim to couple SCS-CN modeling with advanced climate projections and nature-based solutions (such as green infrastructure to enhance infiltration and reduce runoff) to further explore pathways for sustainable water management.

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