

Assessing Hydrological Impacts of Land-Use and Land-Cover Change in Wadi Bani Malik, Saudi Arabia

Ali Albagshi and Ahmed Al-Areeq*

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ABSTRACT

Land-use and land-cover (LULC) changes substantially alter hydrological processes by modifying infiltration, surface runoff, and flow routing, particularly in rapidly urbanizing arid watersheds. This study evaluated the hydrological impacts of LULC changes in Wadi Bani Malik, Jeddah, Saudi Arabia using a scenario-based hydrologic modelling approach. Historical (1999) and recent (2024) LULC maps were integrated with rainfall, soil, and topographic data to simulate watershed responses using HEC-HMS under multiple design storm scenarios. Simulations quantified changes in peak discharge, runoff volume, and hydrograph characteristics under historical and recent LULC conditions. The results indicated that urban expansion between 1999 and 2024 increased the peak discharge and runoff volume across all return periods. For the 2-year return period, peak discharge increased by 21.4% and runoff volume increased by 12.8%; whereas for the 100-year return period, these increases were 5.0% and 10.5%, respectively. The results revealed a nonlinear hydrological response, with the relative impact of LULC change being more pronounced for frequent, lower-magnitude storms than for extreme events.

Keywords: land-use change, hydrologic modelling, urbanization, flood risk

1. INTRODUCTION

1.1. Research Background. Land-use and land-cover (LULC) changes, particularly rapid urban expansion, can substantially alter watershed hydrology by increasing imperviousness, reducing infiltration, and accelerating surface runoff^{1,2}. These changes produce flashier hydrographs, higher peak discharges, and greater runoff volumes, especially where rainfall is highly variable, and catchment responses are sensitive to spatial heterogeneity³.

1.2. Literature Review and Research Gap. Previous studies have shown that urbanization increases runoff generation and peak discharge across a wide range of climatic and geomorphological settings⁴. Hydrologic modelling approaches, particularly HEC-HMS coupled with the Soil Conservation Service Curve Number (SCS-CN) method, have been widely applied to quantify the effects of LULC change on watershed response⁵. In Jeddah and other arid regions, flood behavior is strongly influenced by topography, drainage network characteristics, and rainfall intensity, while accurate terrain representation and rainfall inputs are essential for reliable hydrologic modelling^{6–13}.

However, a key limitation of previous studies is that the impact of LULC change is often evaluated in absolute terms without systematically examining the way in which its relative influence varies across different storm magnitudes. In arid environments where infiltration–excess overland flow dominates during intense

rainfall, the sensitivity of the runoff response to the land-surface characteristics may diminish as the storm intensity increases. Despite its importance, this nonlinear behavior has not been sufficiently quantified in urban wadi systems.

1.3. Research Contributions. This study investigates how hydrological sensitivity to LULC changes varies across storm return periods in Wadi Bani Malik, a rapidly urbanizing watershed in Jeddah. Using LULC data for 1999–2024 under a consistent HEC-HMS modeling framework, the study evaluates changes in peak discharge, runoff volume, and hydrograph characteristics for return periods ranging from 2 to 100 years. By integrating remote sensing, rainfall frequency analysis, and hydrologic modelling, the study provides practical insights for stormwater management and flood mitigation in rapidly urbanizing arid watersheds.

1.4. Research Objectives. This study aimed to assess the hydrological impacts of LULC change on the rainfall–runoff response in Wadi Bani Malik. The specific objectives were to: (1) quantify LULC transitions between 1999 and 2024 using Landsat; (2) develop hydrologic model inputs based on LULC, soil, and rainfall data; (3) simulate and compare runoff responses under historical and recent LULC conditions across multiple return periods; and (4) evaluate the way in which the sensitivity of the hydrological response to LULC change varied with storm magnitude.

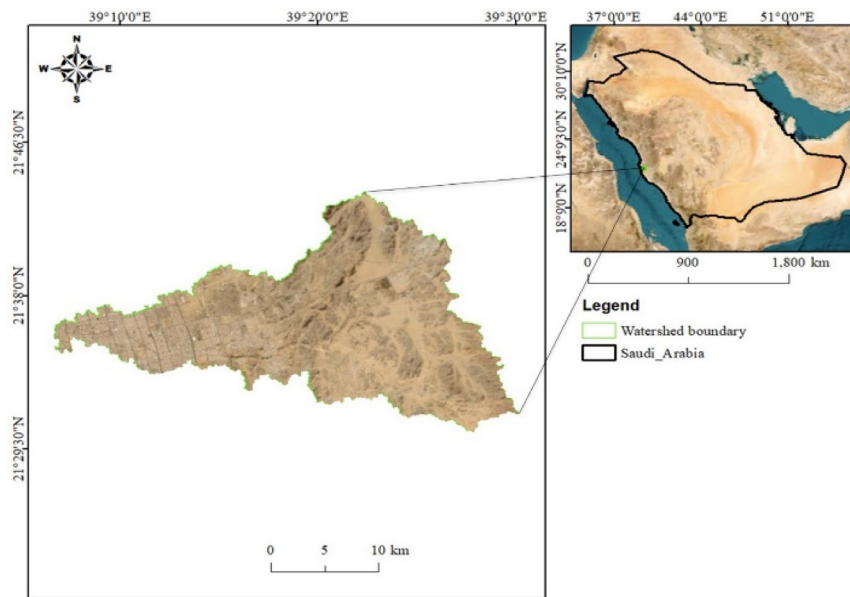


Figure 1. Study region (Wadi Bani Malik, Jeddah, Saudi Arabia)

2. STUDY AREA

This study focused on the Wadi Bani Malik watershed in eastern Jeddah, western Saudi Arabia (Figure 1). The watershed extends between 21°30'N–21°42'N latitude and 39°7'30"E–39°30'E, covering approximately 1,821 km², based on 30-m resolution Shuttle Radar Topography Mission (SRTM) digital elevation model. The terrain consists of mountainous uplands in the east, reaching elevations of approximately 675 m, and a low-lying coastal plain along the Red Sea. This topographic gradient directs runoff toward the urbanized coastal area of Jeddah, increasing flood susceptibility during intense rainfall events.

Jeddah has experienced rapid urban expansion over recent decades, driven by population growth and infrastructure development. Urban growth has extended into natural wadi systems, including Wadi Bani Malik, increasing impervious surfaces, modifying natural drainage pathways, and reducing infiltration capacity within the watershed¹⁴. Jeddah has an arid climate characterized by low annual rainfall, high temperatures, and strong interannual rainfall variability. Most rainfall occurs between November and April as short-duration, high-intensity convective storms that frequently generate flash floods^{15–17}. The watershed is dominated by ephemeral drainage channels that remain dry for most of the year but convey substantial runoff during extreme rainfall events.

Major flood events in 2009 and 2011 demonstrated the vulnerability of Jeddah to flash flooding, resulting in substantial loss of life and widespread damage to infrastructure^{15,18}. In Wadi Bani Malik, rapid urban expansion between 1999 and 2024 increased impervious surfaces and altered natural drainage pathways, further increasing flood susceptibility¹⁹. These climatic and anthropogenic factors make the watershed an appropriate case study for evaluating the hydrological impacts of LULC change.

3. DATA AND METHODS

3.1. Data Collection and Preprocessing. Four primary datasets were used: (i) Landsat imagery for LULC classification,

(ii) hydrologic soil group (HSG) data, (iii) rainfall records from the J134 gauge station, and (iv) a 30-m SRTM digital elevation model (DEM). All datasets were projected to a common coordinate system and processed within a GIS environment to ensure spatial consistency. The overall methodological workflow is presented in Figure 2.

3.2. DEM and Watershed Delineation. The 30-m SRTM DEM was hydrologically conditioned using standard GIS procedures, including sink filling, flow direction, flow accumulation, and watershed delineation. Basin characteristics such as drainage area, slope, flow length, and stream networks were derived and used as inputs to the HEC-HMS model.

3.3. LULC Classification. LULC maps provide important insights into the spatial allocation of different land-use categories, including green areas, urban zones, roads, bare land, and water bodies. The maps were produced from Landsat 7 imagery (1999) and Landsat 8 imagery (2024) using advanced machine-learning classification procedures, including Maximum Likelihood classifiers, Random Trees, and Support Vector Machine (SVM). Training samples representing the main LULC classes were selected based on visual interpretation. The same training datasets were applied across all the three algorithms to ensure consistency and enable a reliable comparison of their performances. Each classification model was implemented independently in ArcMap. LULC areas are reported as both square kilometres (km²) and the percentage (%) of the total watershed area in Table 1.

The two LULC maps, illustrated in Figure 3, highlight significant LULC transformations in the watershed over the 25-year period. According to Table 1, urban areas increased markedly from 47.1 km² (10.5%) in 1999 to 65.0 km² (14.5%) in 2024. The road network expanded from 17.9 km² (4.0%) to 24.3 km² (5.4%), indicating a considerable growth in impervious surfaces. Green areas also increased by 82.9%, from 6.1 km² to 11.2 km², which largely reflected the landscaping efforts and planned vegetation associated with urban development. In contrast, bare land

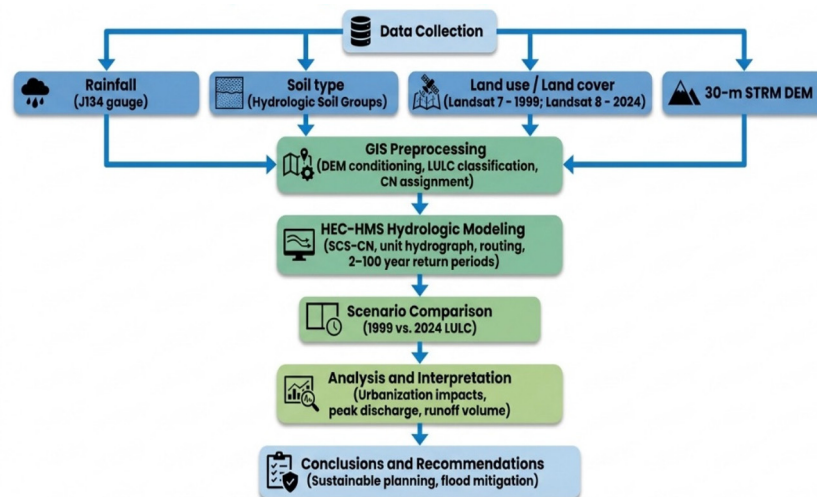


Figure 2. Methodological flowchart for runoff modeling and DEM-based comparison using SRTM data

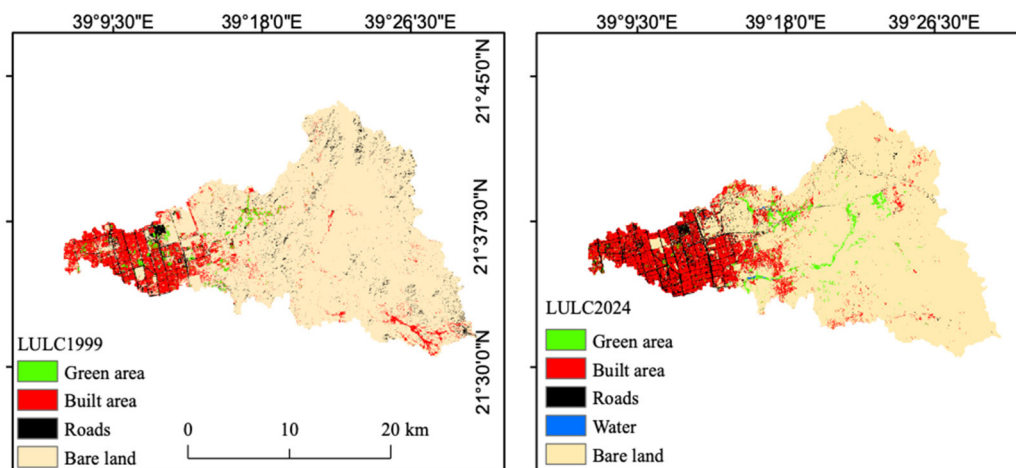


Figure 3. LULC maps of Wadi Bani Malik in 1999 and 2024

decreased by 7.9%, from 377.4 km² to 347.7 km², and water bodies, which were absent in 1999, covered 0.3 km² (0.07%) of the classified watershed by 2024. Although green areas also increased, the overall expansion of impervious surfaces indicates a greater potential for runoff generation and flood risk.

3.4. Soil and Infiltration Characteristics. Hydrologic soil group (HSG) data were used to characterize soil infiltration and runoff potential. The watershed is dominated by HSG C soils, indicating moderate to low infiltration capacity, with

smaller areas classified as HSG B, D, and C/D (Figure 4). These data were used to assign curve numbers (CNs) for HEC-HMS simulations.

3.5. Rainfall Analysis. Rainfall frequency analysis using the Log-Pearson Type III distribution was used to derive design rainfall for return periods of 2, 5, 10, 25, 50, and 100 years. The resulting IDF curves (Figure 5) provided rainfall inputs for the HEC-HMS simulations.

Table 1. LULC variations in the Wadi Bani Malik watershed between 1999 and 2024

LULC	2024 (km ²)	2024 (%)	1999 (km ²)	1999 (%)	Difference (%)
Green area	11.21	2.5	6.13	1.37	82.9
Urban	65	14.49	47.1	10.5	38
Roads	24.3	5.42	17.9	3.99	35.8
Bare land	347.7	77.53	377.4	84.15	-7.9
Water	0.3	0.07	0	0	New class ^a
Total	448.51	100	448.53	100	—

^aWater bodies were absent in 1999; percentage change is not applicable as this was established as a new land-cover class in 2024.

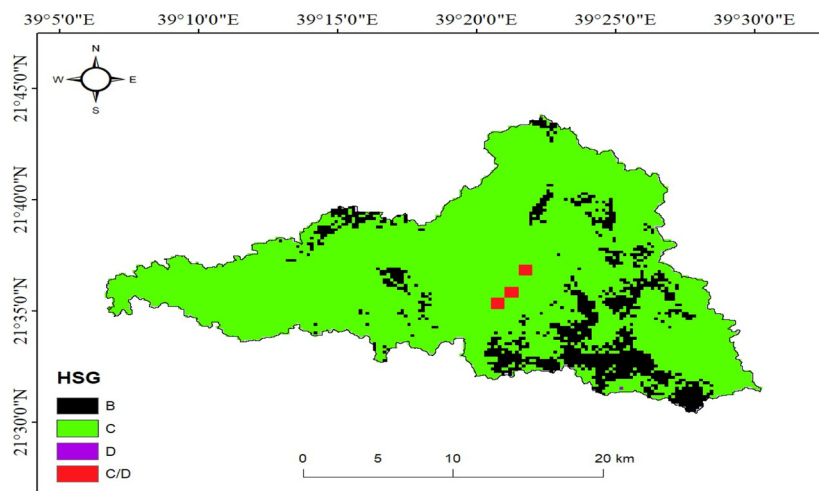


Figure 4. Soil group distribution of Wadi Bani Malik, Jeddah, Saudi Arabia

3.6. Hydrologic Modelling (HEC-HMS) and Model Setup. Rainfall–runoff simulations were performed using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS), which was configured to evaluate the hydrological response of Wadi Bani Malik under the 1999 and 2024 LULC scenarios. Runoff losses were estimated using the Soil Conservation Service Curve Number (SCS-CN) method, runoff transformation was performed using the SCS dimensionless unit hydrograph, and channel routing was simulated using the Muskingum method²⁰. The runoff depth was estimated using the SCS-CN method as follows:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}, \text{ for } P > 0.2S, \quad (1)$$

$$Q = 0, \text{ for } P \leq 0.2S, \text{ and} \quad (2)$$

$$S = \frac{25400}{CN} - 254 \quad (3)$$

where Q is runoff depth; P is rainfall depth; S is potential maximum retention; and CN is the curve number (dimensionless).

Curve numbers (CNs) were assigned to each LULC–soil group combination using the standard NRCS TR-55 tables (USDA, 1986). Urban areas, roads, green areas, bare land, and water bodies were classified according to the corresponding NRCS land-use categories (Table 2). Area-weighted composite

CN values were then calculated by overlaying the LULC and HSG layers in GIS and imported into HEC-HMS for the 1999 and 2024 scenarios.

The resulting CNs were then inputted into the HEC-HMS model for each LULC scenario (1999 and 2024). Excess rainfall was transformed into runoff hydrographs using a SCS dimensionless unit hydrograph.

$$T_p = \frac{d}{2} + T_l \quad (4)$$

$$Q_p = \frac{0.208A}{T_p} \quad (5)$$

$$T_l = 0.6T_c \quad (6)$$

Here, A is the sub-basin area (km^2), and T_l is the basin lag time. T_c is the time of concentration. Channel routing was performed using the Muskingum method. The routing parameter K was estimated from the reach length and average wave celerity for each stream reach, while the weighting factor X was fixed at 0.2, which is commonly adopted for ephemeral wadi channels with predominantly diffusive flow conditions.

4. RESULTS AND DISCUSSION

4.1. Hydrograph Response and Simulation Results.

Using the 24-h rainfall depths, design storms were generated for use in the HEC-HMS for the two LULC scenarios (1999 and 2024). The resulting hydrographs at the outlet for 2 year and 100-year return periods are shown in Figures 6a and 6b, respectively. In each case, the 2024 scenario produces a steeper rising limb, earlier time to peak, and higher peak discharge than the 1999 scenario, reflecting increased imperviousness and reduced infiltration capacity after urban expansion.

Consistent trends are evident across the return periods. As summarized in Table 3, for the 2-year event, the peak discharge increases from $36 \text{ m}^3/\text{s}$ in 1999 to $43.7 \text{ m}^3/\text{s}$ in 2024, and the runoff volume increases from $1.121 \times 10^6 \text{ m}^3$ to $1.2645 \times 10^6 \text{ m}^3$, equivalent to an increase of 21.4% and 12.8%, respectively. For the 100-year event, the peak discharge increases from $904 \text{ m}^3/\text{s}$

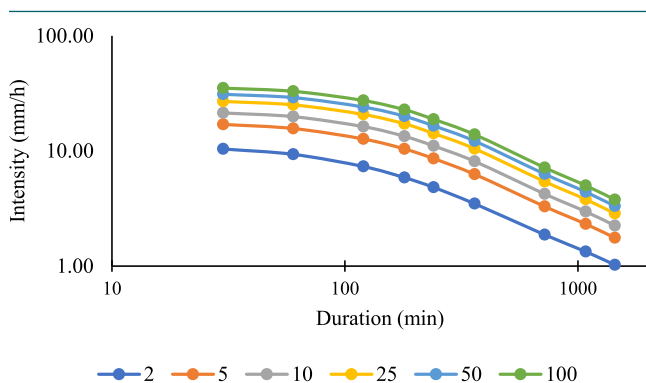
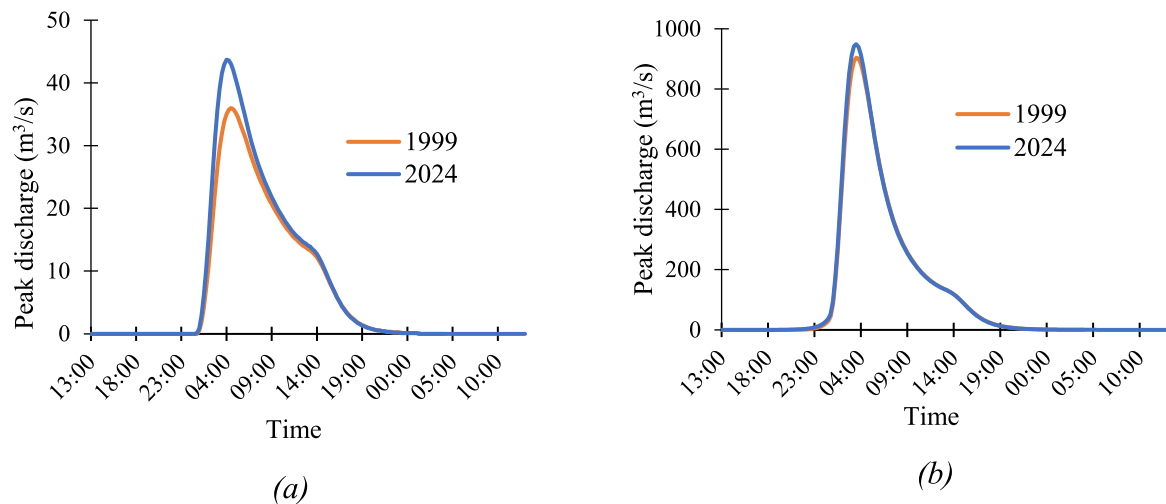


Figure 5. IDF curves for Wadi Bani Malik developed from the DDF analysis

Table 2. CNs assigned by LULC class and HSG based on NRCS TR-55 reference tables

LULC class	HSG B	HSG C	HSG C/D	HSG D
Urban	85	90	92	95
Roads	89	92	93	98
Green area	69	79	82	84
Bare land	72	82	85	87
Water	100	100	100	100

**Figure 6.** Comparison of outflow for (a) the 2-year return period and (b) the 100-year return period in 1999 and 2024

to 949 m³/s and runoff volume increases from 1.88145×10^7 m³ to 2.07936×10^7 m³, corresponding to increases of 5.0% and 10.5%, respectively. Intermediate return periods (5–50 years) showed a similar behavior.

The decreasing percentage increase in the peak discharge at higher return periods reflects nonlinear runoff response behavior. Under extreme rainfall conditions, the infiltration capacity was exceeded in both scenarios, reducing the proportional difference between the pre- and post-urban conditions. This pattern is consistent with findings reported in comparable urbanizing watersheds, where the relative sensitivity of flood peaks to land-use change diminished as the storm magnitude increased^{21,22}. Overall, the simulations demonstrated that LULC changes between 1999 and 2024 amplified the flood response in Wadi Bani Malik, producing larger and earlier peaks and greater runoff volumes across all designed storms, consistent with recent hydrological modeling studies linking impervious surface expansion to increased runoff generation^{23,24}.

4.2. Model Uncertainty and Limitations. The hydrological simulations presented in this study were subject to

uncertainties associated with the model structure and parameter selection. In particular, the SCS-CN method is sensitive to parameter values and assumes spatially homogeneous soil and land-surface conditions within each subbasin. Variations in CNs, soil classification, and land-use representation can influence the magnitude of the simulated runoff and peak discharge. Formal sensitivity or uncertainty analyses were not performed in this study; therefore, the absolute values of the peak discharge and runoff volume should be interpreted with caution. However, the primary objective of this study was to evaluate the relative impact of LULC change using a consistent scenario-based modelling framework. Comparative differences between scenarios were considered robust because both the 1999 and 2024 simulations were conducted using identical model structures, parameters, and assumptions.

Additional sources of uncertainty included potential classification errors in LULC mapping, assumptions of stationarity in rainfall frequency analysis, and limitations in representing the spatial variability in rainfall and infiltration processes. Future research should incorporate sensitivity analysis, model calibration using

Table 3. HEC-HMS simulation results for peak discharge (*Q*) and runoff volume (*V*) under 24-h design storms

Return period (year)		2	5	10	25	50	100
1999	Q (m ³ /s)	36	189.1	335	548.8	722	904
	V (m ³) (1000)	1121.1	4795.4	8038.1	12703.1	16456.6	18814.5
2024	Q (m ³ /s)	43.7	208.4	360.1	582.7	762.5	949
	V (m ³) (1000)	1264.5	5053.5	8353.5	13075.4	16862.8	20793.6
Difference (%)	Q	21.4	10.2	7.5	6.2	5.6	5
	V	12.8	5.4	3.9	2.9	2.5	10.5

observed discharge data, and uncertainty quantification to further improve the reliability of hydrological predictions. Despite these limitations, the results provide meaningful insights into the way in which urbanization influenced hydrological response patterns, particularly in terms of relative changes across storm magnitudes.

5. CONCLUSION AND RECOMMENDATIONS

Urban expansion between 1999 and 2024 increased peak discharge and runoff volume for all simulated storm events, with the largest relative increases occurring during frequent, lower-magnitude storms. These findings demonstrate that urbanization has increased flood susceptibility in Wadi Bani Malik by reducing infiltration and accelerating surface runoff. Although the scenario-based modelling framework ensured a robust comparative analysis, uncertainties remain owing to the assumptions inherent in the SCS-CN method, rainfall stationarity, and LULC classification accuracy. Therefore, the absolute discharge values should be interpreted with caution, although the relative differences between the scenarios are considered reliable. From a practical perspective, the results underscore the importance of incorporating evolving land-use conditions into hydrological assessments and stormwater infrastructure design. The heightened sensitivity of moderate storm events suggested that urbanization may increase flood frequency, even without changes in the extreme rainfall magnitude.

Integrated watershed management strategies are required flood resilience. These include the adoption of green infrastructure (e.g., permeable pavements, detention systems, and vegetated swales), protection of natural drainage pathways, and incorporation of future land-use scenarios into hydrologic and hydraulic modelling. Strengthening rainfall and discharge monitoring networks is essential for improving forecasting and early warning systems. Future research should focus on incorporating non-stationary rainfall analysis, climate change projections, and physically based distributed models, along with field-based calibration and uncertainty quantification, to improve the predictive capability under changing environmental conditions.

AFFILIATIONS AND AUTHOR DETAILS

Undergraduate Author

Ali Albagshi – Department of Civil and Environmental Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia; 0009-0006-1167-722X
Email: s202159450@kfupm.edu.sa

Corresponding Author

Ahmed Al-Areeq – Research Mentor, Assistant Professor, Civil and Environmental Engineering Department & Interdisciplinary Research Center for Membranes and Water Security, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia; 0000-0003-0618-8190
Email: ahmed.areeq@kfupm.edu.sa

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