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RESEARCH ARTICLE

HYDROLOGICAL AND HYDRAULIC MODELING FOR FLOOD RISK ASSESSMENT IN WADI YESHBUM- SHABWA GOVERNORATE, IN YEMEN

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Abstract

Flash floods in arid regions pose severe threats to life and infrastructure, yet quantitative hydrological data are frequently absent. This study presents the first hydrologic model for the ungauged Wadi Yeshbum basin (337.48 km²) in Shabwah Governorate, Yemen, using the HEC-HMS model within a GIS framework. Morphometric parameters were derived from a 30 m SRTM DEM, revealing a steep average slope (10.5%), a well-developed drainage network (drainage density 1.8 km/km²), and a short time of concentration (4.38 h). The spatially distributed curve number (CN) was computed from FAO soil data and ESA CCI land cover, yielding a weighted average of 83, indicative of high runoff potential. Historical daily rainfall (1994–2024) from CHIRPS was used to fit the Gumbel distribution; 24-h design storms for return periods of 20, 50, and 100 years were estimated as 34.3, 40.5, and 44.9 mm, respectively. The SCS unit hydrograph method was applied to transform excess rainfall into direct runoff. Simulated peak discharges were 733.8, 867.5, and 963.7 m³/s with corresponding runoff volumes of 8.88, 11.72, and 13.03 million m³. Because no observed streamflow data were available for calibration, a generalized likelihood uncertainty estimation (GLUE) based on 500 Monte Carlo runs gave a 95% confidence interval for the 100-year peak discharge of 712.7–1177.7 m³/s. Sensitivity analysis revealed that peak discharge is highly sensitive to CN (coefficient 3–4) and moderately sensitive to the time of concentration (coefficient ~0.7–1.0). The results demonstrate that the basin exhibits a rapid, flashy hydrological response and that a large fraction (77–86%) of extreme rainfall becomes direct runoff. The modeling framework is transferable to other data-scarce arid basins and provides quantitative baseline information for flood mitigation planning in Yemen, though all results should be considered uncalibrated screening-level estimates.

Keywords: Hydrologic modeling; Hydraulic modeling; Ungauged basins; Flood mitigation; Runoff estimation; Wadi Yeshbum; Yemen.

1. Introduction

Flash floods are among the most destructive natural hazards worldwide [1,2,3,4] responsible for approximately one-third of all natural disaster fatalities [5,6] In arid and semi-arid regions, short-duration, high-intensity rainfall over dry [7], low-permeability catchments generates rapid, violent surface runoff. [8] Yemen, located on the southern Arabian Peninsula, is exceptionally vulnerable to flash floods because of its rugged topography and the concentration of rainfall in a few intense events. The country has experienced several devastating floods, including the 2008 Hadramout event that caused extensive damage to infrastructure, agriculture, and livelihoods [3,7]. Yet, Yemen suffers from a severe lack of hydrometric stations, reliable precipitation records, and field access, making conventional hydrological analysis extremely difficult.

Hydrological models driven, by remote sensing and global datasets have become indispensable tools in ungauged basins. The Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS) [1,2,9] is widely used to simulate rainfall-runoff processes. Its physically based parameters, combined with the Soil Conservation Service curve number (SCS-CN) method (USDA SCS, 1985) [10], allow for credible runoff estimation even without observed streamflow data. Numerous applications in arid environments have demonstrated the utility of this approach. For example, modelled Wadi Safaga [11] in Egypt and estimated a

100-year peak discharge of 698.4 m³/s for a 301 km² basin. applied HEC-HMS to [12] Wadi Aseer in Saudi Arabia (280 km²) and reported a 100-year peak of 280 m³/s, while analysed [13] the Khazir River in northern Iraq (1400 km²) obtaining peaks between 10.4 and 66.4 m³/s.

Despite the growing international literature, no peer-reviewed hydrologic modelling study has been conducted for any Yemeni basin. The Wadi Yeshbum catchment in Shabwah Governorate exemplifies this gap: it is repeatedly affected by flash floods that threaten downstream villages, roads, and agricultural areas, yet no quantitative flood assessment exists. This study aims to fill that gap by developing the first integrated hydrological model for Wadi Yeshbum using HEC-HMS within a GIS environment. The specific objectives are: (1) to extract morphometric parameters from a digital elevation model; (2) to determine the spatially distributed curve number based on soil and land cover maps; (3) to simulate surface runoff for design storms with 20-, 50-, and 100-year return periods; and (4) to quantify the sensitivity and uncertainty of the simulated peak discharges.

2. Study Area

Wadi Yeshbum is an ephemeral stream system situated in Shabwah Governorate, southeastern Yemen, approximately between latitudes 14°45′ N and 15°10′ N and longitudes 46°30′ E and 47°00′ E. The basin drains from the northern highlands southward toward the desert plains, with its outlet near the village of Yeshbum (Fig. 1). The drainage area covers 337.48 km², and the main channel length is 42.7 km. Elevations range from 929 m a.s.l. at the outlet to 1975 m in the upstream mountains, yielding a total relief of 1046 m and an average slope of 10.5%. The time of concentration, estimated using the Kirpich equation [14], is 4.38 h, which reflects the steep terrain and rapid runoff response. The form factor is 0.18, indicating an elongated shape that tends to produce somewhat lower peak flows than circular basins of similar area [15].

The climate is arid, with hot summers (mean July temperature ~32°C) and mild winters (mean January ~18°C). Mean annual rainfall for the period 1994–2024 is 125.3 mm, concentrated in two brief rainy seasons: March–May and July–September. The interannual variability is high (coefficient of variation ≈ 0.36). Potential evaporation exceeds 2500 mm/year.

According to the FAO Digital Soil Map of the World and ESA CCI [16] Land Cover data for 2020 [17] the basin is dominated by bare areas (62.6%) and sparse grassland/shrubland (25.6%); watercourses and scattered settlements account for 6.7% and 5.2%, respectively. The dominant soil types are Lithosols and Regosols in the highlands and Aridisols in the plains. Hydrologic soil groups (HSG) are predominantly C and D, signifying low infiltration capacity and high runoff generation potential.

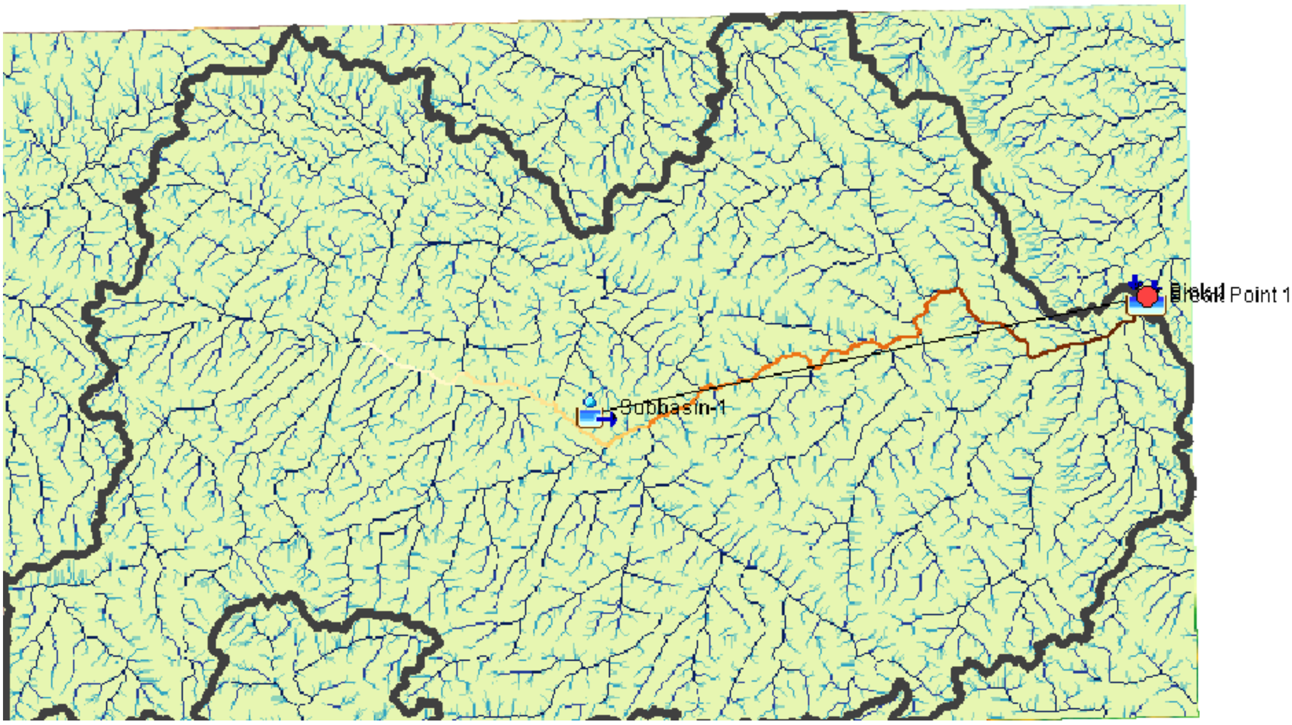

Fig. 1: Location map of Wadi Yeshbum basin, Shabwah Governorate, Yemen.

3. Data and Methods

3.1 Data Sources and Pre-processing

A 30 m Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) was downloaded from the USGS Earth Explorer. The DEM was processed in ArcGIS 10.8 with the HEC-GeoHMS 10.2 extension to delineate the basin boundary [1,2], extract the stream network, and compute morphometric parameters.

Daily rainfall data for the historical period 1994–2024 were obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) [18] via the Google Earth Engine and Climate Engine [19,20] platforms. Annual maximum 24 h rainfall series were extracted and used for frequency analysis.

Soil information was derived from the FAO Digital Soil Map (version 1.2) and land cover from the European Space Agency Climate Change Initiative [17] Land Cover product (300 m resolution, 2020). Both layers were reclassified to assign hydrologic soil groups and land cover classes for CN determination.

3.2 Design Storm Estimation

The annual maximum 24 h rainfall series was fitted to the Gumbel distribution using the method of moments. The quantiles for return periods of 20, 50, and 100 years were then computed to obtain design storm depths. The 24 h rainfall was temporally distributed using the SCS Type II dimensionless hydrograph. While this distribution was developed primarily for the United States, it has been widely adopted in arid region studies due to the absence of local intensity-duration-frequency (IDF) relationships. Its use here is justified by the similarity in storm characteristics—short, intense convective events—common to both the US Midwest and arid Arabian Peninsula environments. Nevertheless, future development of local IDF curves would improve the temporal distribution of design storms

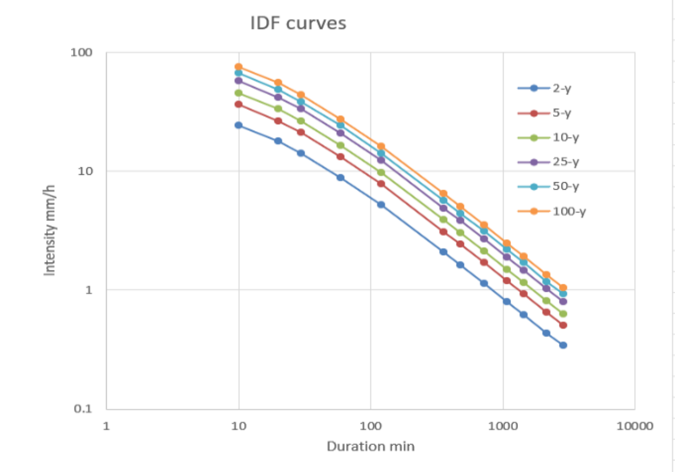

Fig. 2: SCS Type II dimensionless hydrograph for 24-hour design storm distribution.

3.3 Curve Number Estimation

A grid-based curve number map was created by intersecting the HSG map with the land cover map (Fig. 3). CN values for each combination were taken from standard SCS tables [10] for arid environments (USDA SCS, 1985) under average antecedent moisture condition (AMC II). The area-weighted CN for the whole basin was calculated, and the resulting value of 83 was used in the lumped HEC-HMS model [21].

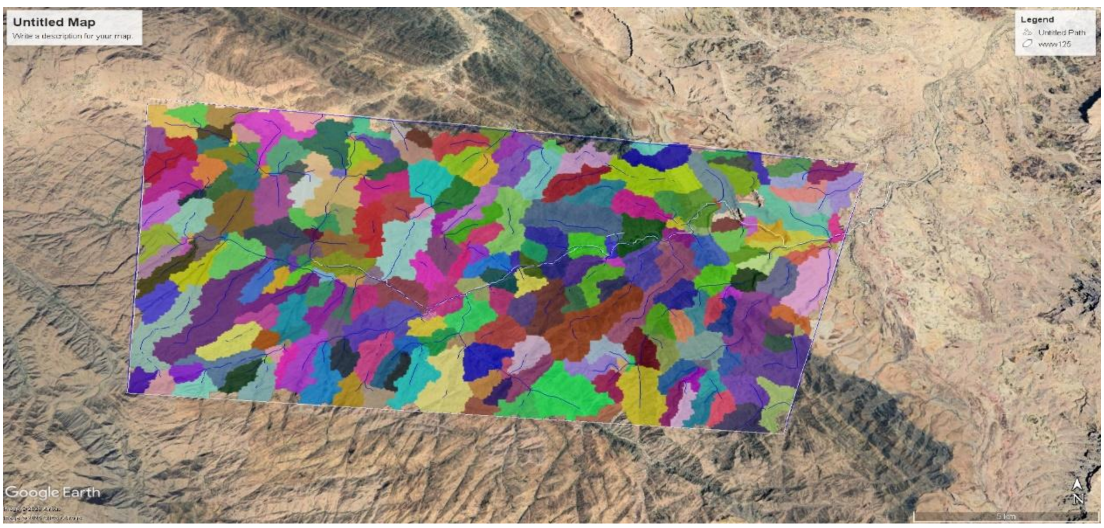

Fig. 3: Spatial distribution of Curve Number (CN) for Wadi Yeshbum basin.

3.4 HEC-HMS Model Setup

The basin was represented as a single sub-basin with an outlet at the downstream end. This lumped approach was adopted due to the absence of distributed rainfall and flow data; however, it may oversimplify runoff routing processes, particularly in the main channel. The following methods were selected in HEC-HMS 4.8:

Loss method: SCS Curve Number (CN = 83)
Transform method: SCS Unit Hydrograph. The lag time was taken as 0.6 × Tc = 2.63 h
Baseflow: None, given that the wadi is ephemeral
Routing: Not applied in this lumped configuration

Simulations were run for each design storm (20-, 50-, and 100-year) using a 5-min computational time step. Peak discharge (Qp) and total runoff volume were extracted

3.5 Sensitivity and Uncertainty Analyses

Sensitivity of the peak discharge to CN and Tc was assessed by varying each parameter by ±5% and ±10% from its base value while keeping others constant. The sensitivity coefficient was defined as the ratio of percentage change in Qp to percentage change in the parameter.

Because no observed streamflow data exist for formal calibration, parameter uncertainty was quantified using the Beven&Binley1992 (GLUE) framework [22,23]. A Monte Carlo sampling of 500 parameter sets was performed, with CN uniformly drawn from 75–91 and Tc from 3.5–5.3 h. For each set the 100-year design storm was simulated, and the distribution of the resulting Qp was used to construct the 95% confidence interval

4. Results

4.1 Morphometric Characteristics

Table 1 summarises the main morphometric features of Wadi Yeshbum. The basin’s size, steepness, and well-developed drainage network confirm its flash-flood potential.

Table 1: Morphometric parameters of Wadi Yeshbum basin.

Parameter	Symbol	Value	Unit
Basin area	A	337.48	km²
Basin perimeter	P	115	km
Maximum elevation	Hmax	1975	m
Minimum elevation	Hmin	929	m
Average slope	S	10.5	%
Main channel length	L	42.7	km
Drainage density	Dd	1.8	km/km²
Time of concentration	Tc	4.38	h
Lag time	Tlag	2.63	h
Form factor	Rf	0.18	–

4.2 Design Rainfall Depths

The Gumbel-derived 24-h rainfall depths for the selected return periods are shown in Table 2

Table 2: Design 24-h rainfall depths for Wadi Yeshbum.

Return period (years)	Rainfall depth (mm)	95% confidence interval (mm)
20	34.3	41.2 – 28.6
50	40.5	49.7 – 33.1
100	44.9	44.9 ± 18.5

4.3 Curve Number Mapping

The area-weighted CN was determined as 83 (Table 3 and Fig. 2), reflecting the prevalence of low-infiltration soils and sparse vegetation. The high proportion of HSG-D soils under bare land and watercourses (together 69.3% of the area) drives the elevated runoff potential.

Table 3: Curve number (AMC II) by land cover and hydrologic soil group.

Land cover class	HSG	Area (km²)	% Area	CN
Bare areas	D	211.26	62.6	85
Sparse grassland/shrubland	C	86.39	25.6	78
Watercourses	D	22.61	6.7	92
Scattered settlements	C	17.54	5.2	75
Total		337.48	100	83 (weighted)

4.4 Runoff Simulation

Table 4 presents the simulated [10] peak discharges, runoff volumes, and runoff coefficients (Cr = runoff volume / (area × rainfall depth)) for each return period. The 100-year event generates a peak of 963.7 m³/s and a total runoff volume of 13.03 million m³ with 86% of the rainfall converted into direct runoff. The runoff coefficient increases from 0.77 at the 20-year event to 0.86 at the 50- and 100-year events, indicating that nearly all additional rainfall becomes runoff once the initial abstraction is exceeded. While these values are high, they are consistent with the basin's characteristics: steep slopes (10.5%), low-permeability soils (predominantly HSG C and D), sparse vegetation cover (62.6% bare areas), and the SCS-CN method's inherent assumption that runoff increases nonlinearly with rainfall depth. Similar runoff coefficients (0.75–0.85) have been reported for other arid basins [11,12] with comparable physical characteristics

Table 4: Simulated peak discharge, runoff volume, and runoff coefficient.

Return period (yr)	Rainfall depth (mm)	Peak discharge (m^3/s)	Runoff volume (10^6 m^3)	Runoff coefficient (Cr)
20	34.3	733.8	8.88	0.77
50	40.5	867.5	11.72	0.86
100	44.9	963.7	13.03	0.86

The simulated hydrographs for all return periods are presented in Fig. 4, showing the rapid rise and recession characteristic of flash flood events in arid environments

4.5 Sensitivity Analysis

The sensitivity of the 100-year peak discharge to CN and Tc is displayed in Tables 5 and 6. The peak discharge is highly sensitive to CN: a ±10% change in CN results in a ±15–40% change in Qp, with sensitivity coefficients ranging from 3.08 to 3.97. The response to Tc is less pronounced but still notable; a ±10% change in Tc produces a ∓7–20% change in Qp, with sensitivity coefficients of 0.7–. The negative sign indicates that a longer Tc (i.e., slower concentration) reduces the peak

The Equation for the Sensitivity Coefficient is

$$S = \frac{\Delta Q_p / Q_{p,base}}{\Delta P / P_{base}}$$

Table 5: Sensitivity of 100-year peak discharge to CN.

CN	Peak discharge (m^3/s)	Change in Q_p (%)	Sensitivity coefficient
74.7 (−10%)	666.9	−30.8	3.08
78.9 (−5%)	815.3	−15.4	3.08
83 (base)	963.7	–	–
87.2 (+5%)	1139.1	+18.2	3.64
91.3 (+10%)	1346.3	+39.7	3.97

Table 6: Sensitivity of 100-year peak discharge to Tc.

Tc (h)	Peak discharge (m^3/s)	Change in Q_p (%)	Sensitivity coefficient
5.04 (+20%)	824.9	−14.4	0.72
4.62 (+10%)	895.2	−7.1	0.71
4.20 (base)	963.7	–	–
3.78 (−10%)	1050.4	+9.0	0.90
3.36 (−20%)	1154.5	+19.8	0.99

4.6 Uncertainty Analysis (GLUE)

The GLUE analysis produced a 95% confidence interval for the 100-year peak discharge of 712.71177.7 m^3/s, with a mean of 945.2 m^3/s and a median of 962.5 m^3/s. The coefficient of variation (CV = 0.125) indicates a moderate spread, confirming that while the median estimate is robust, parameter uncertainty can influence the result by approximately ±20% around the base value

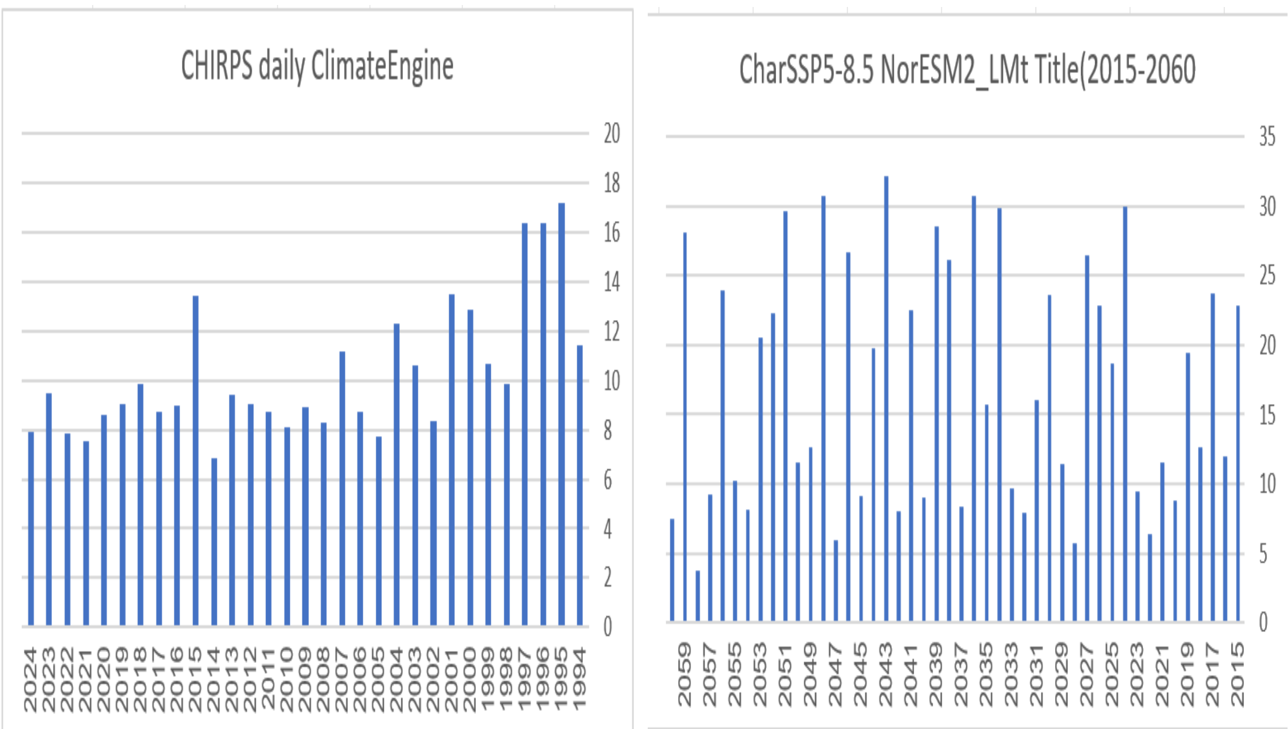

Fig. 4: Simulated flood hydrographs for 20-, 50-, and 100-year return periods (showing rapid rise and recession typical of arid flash floods).

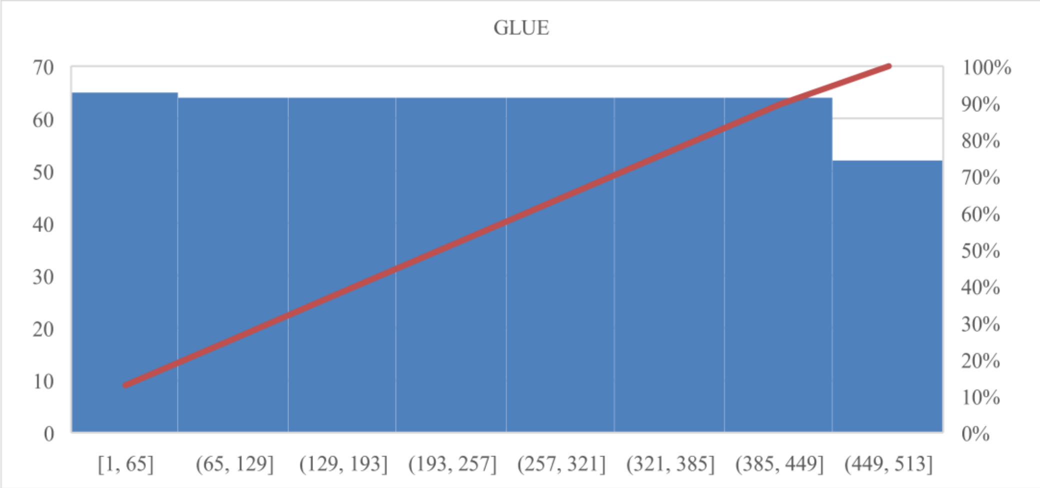

Fig. 5: Generalized Likelihood Uncertainty Estimation (GLUE) results for the 100-year peak discharge, showing the 95% confidence interval (712.7 – 1177.7 m³/s).

Table 7: Comparison of flood estimates in selected arid basins (100-year event).

Study	Basin	Area (km²)	Q_p (m³/s)	Runoff volume (10⁶ m³)
This study	Wadi Yeshbum, Yemen	337.48	963.7	13.03
Abuzeid et al. (2025)	Wadi Safaga, Egypt	301	698.4	12.29
Youssef et al. (2022)	Wadi Aseer, Saudi Arabia	280	280	10.5
Khaleel et al. (2022)	Khazir River, Iraq	1400	66.4	2.23

5. Discussion

5.1 Flood Generation Potential

The high weighted CN (83) coupled with the steep terrain (10.5% slope) and short concentration time (4.38 h) explains the flashy nature of floods in Wadi Yeshbum. The SCS method indicates that once the initial abstraction (about 8 mm for CN 83) is met, a large proportion of additional rainfall becomes direct runoff. Consequently, the 100-year storm produces a runoff coefficient of 0.86, meaning that infrastructure downstream must be designed to convey almost the entire storm volume. The peak discharge of 963.7 m³/s for a 337.48 km² basin is substantial and would severely impact the narrow valley sections near Yeshbum and other settlements [24].

5.2 Comparison with Similar Arid Basins

Table 7 compares the present results with three studies conducted in comparable environments. Our basin yields a higher peak discharge per unit area than Wadi Safaga (Egypt) [11] and Wadi Aseer (Saudi Arabia) [12], but a much higher runoff volume per unit area. The lower peak in Wadi Aseer can be attributed to a flatter terrain and less impervious surface cover, while the much larger Khazir River basin (Iraq) [25] integrates several sub-basins with longer concentration times, damping the peak. The general agreement in order of magnitude confirms the physical plausibility of our estimates.

5.3 Sensitivity and Uncertainty Implications

The high sensitivity of Qp to CN (coefficient ~3–4) underlines the importance of accurate CN estimation. The CN value of 83 was derived from globally available soil and land cover datasets, which may not capture local variations in soil infiltration capacity or land use changes. The GLUE [25] analysis confirms that the true 100-year peak could lie between about 710 and 1180 m³/s. Consequently, any flood mitigation design should consider the upper bound of this interval to ensure safety.

5.4 Limitations and Future Work

The principal limitation of this study is the absence of observed streamflow data, which prevents formal model calibration. The results must therefore be regarded as screening-level estimates [26,27]. Other sources of uncertainty include the spatial resolution of the DEM and the rainfall product (CHIRPS), the assumption of a single sub-basin, and the reliance on global soil data for CN assignment. Future research should aim to install temporary hydrometric stations in the wadi and to collect field soil infiltration measurements. Integrating the HEC-HMS output with a 2D hydraulic model (e.g., HEC-RAS) would enable the production of flood inundation maps and the identification of specific vulnerable sites. Additionally, the preliminary CMIP6-based rainfall projections for 2015–2060 suggest an increase in mean annual rainfall (SSP5-8.5 mean ≈ 17.2 mm for the domain, though these values need further validation against local station data). A preliminary HEC-HMS run using a projected 100-year storm depth under the SSP5-8.5 scenario yielded a peak discharge of approximately 715 m³/s, indicating that even under moderate assumptions future flood magnitudes may remain high, warranting further detailed analysis [23,28,29].

6. Conclusions

This study presents the first event-based hydrologic model for an ungauged Yemeni basin, demonstrating the feasibility of combining freely available global datasets with HEC-HMS to assess flash flood potential. The key findings are:

1. Morphometric analysis reveals a steep (10.5%), elongated basin with a well-developed drainage network and a short time of concentration (4.38 h), conducive to rapid flood generation.
2. The area-weighted CN is 83, driven by extensive bare land and low-permeability soils (HSG C and D).
3. Simulated 24-h design storms produce peak discharges of 733.8, 867.5, and 963.7 m³/s for return periods of 20, 50, and 100 years, with runoff coefficients reaching 0.86 for the larger events.
4. The GLUE-based 95% confidence interval for the 100-year peak is 712.7–1177.7 m³/s, reflecting significant but quantifiable parameter uncertainty.
5. Sensitivity analysis identifies the curve number as the dominant uncertain parameter, highlighting the need for local soil surveys.

The methodology is fully reproducible and can be transferred to other data-scarce basins in Yemen and similar arid regions. The flood estimates provide a scientific basis for structural mitigation measures, such as stormwater harvesting dams, diversion channels, and flood-proofed crossings, which are urgently needed to protect the vulnerable communities along Wadi Yeshbum.

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مقالة بحثية

النمذجة الهيدرولوجية والهيدروليكية لتقييم مخاطر الفيضانات في وادي يشبم - محافظة شبوة، اليمن

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المُلخّص

تشكل الفيضانات المفاجئة في المناطق القاحلة تهديدات خطيرة للأرواح والبنية التحتية، ومع ذلك، غالبًا ما تغيب البيانات الهيدرولوجية الكمية. تقدم هذه الدراسة أول نموذج هيدرولوجي لحوض وادي يشبوم غير المقاس (337.48 كم²) في محافظة شبوة، اليمن، باستخدام نموذج HEC-HMS ضمن إطار نظم المعلومات الجغرافية. استُخلصت المعايير المورفومترية من نموذج الارتفاع الرقمي SRTM بدقة 30 مترًا، وكشفت عن انحدار متوسط حاد (10.5%)، وشبكة تصريف متطورة (كثافة التصريف 1.8 كم/كم²)، وفترة تركيز قصيرة (4.38 ساعة). حُسب رقم المنحنى (CN) الموزع مكانيًا من بيانات التربة لمنظمة الأغذية والزراعة (FAO) وغطاء الأرض ESA CCI، مما أسفر عن متوسط مرجح قدره 83، وهو ما يشير إلى إمكانية جريان سطحي عالية. استُخدمت بيانات هطول الأمطار اليومية التاريخية (1994-2024) من CHIRPS لمطابقة توزيع غامبل. تم تقدير كميات الأمطار التصميمية المتوقعة خلال 24 ساعة لفترات تكرار 20 و50 و100 عام، حيث بلغت 34.3 و40.5 و44.9 ملم على التوالي. وطُبقت طريقة الرسم البياني الهيدروغرافي لوحدة SCS لتحويل فائض الأمطار إلى جريان سطحي مباشر. وبلغت ذروة التصريفات المحاكاة 733.8 و867.5 و963.7 متر مكعب/ثانية، مع أحجام جريان سطحي مقابلة قدرها 8.88 و11.72 و13.03 مليون متر مكعب. ونظرًا لعدم توفر بيانات تدفق المياه المرصودة للمعايرة، فقد أعطى تقدير عدم اليقين بالاحتمالية المعممة (GLUE)، استنادًا إلى 500 عملية محاكاة مونت كارلو، فاصل ثقة بنسبة 95% لذروة التصريف خلال 100 عام يتراوح بين 712.7 و1177.7 متر مكعب/ثانية. أظهر تحليل الحساسية أن ذروة التصريف تتأثر بشدة بتركيز الملوثات (معامل 3-4) وتتأثر بشكل متوسط بزمن التركيز (معامل 0.7-1.0 تقريبًا). وتُبين النتائج أن الحوض يُظهر استجابة هيدرولوجية سريعة ومفاجئة، وأن نسبة كبيرة (77-86%) من الأمطار الغزيرة تتحول إلى جريان سطحي مباشر. يُمكن تطبيق إطار النمذجة على أحواض جافة أخرى تفتقر إلى البيانات، ويُوفر معلومات أساسية كمية لتخطيط الحد من الفيضانات في اليمن، مع العلم أن جميع النتائج تُعد تقديرات أولية غير مُعايرة.

الكلمات المفتاحية: النمذجة الهيدرولوجية؛ النمذجة الهيدروليكية؛ الأحواض غير المرصودة؛ تخفيف آثار الفيضانات؛ تقدير الجريان السطحي؛ وادي يشبم؛ اليمن.

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