

Spatial Hydrological Modeling of Flash Flood Runoff Impacting the Benghazi City: An Integration of GIS, Morphometric Analysis, and SCS-CN Methodologies

Mohamed Faraj El Megrhi^{1*}, Mohammed Ahmed Zoubi², Wesam Al Farsi³, Abdullhamid Ali Abdullah⁴
^{1,2,3,4}Department of Civil Technology, Faculty of Science and Technology, Qaminis, Libya

النمذجة الهيدرولوجية المكانية لجريان الفيضانات المفاجئة المؤثرة على مدينة بنغازي: تكمّل نظم المعلومات الجغرافية، والتحليل المورفومتري، ومنهجيات منحني رقم التربة (SCS-CN)

محمد فرج المقرحي^{1*}، محمد احمد زوبي²، وسام الفارسي³، عبد الحميد الزوي⁴
^{1,2,3,4}قسم التقنية المدنية، كلية العلوم والتقنية، قمينس، ليبيا

*Corresponding author: mohamedbaleid79@gmail.com

Received: July 15, 2026

Accepted: September 25, 2025

Published: October 11, 2026

Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Abstract:

Unmanaged spatial growth across the Benghazi coastal plain has severely altered regional hydrologic regimes, exposing urban infrastructure to un quantified flood risks originating from the peripheral Al Rajmah escarpment. This study addresses the critical research gap in ungauged semi-arid coastal watersheds by delivering a GIS based hydro morphometric assessment, integrating Benina station IDF data with the SCS-CN framework to evaluate surface runoff dynamics across eleven catchments under 5-to-100-year return periods. The analysis reveals a compound dual hydrodynamic regime governing urban inundation. Steep escarpment small basins (Basins 3-10) generate rapid flash flood surges driven by short flow paths (1.07-1.75km) and steep hydraulic gradients (ΔH up to 98m), yielding times of concentration under 30 minutes (T_c 15min in Basin 3) that instantly surcharge perimeter drainage networks. Conversely, regional wadi systems Wadi Al Qattara (Basin2, 1320.87km²) and Wadi Al Dirjati (Basin11, 193.71km²) dominate volumetric yields due to their scale and high order channel development. Predominant clay rich soils (HSG C and D), drive cumulative regional runoff volumes from 218.68x10⁶m³ (5year) to 453.30x10⁶m³ (100year), with Basin2 contributing over 85% (388.44x10⁶m³). To mitigate this compound risk, an integrated engineering framework is proposed, combining upstream check dams, dry detention basins, and engineered channel armoring with culvert, real time early warning telemetry, and hydraulic buffer easements. This research provides a transferable hydro engineering blueprint for flood risk management in rapidly expanding coastal semi-arid plains.

Keywords: SCS-CN Modeling; Flash Flood Risk; Benghazi Plain; Al Rajmah Escarpment; GIS Hydrology.

الملخص:

أدى التوسع العمراني غير المضبط عبر مدينة بنغازي إلى اختلال النظم الهيدرولوجية الإقليمية، مما عرض البنية التحتية الحضرية لمخاطر فيضانات غير مقدرة بدقة مصدرها حافة الرجمة المجاورة. تسعى هذه الدراسة إلى تغطية الفجوة البحثية القائمة في الأحواض الساحلية شبه الجافة وغير المقاسة، عبر إنجاز تقييم هيدرولوجي باستخدام نظم المعلومات الجغرافية (GIS)، مع دمج بيانات شدة مدة تكرار الأمطار (IDF) لمحطة بنينا مع نموذج منحني رقم التربة (SCS-

CN) لتقدير ديناميكيات الجريان السطحي عبر أحد عشر حوضاً هيدروليكيًا لفترات رجوع تتراوح بين 5 إلى 100 سنة. أفرزت التحليلات نظاماً هيدروديناميكياً مركباً ومزدوجاً يحكم عمليات الغمر؛ حيث تولد الأحواض الصغرى المنحدرة على الحافة (الأحواض 3-10) فيضانات سريعة الاستجابة نتيجة قصر مسارات التدفق (1.07 - 1.75 كم) والانحدارات الحادة (بفروق مناسب تصل إلى 98 متراً)، مما ينجم عنه أزمّة تركيز تقل عن 30 دقيقة (نحو 15 دقيقة في الحوض رقم 3)، وتجاوز لحظي للطاقة الاستيعابية لشبكات التصريف المحيطة. وفي المقابل، تسيطر أنظمة الأودية الإقليمية الكبرى ممثلة في وادي القطارة (الحوض 2 بمساحة 1320.87 كم²) ووادي الدرجاتي (الحوض 11 بمساحة 193.71 كم²) على الحجوم الكلية للجريان نظراً لاتساع نطاقها وتطور شبكات قنواتها. ومع هيمنة التربة ذات المحتوى العالي من الصلصال، ترتفع حجوم الجريان السطحي التراكمية الإقليمية من 218.68 مليون متر مكعب عند فترة رجوع 5 سنوات لتصل إلى 453.30 مليون متر مكعب عند فترة رجوع 100 سنة، حيث يسهم حوض القطارة وحده بأكثر من 85% من الإجمالي (388.44 مليون متر مكعب). ولمواجهة هذه المخاطر المركبة، تطرح الدراسة منظومة هندسية متكاملة تجمع بين السدود التعويقية، وأحواض التهئة الجافة، وتحسين مجاري الأودية، والعبّارات الصندوقية العرضية، ومنظومات الإنذار المبكر اللحظي، إلى جانب الممرات العازلة الهندسية. يقدم هذا البحث إطاراً هيدروليكيًا هندسياً قابلاً للتعميم لإدارة مخاطر الفيضانات في البيئات الساحلية شبه الجافة والمتسارعة النمو.

الكلمات المفتاحية: نموذج SCS-CN؛ مخاطر الفيضانات المفاجئة؛ سهل بنغازي؛ حافة الرجمة؛ هيدرولوجيا نظم المعلومات الجغرافية.

Introduction:

Over the past several decades, a marked escalation in the frequency and magnitude of extreme meteorological events has been documented globally. Among these events, flash floods represent one of the most destructive natural hazards, imposing severe constraints on urban stability and infrastructure resilience. In semi-arid regions, such hydrological events are typically induced by short duration, high intensity precipitation over catchments characterized by low infiltration capacities. Consequently, high magnitude surface runoff is rapidly generated and routed through ephemeral channel networks (wadis), resulting in substantial risk to human populations, structural assets, and municipal transport networks. Within the semi-arid coastal plain of eastern Libya, the municipality of Benghazi presents a critical case of hydro geomorphic vulnerability. Situated on a low relief coastal plain, the urban matrix is topographically bounded to the east and southeast by the Al Rajmah escarpment. Due to this specific morphotectonic positioning, the metropolitan area serves as the terminal receiving zone for several major ephemeral drainage basins originating within the higher elevations of Al Jabal Al Akhdar and the Al Rajmah highlands. The primary contributing systems impacting the urban plain include Wadi Al Qattara, Wadi Al Darajati, Wadi Al Rajmah, Wadi Al Dulaimi, Wadi Al Fiya, and Wadi Jabr. Historical records document severe inundation events across the city in 1938, 1954, 1961, and 1976, establishing that flash flooding in this basin plain transition zone is a recurring geomorphological process rather than an isolated anomaly [1].

This natural spatial vulnerability has been further compounded by climatic shifts and unmanaged urban expansion. Alterations in regional rainfall patterns have increased the probability of high intensity storm events. Simultaneously, rapid urbanization across the Benghazi plain has led to structural encroachment upon active floodplains and historical drainage corridors. The partial obliteration or restriction of natural wadi channels, combined with the structural limitations of the existing municipal storm water drainage network, has significantly elevated overall flood susceptibility.

Despite these documented historical occurrences and increasing urban exposure, a critical gap remains in localized hydrological planning. Spatially explicit flood hazard estimations and quantitative assessments of escarpment-derived runoff entering the urban boundary are largely absent from current municipal master plans. The reliance on generalized regional assumptions fails to account for the complex spatial interactions between extreme precipitation events and heavily modified terrain profiles. Consequently, a comprehensive quantitative baseline regarding surface runoff generated by peripheral natural catchments prior to intercepting the urban perimeter has not been fully established. High-resolution, spatially distributed hydrological modeling is therefore required to delineate these flow paths and inform structural mitigation strategies.

Problem Statement:

The fundamental engineering problem addressed in this study arises from the unmanaged spatial intersection between natural drainage pathways descending from the Al Rajmah escarpment and the expanding urban boundary of Benghazi. As rapid land transformation converts permeable rural soils and natural wadi corridors into impermeable urban surfaces, the natural infiltration capacity of these catchments is severely diminished, leading to altered hydrologic response times and increased runoff potential. Contemporary infrastructure development within the municipality has proceeded largely without integration of spatially distributed hydrological modeling. Specifically, external surface runoff

volumes and peak discharge rates originating from the elevated peripheral basins are rarely incorporated into the hydraulic design calculations of internal municipal storm water systems. Consequently, during high intensity precipitation events modeled across various return periods using updated Intensity Duration Frequency (IDF) data, substantial runoff volumes discharge unhindered into the urban environment. This issue highlights a critical structural and planning mismatch: the coastal urban plain receives major influxes of un quantified external floodwater that existing drainage networks were neither dimensioned to intercept nor capacity engineered to convey. The absence of integrated hydro morphometric characterization and dynamic runoff modeling leaves municipal civil infrastructure continuously exposed to severe inundation risks.

Significance of the Study:

The primary engineering value of this investigation lies in the generation of quantitative hydrological parameters required for the capacity evaluation, structural optimization, and retrofitting of municipal hydraulic infrastructure. By integrating Intensity Duration Frequency (IDF) relationships from the Benina meteorological station with Soil Conservation Service Curve Number (SCS-CN) spatial modeling, actionable estimates of peak discharge rates and direct runoff volumes are established across multiple return periods. These data provide essential design criteria for civil engineers designing surface drainage systems, retention basins, and hydraulic control structures. From a spatial planning and disaster risk management perspective, a quantitative framework for assessing infrastructural exposure across the Benghazi metropolitan area is established. High resolution watershed delineation and morphometric extraction enable municipal authorities to pinpoint critical flow accumulation zones and potential inundation points. These findings provide an empirical basis for enforcing land use regulations, restricting unauthorized construction within active wadi corridors, and prioritizing capital allocation for flood control works.

On a broader methodological level, this study addresses a persistent research gap concerning un gauged, escarpment-bounded semi-arid catchments. Due to the lack of continuous stream flow monitoring networks in the region, a replicable workflow combining Digital Elevation Models (DEM), pedological mapping, and land-use classification within a Geographic Information System (GIS) is demonstrated. This modeling approach serves as a viable methodology for flood hazard assessment in topographically similar semi-arid environments across North Africa.

Research Objectives:

To address the hydrological and infrastructural challenges identified in the problem statement, the primary objectives of this investigation are structured as follows:

- To delineate the peripheral drainage basins descending from the Al Rajmah escarpment toward the Benghazi city and extract key hydro morphometric parameters controlling catchment response using high resolution Digital Elevation Models (DEM) within a GIS environment.
- Classify spatial variations in land cover and Hydrologic Soil Groups (HSG) across the designated watersheds for the construction of composite Curve Number (CN) layers, thereby parameterizing surface retention and infiltration capacities.
- Calculate direct runoff depths, and cumulative volumes, entering the urban matrix across multiple storm return periods by integrating the SCS-CN model with localized Intensity Duration Frequency (IDF) data from the Benina station.
- Quantify total hydraulic loading rates at key urban interception points, delivering actionable engineering metrics for storm water network optimization and infrastructure upgrading.

Literature Review:

To establish a robust methodological foundation and contextualize the spatiohydrological dynamics evaluated in this study, recent literature has extensively documented the evolution of flash flood modeling, morphometric drainage analysis, and curve number recalibration. Across global, regional, and semi-arid environments, integrated GIS platforms, satellite derived elevation data, and continuous hydrometeorological frameworks have become pivotal in assessing direct surface runoff and cross-drainage **infrastructure vulnerabilities**:

GIS based flash flood runoff model was implemented by Gioti et al. (2013) through the integration of high-resolution Digital Elevation Models (DEM) and meteorological data to simulate travel time routing and derive hydrographs for flood hazard prediction [2]. In a morphometric evaluation, the drainage network of the Hasab catchment in the southern Iraqi desert was quantitatively analyzed by Maarooof et al. (2026) using SRTM DEMs, satellite imagery, and topographic maps to determine stream ordering, bifurcation ratios, and structural influences on flow patterns [3]. Spatial modeling of surface runoff and flash flood risk in the Zanta Basin, Duhok Governorate, was conducted by Mohammed (2026) using the Soil Conservation Service Curve Number (SCS-CN) model in a GIS environment powered by 24-year precipitation data from NASA POWER [4]. In a regional Libyan context, surface runoff depth of the Wadi Derna Basin was estimated by Ashoor (2022) through the integration of GIS and SCS-CN

methodologies, taking into consideration antecedent soil moisture conditions, hydrologic soil groups, and land cover variations [5].

To overcome the limitations of tabular Curve Numbers, a hybrid hydrological model was developed by Abdel Ani et al. (2026) for the Wadi Al Rahma basin by integrating the traditional SCS-CN method with the Random Forest machine learning algorithm to dynamically recalibrate curve numbers based on local environmental and topographic variables [6]. The hydrodynamic effects of storm kinematics following the Bu Mansour dam failure in Wadi Derna were modeled by Samir et al. (2025) using 2D HEC-RAS simulations to demonstrate the influence of storm velocity and watershed morphology on hydrograph attributes [7]. Event based hydrological modeling for the un gauged Wadi Yeshbum basin in Yemen was established by Tawhal and Nagi (2026) using HEC-HMS, SCS-CN, CHIRPS rainfall records, and Generalized Likelihood Uncertainty Estimation (GLUE) [8]. Urban drainage capacity in Edaiken, Nigeria, was reengineered by Oladosu et al. (2026) through DEM based catchment delineation, Rational Method surface runoff modeling, and Manning hydraulic equations [9]. Surface runoff in the Wadi Uranah basin, Saudi Arabia, was evaluated by Al Dawood et al. (2020) by coupling GIS and remote sensing with a slope adjusted SCS-CN formulation [10].

Quantitative assessment of annual runoff volume in the Wadi El Nile drainage basin, Yemen, was performed by Al Guhmari (2024) utilizing the SCS-CN model, Landsat-8 land cover classification, and GIS spatial matrix [11]. Finally, flash flood susceptibility in Wadi Al Disah, Saudi Arabia, was modeled by Bashir et al. (2026) using high resolution ALOS PALSAR DEMs to reconcile the scale dependent Morphometric Ranking Method with the scale independent El Shamy approach [12]. The present research fills this crucial scientific gap by providing a multi-tiered, integrated spatial hydrological model that bridges geomorphometric analysis and SCS-CN methodologies to evaluate and mitigate flash flood runoff impacts, thereby offering robust decision support capabilities for sustainable urban planning and water resources management in un gauged arid environments.

Study Area:

The study area encompasses the municipality of Benghazi, situated in northeastern Libya along the southern coast of the Mediterranean Sea. According to the administrative boundaries established under the Third Generation Master Plan, the municipal boundary covers a total spatial extent of approximately 80234.4 hectares. The continuous urban perimeter is defined by the primary outer ring road belt, originating in the western sector of Qanfuda, traversing toward the Cement Factory roundabout, and extending through the eastern sub-urban corridors of Benina and Sidi Khalifa. Consequently, the study domain incorporates a complex matrix of urban and peri-urban districts, including Qanfuda, Al Qawarsha, Al Nawagiya, Buatni, Al Hawari, Benina, Budzira, Al Kwayfiya, Sidi Khalifa, and the dense central urban core of Benghazi (Figure 1). The municipality of Benghazi is bounded to the east by the Al Rajma escarpment, a dominant morphotectonic feature intersected by numerous drainage channels that form contributing basins discharging directly along the city's eastern and southern perimeters. While runoff from certain catchments attenuates prior to reaching the Benghazi Tokra coastal arterial road, major systems most notably Wadi Al Qattara traverse the urban plain to discharge into the Mediterranean Sea. Furthermore, several ancestral drainage courses, despite being masked by intensive urban encroachment, remain active as preferred overland flow paths, inducing severe localized inundation during peak flood events. The study area is located in Benghazi and its eastern drainage catchments between longitudes 20° 50' 0" E, 20° 0' 0" E, and latitudes 33° 0' 0" N, 31° 30' 0" N (Figure 2).

The elevated escarpment margin is dissected by numerous ephemeral drainage networks, forming multiple catchments that discharge surface runoff directly onto the eastern and southeastern municipal borders. While certain upstream runoff volumes attenuate or pool prior to reaching the primary Benghazi Tokra regional highway, major ephemeral systems most notably Wadi Al Qattara possess sufficient hydraulic capacity to breach the urban perimeter and convey discharge through the city matrix into the Mediterranean Sea. Furthermore, intensive anthropogenic expansion has progressively encroached upon and obliterated natural channel networks within the urban interior. Despite physical channel degradation, these historical drainage pathways continue to function as preferential hydro dynamic corridors during intense storm events, concentrating surface runoff and causing severe localized inundation across the urban grid.

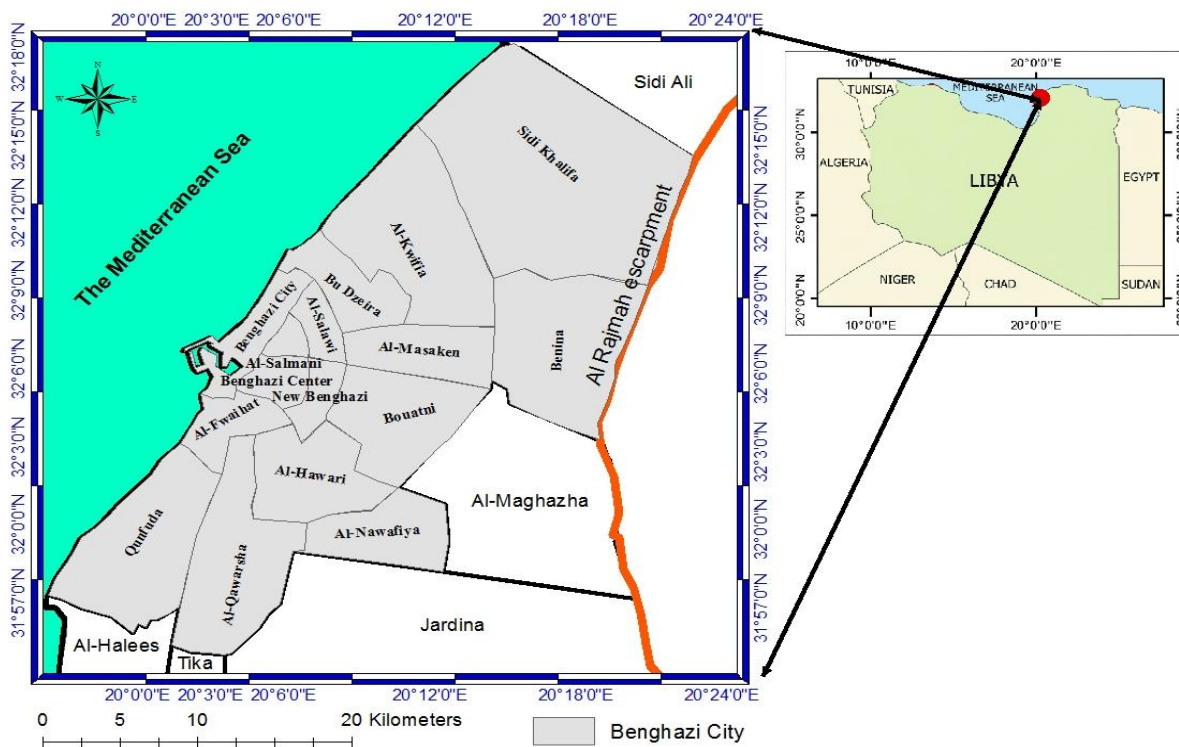


Figure (1): Administrative Divisions of Benghazi City Under the Third Generation Master Plan, (Adapted by the author in ArcGIS 10.8 from the Urban Planning).

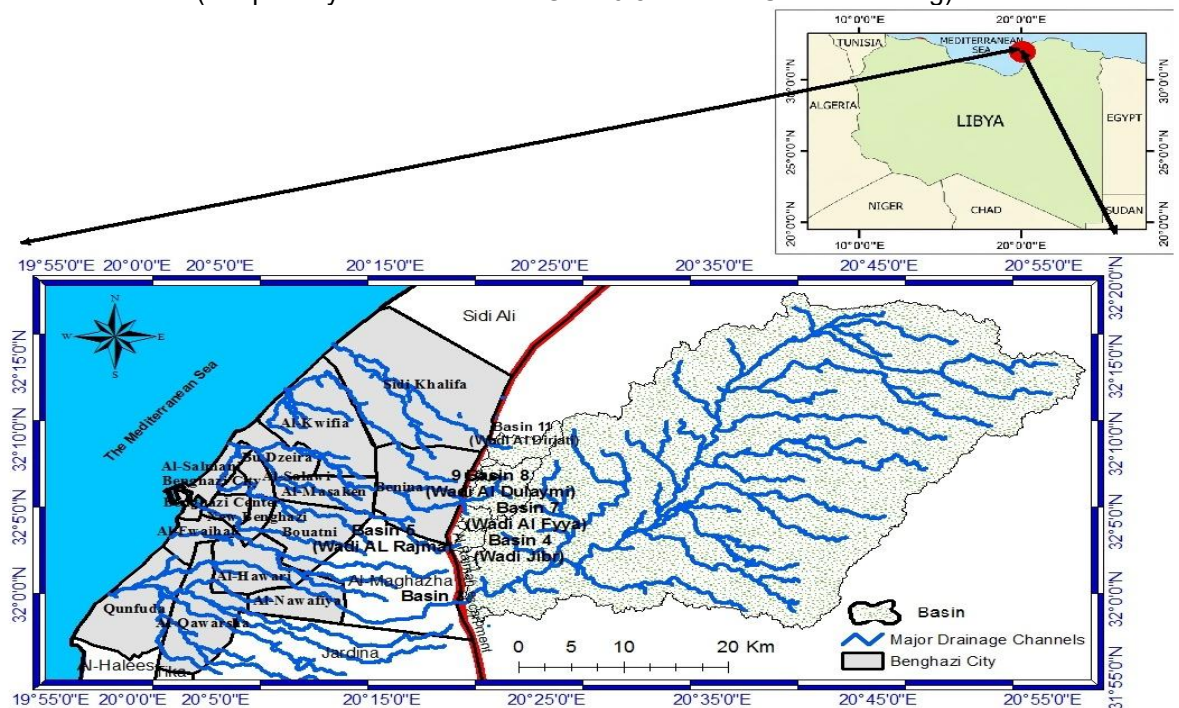


Figure (2): Location map of the study area using ArcGIS 10.8 from DEM based digital hydrological analysis of the catchments impacting the study area.

Study Methodology:

The theoretical foundation of this investigation is anchored in physical catchment hydrology overland flow theory, which govern the non-linear partitioning of extreme precipitation into direct surface runoff within semi-arid environments. By synthesizing the empirical Soil Conservation Service Curve Number (SCS-CN) model with quantitative hydro-morphometric principles, this conceptual framework establishes the hydrodynamic mechanisms driving flood generation from elevated escarpment catchments onto coastal urban plains.

Geospatial Hydrological Processing Workflow (DEM Processing via ArcGIS 10.8:

Hydrological modeling was conducted using Shuttle Radar Topography Mission (SRTM) DEM data processed within ArcGIS 10.8 (ArcToolbox environment). Topographic features governing surface runoff, channel slope, and flow accumulation were extracted following standard spatial workflows [13]:

1. **Depression Filling (Fill):** Impurities and artificial sinks within the DEM surface were removed to ensure continuous hydrodynamic flow routing.
2. **Flow Direction Determination (Flow Direction):** Hydro-steepest descent vectors were calculated using the D8 algorithm to direct surface flow from each cell to its adjacent neighbor.
3. **Flow Accumulation (Flow Accumulation):** Cumulative cell contribution matrices were generated to identify primary drainage corridors.
4. **Channel Extraction (Con Tool):** High-precision raster stream networks were isolated by applying a specific cell accumulation threshold.
5. **Raster-to-Vector Conversion (Stream to Feature):** Extracted stream networks were converted from grid cells to vector polyline layers.
6. **Stream Ordering (Stream Order):** Channel hierarchies across the basins were classified according to Strahler's ordering system.
7. **Watershed Delineation (Watershed):** Individual catchment boundaries impacting the urban plain were isolated based on specified outlet pour points.
8. **Spatial Geometry Clipping (Clip):** Extracted raster watersheds were converted into polygon shape files and utilized to crop DEM elevation datasets and internal stream networks for basin-specific morphometric analysis.

evaluation of watershed morphometry provides critical insights into underlying hydrogeomorphic processes and basin susceptibility to flash flooding. Key spatial parameters were extracted using ArcGIS 10.8 to model surface runoff generation mechanisms and channel **flow routing behavior** [14]:

- **Catchment Area (A):** Defines the total contributing surface area circumscribed by the topographic drainage divide, which captures and concentrates effective precipitation toward the principal basin outlet.
- **Catchment Length (L):** Measured along the primary drainage line from the basin outlet to the most hydraulically remote point along the watershed perimeter, serving as a key variable for calculating concentration time and hydrograph response lag.
- **Mean Catchment Width (W):** Determined by the ratio of total drainage area to the principal channel length, reflecting the plan form geometry, lateral distribution, and structural elongation of the watershed.
- **Topographic Relief and Gradient:** Computed from the elevation differential between the upland headwaters and the lowland outlet, governing potential energy gradients, overland flow velocities, and peak discharge kinetics.

SCS-CN Hydrological Model Formulation:

The Soil Conservation Service Curve Number (SCS-CN) methodology was selected to estimate direct surface runoff. This empirical model is suited for un gauged, semi-arid catchments where observed stream flow gauge records are unavailable. The model synthesizes land use/land cover (LULC), Hydrological Soil Groups (HSGs), (Table1 and Table2), antecedent moisture conditions (AMC), and soil permeability to derive a dimensionless metric ranging from 0 to 100. Higher CN values indicate low permeability, highly impervious surfaces capable of generating substantial runoff volumes, whereas lower CN values reflect porous soils with high infiltration capacities [15]. To quantify the direct surface runoff depths, times of concentration, and volumetric yields across the evaluated catchments, the empirical mathematical equations derived from the Soil Conservation Service Curve Number (SCS-CN) framework are detailed in Table 3.

Table (1): Hydrologic Soil Group (HSG) Classifications [15].

Group	Soil Properties and Infiltration Characteristics
A	Deep sand or gravel deposits with extremely low clay/silt content; high infiltration and hydraulic conductivity rates.
B	Moderately shallow to deep sandy loam soils with moderate infiltration capacity when thoroughly wetted.
C	Clay loam soils with low infiltration rates when wetted, containing subtle restrictive layers that impede downward water movement.
D	Heavy clay soils with high swelling potential, high water table, or shallow impervious rock layers; extremely low infiltration capacity.

Table (2): Standard SCS-CN Runoff Curve Numbers by Land Use and HSG [15].

Land Use / Cover Description	Condition	HSG			
		A	B	C	D
Cultivated Land	Without soil conservation treatment	72	81	88	91
	With soil conservation treatment	62	71	78	81
Pasture / Natural Range	Poor condition	68	79	86	89
	Good condition	39	61	74	80
Meadow / Grassland	Good condition 75% grass cover)	30	58	71	78
Forest / Woodlands	Light cover / thin litter	45	66	77	83
	Dense cover / rich litter	25	55	70	77
Open Space / Parks	Good condition 75% grass cover)	39	61	74	80
	Fair condition (50-75% grass cover)	47	69	79	84
Commercial Areas	85% Impervious	89	92	94	95
Industrial Districts	72% Impervious	81	88	91	93
Residential (1/8 acre or less)	65% Impervious	77	85	90	92
Paved Parking / Roofs	Impervious	98	98	98	98
Paved Roads	With curbs and storm sewers	98	98	98	98
Gravel Roads	Unpaved	76	85	89	91

Table (3): Mathematical equations used for estimating basin hydrological parameters based on the SCS-CN model [15].

Eq. No.	Hydrological Variable	Mathematical Formulation	Variable Definitions
1	Composite Curve Number	$CN = \frac{\sum CN_i A_i}{\sum A_i}$	CN: Composite curve number. A: Total basin area (km ²). Ai: Area of individual land unit i (km ²). CNi: Curve number for land unit i.
2	Time of Concentration	$T_c = \frac{1.679L^{0.8}(s+1)^{0.7}}{60 \times 1900H^{0.5}}$	Tc: Time of concentration (hr). L: Main channel length (m). H: Average basin slope(m/m) . S: Maximum potential retention (mm).
3	Direct Surface Runoff	$R = \frac{(I - 0.25S)^2}{I + 0.8S}$ $S = \frac{25400}{CN} - 254$	R: Direct surface runoff depth (mm). S: Potential maximum retention (mm). CN: Curve number. I:rainfall intensity mm/hr.
4	Total runoff volume over the catchment	$V_r = R \times A \times 1000$	A: Catchment area (km ²). R: Direct surface runoff depth (mm) Vr: Total runoff volume (m ³)

Data Sources and Acquisition:

A multi-source dataset comprising primary empirical field data and secondary spatial meteorological parameters was integrated to execute the spatial hydrological modeling and flood risk evaluation. Secondary data acquisition encompassed peer reviewed scientific literature, academic dissertations, municipal engineering reports, and official statistical publications issued by relevant governmental authorities in Benghazi. Primary observational data were collected through systematic field reconnaissance across vulnerable municipal districts, catchment outlets, and active wadi channels. Complementary field interviews were conducted with municipal infrastructure officials and long term residents to document historical flood extents and verify local inundation dynamics.

The primary quantitative input parameters required for hydro morphometric extraction, surface reclassification, and hydrological modeling were derived from the following sources:

- **Digital Elevation Model (DEM):** Four Shuttle Radar Topography Mission (SRTM) DEM tiles featuring a 30-meter spatial resolution, acquired via the United States Geological Survey (USGS). This dataset covered the complete spatial domain of Benghazi and its surrounding escarpment basins, serving as the foundational surface for watershed delineation and hydro morphometric parameter extraction [16].
- **Soil Texture and Land Cover Data:** Digital soil classification and land-use maps originally produced by Export Selkhozprom (1980) under regional soil survey frameworks. Soil units categorized under the Soviet classification system were reclassified into standard Hydrological Soil

Groups (HSGs) to establish spatial Curve Number (CN) matrices across the contributing catchments.

- **Meteorological Records:** Intensity Duration Frequency (IDF) precipitation datasets provided by the Libyan Meteorological Organization for the Benina meteorological station (Figuer3), supplying design rainfall intensity values across specified return periods [17].
- **Auxiliary Cartographic Frameworks:** Published peer reviewed journals, regional technical maps, and authoritative online geospatial databases utilized for cross-verification and model calibration.

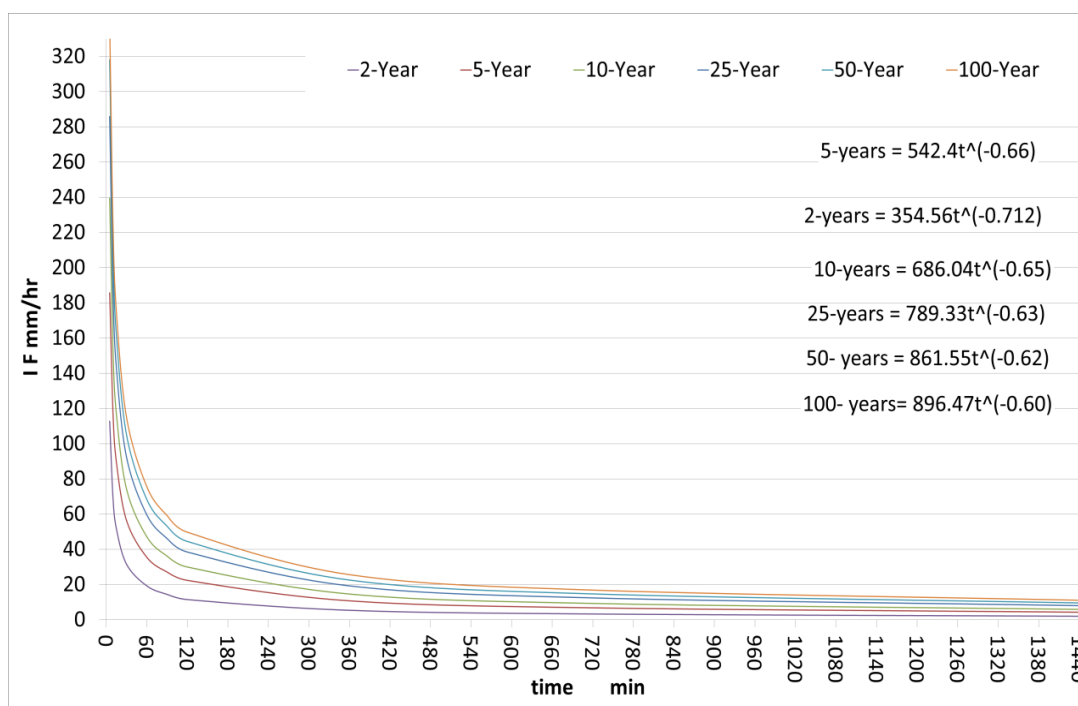


Figure (3): Rainfall Intensity-Duration-Frequency (IDF) curves for Benina Meteorological Station, Benghazi [17].

Hydrological Characteristics of Natural Drainage Basins Influencing the City of Benghazi:

Spatial hydrological characterization of the study region was conducted through the processing of four Digital Elevation Model (DEM) scenes acquired from the United States Geological Survey, supplemented by high resolution satellite imagery retrieved from Google Earth. The spatial domain encompasses the municipality of Benghazi, its suburban fringes, and the elevated topography of the Al Rajma heights and Al Jabal Al Akhdar. Within an ArcGIS 10.8 environment, individual DEM tiles were merged into a continuous surface using mosaicking routines, followed by coordinate transformation to the national projection system (Libyan Geodetic Datum UTM 2006, Zone 34N). Spatial masking (*Extract by Mask*) was subsequently applied to constrain the DEM elevation dataset strictly to the designated study boundary. Through hydromorphometric delineation, eleven primary contributing drainage basins directly impinging upon the urban perimeter of Benghazi were identified, including locally recognized catchments such as Wadi Al Qattara, Wadi Jibr, Wadi Al Rajma, Wadi Al Fyya, Wadi Al Dulaymi, and Wadi Al Dirjati.

To facilitate localized terrain extraction as illustrated in Figures 4 through 14, raster-based basin boundaries were converted into polygon shape files, allowing individual elevation profiles and surface channel networks to be clipped per sub-basin. To evaluate drainage network efficiency and runoff dynamics, stream ordering was executed in accordance with Strahler's hierarchical classification scheme. The structural configuration of the resulting stream network reflects the complex interactions between climatic drivers, landform gradients, and underlying lithological properties specifically rock hardness, matrix permeability, and structural discontinuity density (faults, joints, and fractures). Consequently, core planimetric and relief parameters (basin area, perimeter, principal channel length, and mean width) were derived to establish the physical baseline governing catchment response time, time of concentration, and total runoff volume potential during high intensity storm events (Table4).

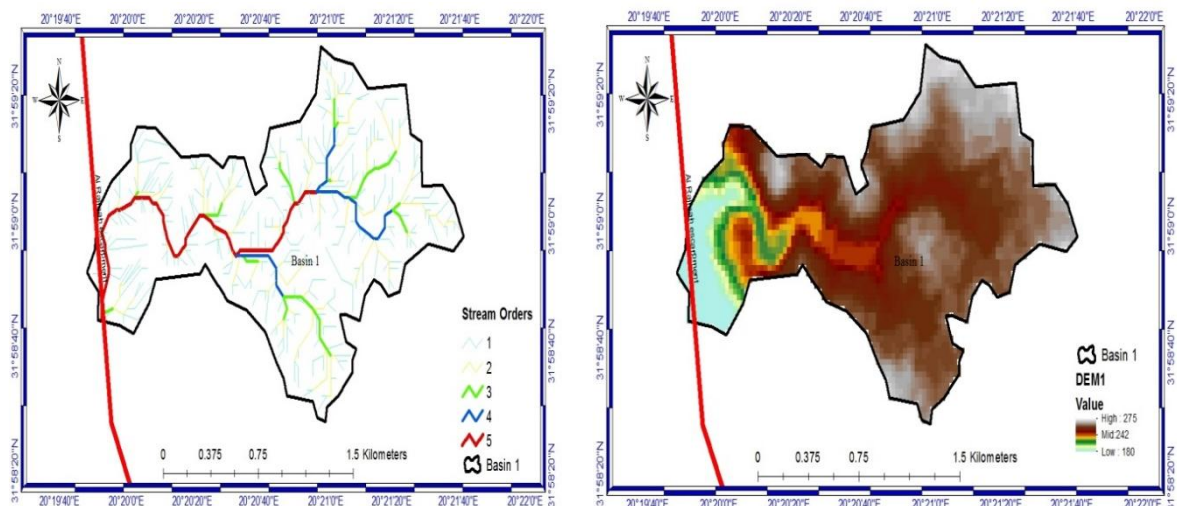


Figure (4): Natural Drainage Basins1, Wadis, Stream Orders, and Natural Ground Elevations, using ArcGIS 10.8, based on digital hydrological analysis of (DEM) for the study area.

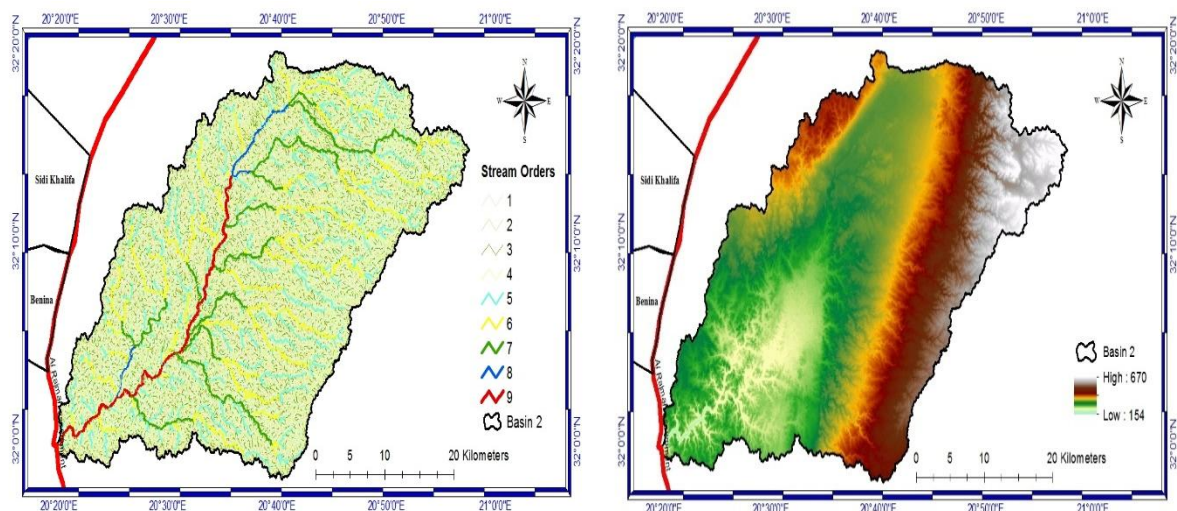


Figure (5): Natural Drainage Basins2(Wadi Al Qattara), Wadis, Stream Orders, and Natural Ground Elevations, using ArcGIS 10.8, based on digital hydrological analysis of (DEM) for the study area.

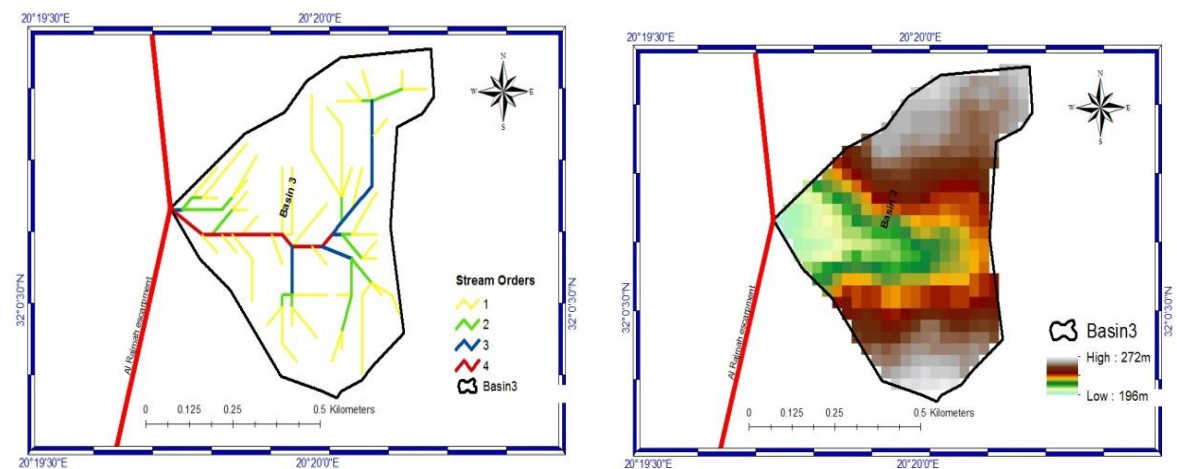


Figure (6): Natural Drainage Basins3, Wadis, Stream Orders, and Natural Ground Elevations, using ArcGIS 10.8, based on digital hydrological analysis of (DEM) for the study area.

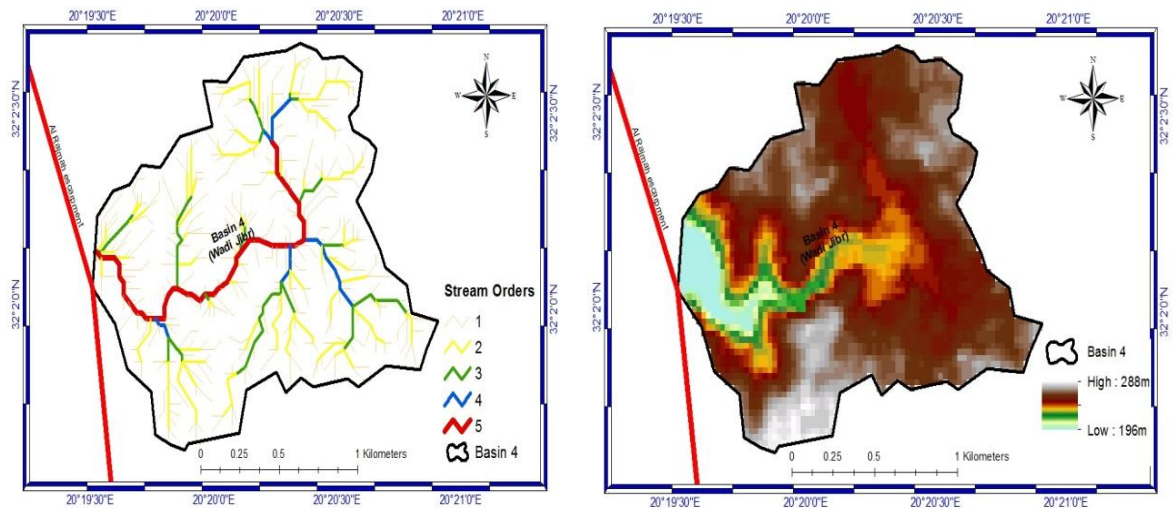


Figure (7): Natural Drainage Basins4(Wadi Jibr), Wadis, Stream Orders, and Natural Ground Elevations, using ArcGIS 10.8, based on digital hydrological analysis of (DEM) for the study area.

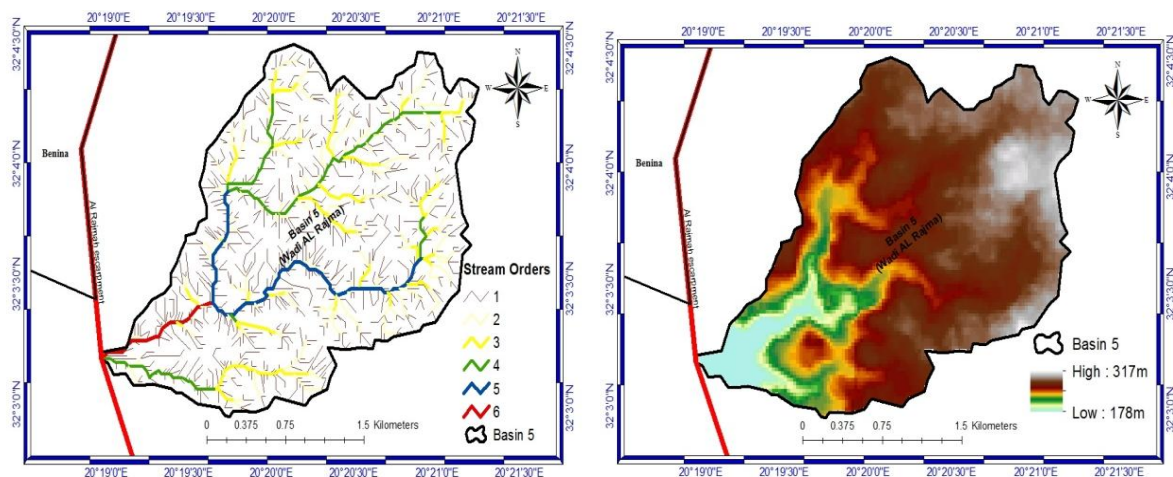


Figure (8): Natural Drainage Basins5(Wadi AL Rajma), Wadis, Stream Orders, and Natural Ground Elevations, using ArcGIS 10.8, based on digital hydrological analysis of (DEM) for the study area.

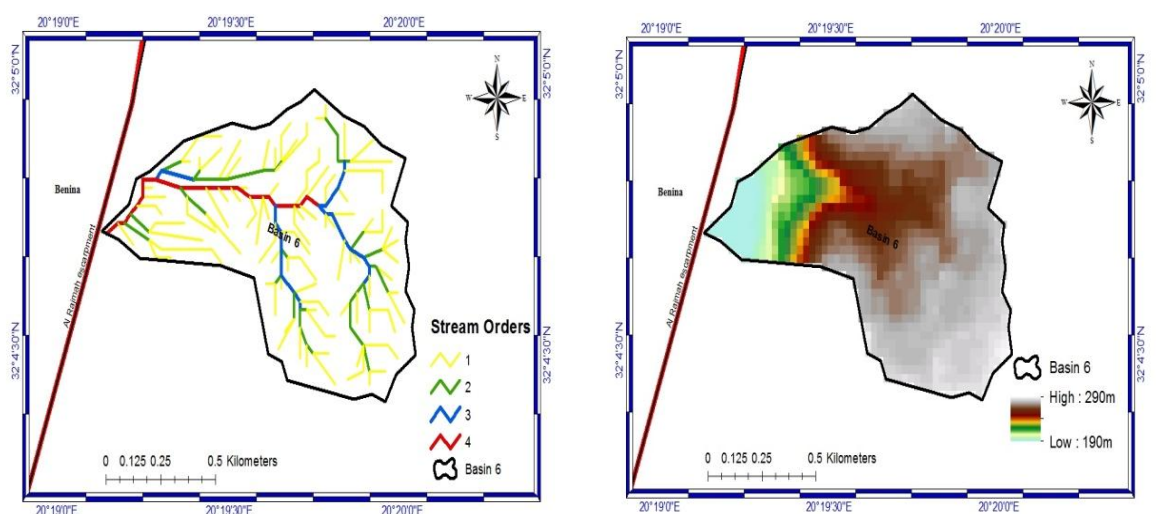


Figure (9): Natural Drainage Basins6, Wadis, Stream Orders, and Natural Ground Elevations, using ArcGIS 10.8, based on digital hydrological analysis of (DEM) for the study area.

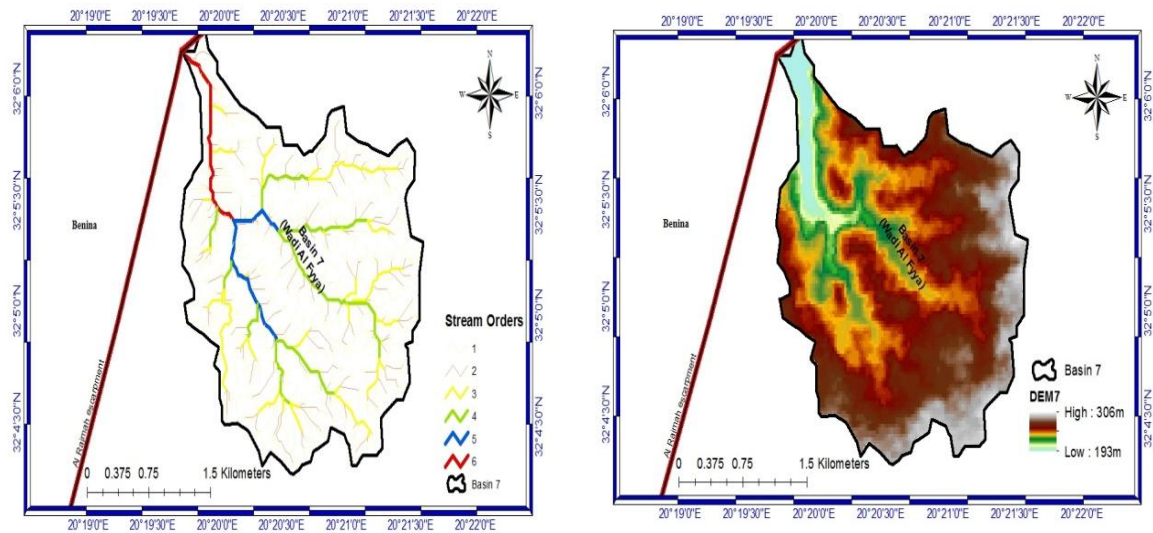


Figure (10): Natural Drainage Basins7(Wadi Al Fyya), Wadis, Stream Orders, and Natural Ground Elevations, using ArcGIS 10.8, based on digital hydrological analysis of (DEM) for the study area.

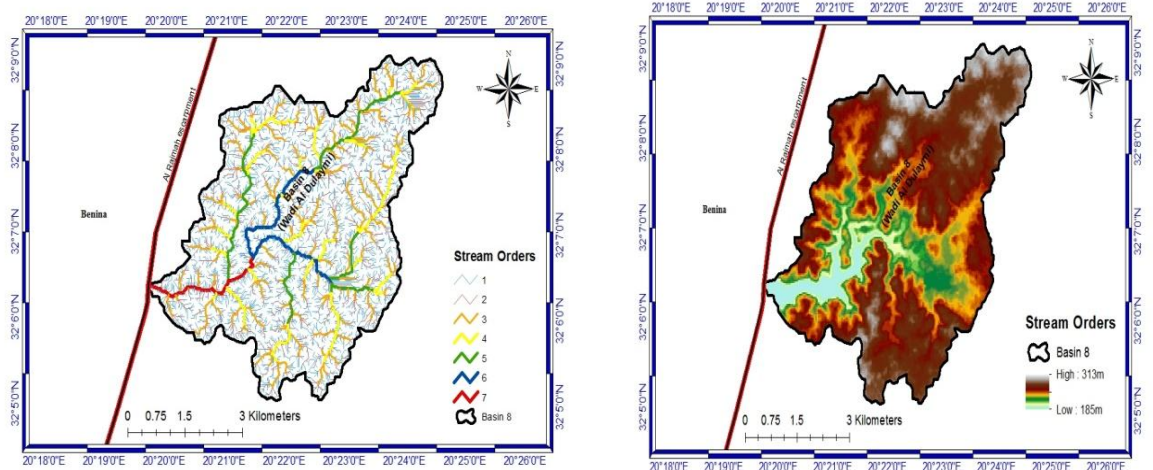


Figure (11): Natural Drainage Basins8(Wadi Al Dulaymi), Wadis, Stream Orders, and Natural Ground Elevations, using ArcGIS 10.8, based on digital hydrological analysis of (DEM) for the study area.

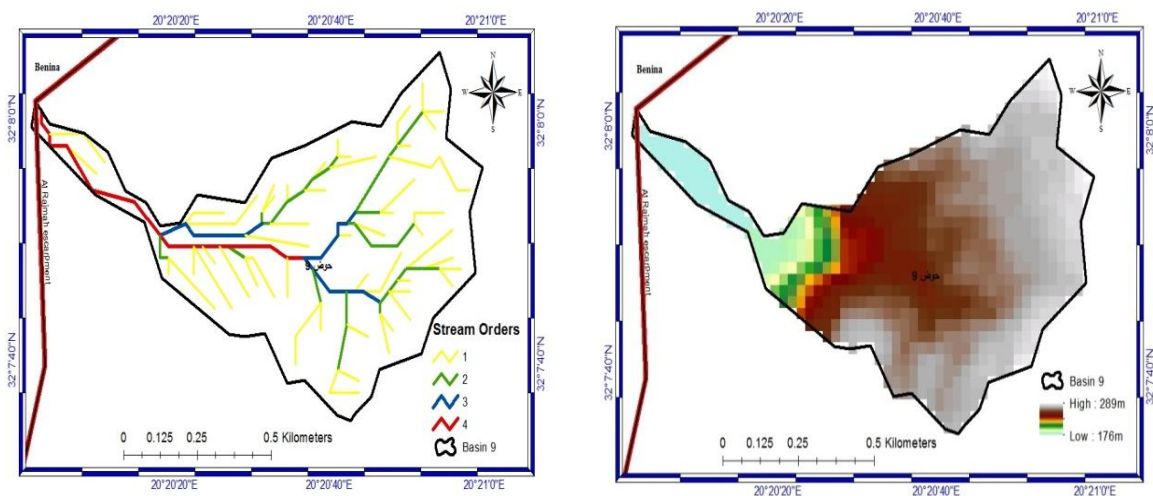


Figure (12): Natural Drainage Basins9, Wadis, Stream Orders, and Natural Ground Elevations, using ArcGIS 10.8, based on digital hydrological analysis of (DEM) for the study area.

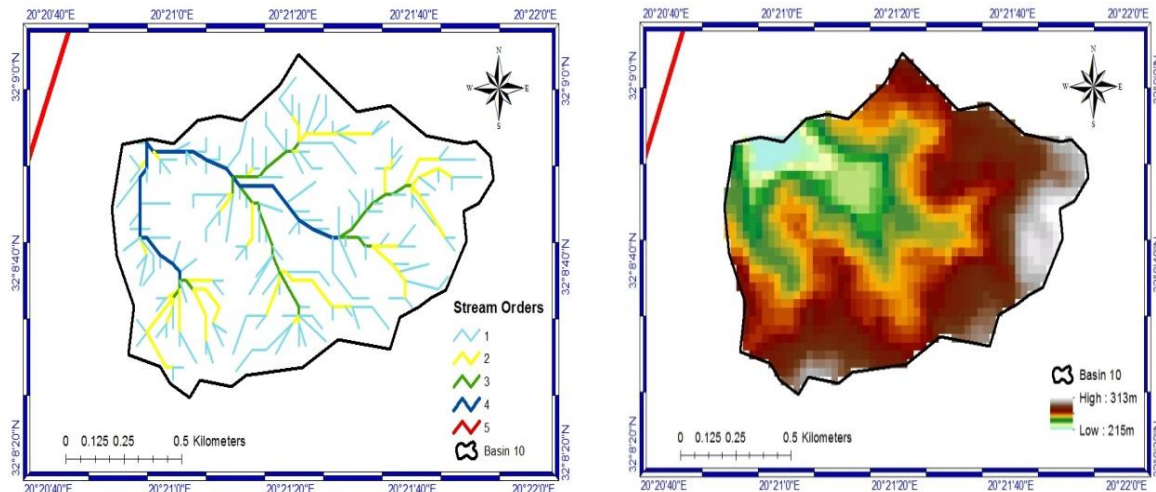


Figure (13): Natural Drainage Basins10, Wadis, Stream Orders, and Natural Ground Elevations, using ArcGIS 10.8, based on digital hydrological analysis of (DEM) for the study area.

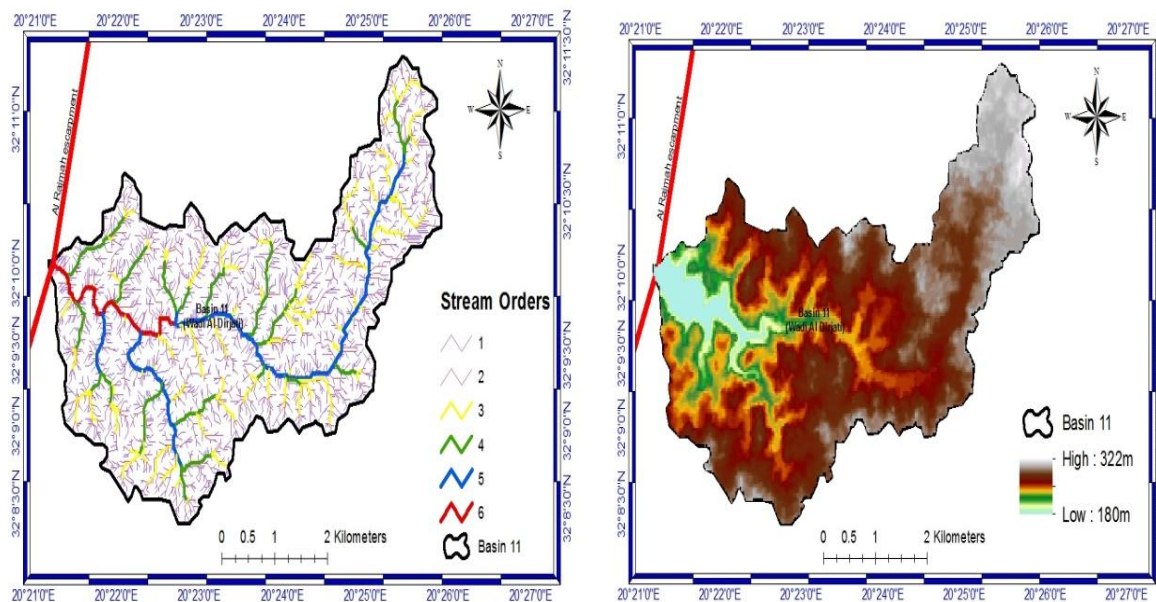


Figure (14): Natural Drainage Basins11(Wadi Al Dirjati), Wadis, Stream Orders, and Natural Ground Elevations, using ArcGIS 10.8, based on digital hydrological analysis of (DEM) for the study area.

Table (4): Spatial and Topographic Characteristics of Drainage Basins Influencing Benghazi, based on spatial hydrological analysis in ArcGIS 10.8.

Parameter	Basin 1	Basin 2 (Wadi Al Qattara)	Basin 3	Basin 4 (Wadi Jibr)	Basin 5 (Wadi Al Rajma)	Basin 6	Basin 7 (Wadi Al Fyya)	Basin 8 (Wadi Al Dulaymi)	Basin 9	Basin 10	Basin 11 (Wadi Al Dirjati)
Area A km ²	2.524	1320.87	0.359	2.525	6.141	0.822	6.952	31.370	0.577	1.191	193.706
Perimeter P km	9.429	231.035	2.538	7.299	12.009	4.110	13.371	31.330	4.399	4.662	27.257
Channel Length L km	4.21	86.74	1.07	3.11	5.29	1.94	4.54	11.20	1.75	1.70	11.58
Width W km	0.599	15.227	0.335	0.811	1.161	0.422	1.532	2.800	0.330	0.702	16.729

Mean Elevation H _{avg} m	250	357	240	196	272	264	273	273	260	273	285
Maximum Elevation H _{max} m	280	670	270	288	317	290	306	313	289	313	322
Minimum Elevation H _{min} m	180	154	200	269	187	190	193	185	176	215	180
Stream Orders Range	1–5	1–9	1–4	1–5	1–6	1–4	1–6	1–7	1–4	1–5	1–6

The lithostratigraphic framework and pedological attributes of the eleven drainage basins influencing the city of Benghazi are governed by Cretaceous to Quaternary geological formations. The headwaters and upland catchment sectors, most notably within the Wadi Al Qattara basin, are underlain by Upper Cretaceous limestones interbedded with nodular chert, stratigraphically capped by dense Eocene micro sandy limestones. Toward the eastern and southwestern basin margins, soft marly calcareous units transition into interbedded marl and thin calcareous sandstone strata. Across the Al Rajma and Al Abyar plateaus, Eocene formations are overlain by weathered Miocene dolomitic and marly limestones containing localized gypsum lenses, with pervasive structural fractures and micro faults infill dominated by fine grained clay deposits and secondary calcite precipitates. Within the low-lying urban perimeter of Benghazi, Neogene and Quaternary deposits predominate, appearing as thin mantles of red residual clay (Terra Rossa) resting over karstic limestone bedrock [1].

To parameterize infiltration dynamics and spatial hydrologic response, soil units were categorized according to the USSR Soil Classification System using digital pedological datasets (1:50000 scale) compiled by *Selkhozpromexport* (1980), digitized and georeferenced within an ArcGIS 10.8 environment under the Libyan Geodetic Datum (UTM Zone 34N). As illustrated in Figuer (15), mechanical and chemical weathering under arid to semi-arid climatic regimes characterized by seasonal temperature variations and erratic precipitation promotes the slow, non-uniform alteration of limestone bedrock into red clay residues. Consequently, exposed dolomitic limestones occur along hilltop crests and valley flanks, while the broader catchment area is dominated by limestone bedrock capped by a thin mantle of Terra Rossa. **The pedological mapping identifies five major soil associations across the contributing basins:**

- **Reddish Brown Arid Soils (R):** Recently formed Mediterranean type soils originating primarily from aeolian desert sands with minor proportions of silt, carbonates, and localized accumulations of salts and gypsum. These soils frequently exhibit surface saline and gypsiferous crusts, elevated pH levels, and favorable intrinsic fertility owing to adequate trace element concentrations.
- **Red Ferrisiallitic Group (Ft, Fcr, Fi):** Comprising Red Ferrisiallitic soils (Ft), concretionary variants (Fcr), and crusted types (Fi), this group covers extensive agricultural tracts across the plateau. Characterized by clay textured profiles ranging from shallow stony to deep horizons, these soils exhibit high calcium carbonate contents and elevated water retention capacities, representing prime arable land following nutrient supplementation and land reclamation.
- **Red Rendzina Soils (Rzr):** Dark, calcareous clay soils associated with semi humid microclimates, providing favorable conditions for forestry and orchards. These profiles are enriched with calcium carbonate and nitrogen, displaying slightly to moderately alkaline reaction rates; inherent nutrient deficits are typically mitigated through balanced fertilization.
- **Lithosols (Lfb, Lb):** Consisting of Reddish (Lfb) and Brown (Lb) Lithosols, these shallow, light silt textured profiles rarely exceed 30cm in depth. Characterized by low nutrient status and high susceptibility to wind and water erosion due to sparse vegetative cover, their utility is predominantly restricted to extensive grazing and marginal agriculture.
- **Non-Monolithic Crusted Soils (CRnm):** Extremely shallow soils featuring a indurated hardpan layer at a depth of approximately 30cm. These profiles are marked by high salinity, low natural fertility, severe nutrient depletion, and heightened vulnerability to soil erosion and surface degradation.

Individual pedological polygons were clipped to catchment boundaries and integrated with land cover layers to derive Soil Conservation Service Curve Number (SCS-CN) (Table5), spatial distributions, enabling the precise calculation of area weighted composite CN values for subsequent runoff modeling across each drainage basin.

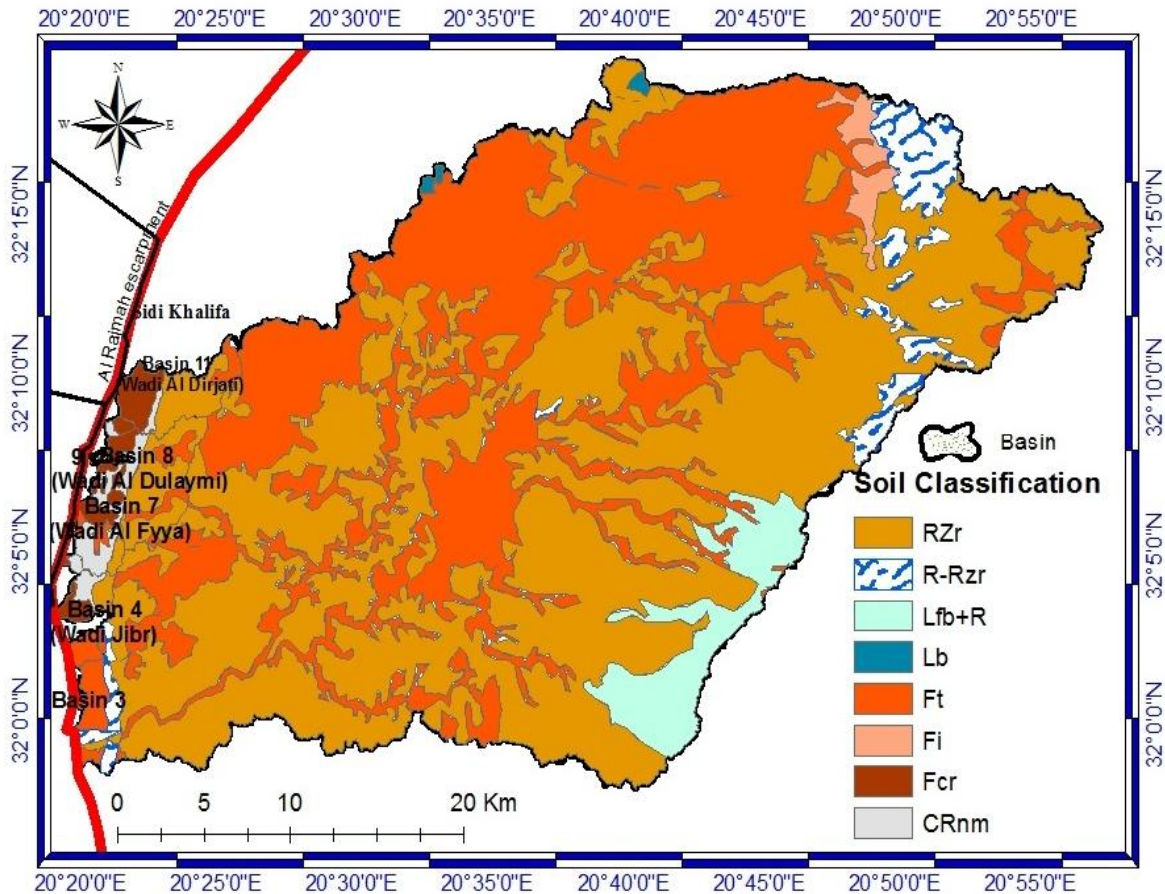


Figure (15): Soil Classification and Distribution Map of the Drainage Basins (Russian Classification), processing in ArcGIS 10.8, digitized from the 1:50000 Soil Map of Eastern Libya

Table (5): Soil Types, Hydrologic Soil Groups, and Curve Numbers for Drainage Basins Influencing Benghazi, based on Tables (1) , and Figure (15) using ArcGIS 10.8 software.

Drainage Basin	Soil Type Classification	Area (m2)	(HSG)	(CN)%
Basin 1	R + Rzr	1197890	C	77
	Ft	1329890	D	83
	Weighted Curve Number (CNw) 80			
Basin 2 (Wadi Al Qattara)	Rzr	671220000	C	86
	R + Rzr	40214500	C	86
	Lfb + R	51110000	A	68
	Lb	2001710	B	79
	Ft	542150000	D	89
	Fi	14182700	D	89
	Weighted Curve Number (CNw) 87			
Basin 3	Ft	359000	D	83
	Weighted Curve Number (CNw)			83
Basin 4 (Wadi Jibr)	Ft	2525000	D	83
	Weighted Curve Number (CNw) 83			
Basin 5 (Wadi AL Rajma)	Rzr	1917270	C	77
	Fcr	2261680	D	83
	CRnm	1922470	D	83
	Weighted Curve Number (CNw) 81.5			
Basin 6	CRnm	822000	D	83
	Weighted Curve Number (CNw) 83			
Basin 7 (Wadi Al Fyya)	Rzr	1448200	C	77
	Ft	1337690	D	83

Basin 8 (Wadi Al Dulaymi)	CRnm	4166200	D	83
	Weighted Curve Number (CNw) 83.5			
	Rzr	15530000	C	77
	Ft	4564200	D	83
	Fcr	6534600	D	77
	CRnm	4741200	D	83
Basin 9	Weighted Curve Number (CNw) 79			
	Fcr	577000	D	83
Basin 10	Weighted Curve Number (CNw) 83			
	Fcr	790005	D	83
	CRnm	401012	D	83
Basin 11 (Wadi Al Dirjati)	Weighted Curve Number (CNw) 83			
	Rzr	9766140	C	77
	Ft	2164580	D	83
	Fcr	6673760	C	77
	CRnm	766164	D	83
	Weighted Curve Number (CNw) 78			

Evaluating surface hydrology and runoff dynamics in arid and semi-arid ephemeral watersheds (wadis) remains paramount for flood risk mitigation and sustainable water resource management. Empirical spatial modeling was executed utilizing the Soil Conservation Service Curve Number (SCS-CN) methodology. The SCS-CN approach represents a globally validated framework for ungauged urbanizing catchments, parameterizing surface runoff response through the integration of digital elevation profiles, pedological distribution maps, and spatial land use/land cover (LULC) classifications. Surface runoff potential is dictated by the Curve Number (CN), a non-dimensional index bounded between 0 and 100. Elevated CN values (CN \to 100) designate impermeable, highly reflective surfaces that impede infiltration and generate rapid surface runoff, whereas lower values denote highly permeable matrix conditions dominated by deep percolation. Spatial overlay analysis within ArcGIS 10.8 was utilized to clip HSG polygons to individual catchment perimeters, enabling the computation of area weighted composite CN values across the eleven watersheds. These parameterizations served as fundamental inputs for deriving key hydrograph characteristics including maximum potential retention (S), direct runoff depth (R), time of concentration (T_c), and Total runoff volume over the catchment (V_r) under three distinct design storm scenarios across 5-, 10-, 50-, and 100-year return periods.

Table (6): Hydrological Characteristics of Drainage Basins Influencing the Study Area Under a 5,10,50,100 Year Return Period Storm Intensity, based on Tables (3,4), and Figure (3).

Drainage Basin	T_c hr	I=185.74 5year mm/hr			I=185.74 10year mm/hr			I=318.18 mm/hr 50 year			I=339.12 mm/hr 100year		
		R m m	S m m	V_r m ³	R m m	S m m	V_r m ³	R m m	S m m	V_r m ³	R m m	S m m	V_r m ³
Basin1	1.4 0	121 .98	63. 50	307887. 86	172 .23	63. 50	434697. 85	247 .68	63. 50	625139. 85	267 .97	63. 50	676359. 31
Basin 2 (Wadi Al Qattara)	22. 13	143 .75	37. 95	189874 262.86	196 .01	37. 95	258899 025.91	273 .40	37. 95	361122 384.47	294 .08	37. 95	388440 407.32
Basin 3	0.2 5	131 .23	52. 02	47112.6 3	182 .44	52. 02	65497.6 2	258 .84	52. 02	92924.2 7	279 .33	52. 02	100277. 98
Basin 4 (Wadi Jibr)	1.8 9	131 .23	52. 02	331363. 17	182 .44	52. 02	460672. 68	258 .84	52. 02	653575. 99	279 .33	52. 02	705297. 79
Basin 5 (Wadi AL Rajma)	1.5 5	126 .59	57. 66	777409. 07	177 .34	57. 66	108904 4.54	253 .29	57. 66	155543 4.73	273 .68	57. 66	168066 9.22
Basin 6	0.4 5	131 .23	52. 02	107873. 48	182 .44	52. 02	149969. 48	258 .84	52. 02	212768. 10	279 .33	52. 02	229605. 86
Basin 7 (Wadi Al Fyya)	1.2 4	132 .79	50. 19	923129. 36	184 .14	50. 19	128016 8.81	260 .68	50. 19	181226 0.07	281 .19	50. 19	195485 9.94

Basin 8 (Wadi Al Dulaymi)	4.6 1	118 .93	67. 52	373079 4.90	168 .81	67. 52	529561 4.84	243 .91	67. 52	765143 2.58	264 .13	67. 52	828575 6.75
Basin 9	0.3 7	131 .23	52. 02	75721.4 1	182 .44	52. 02	105270. 55	258 .84	52. 02	149351. 82	279 .33	52. 02	161171. 02
Basin 10	0.3 8	131 .23	52. 02	156298. 43	182 .44	52. 02	217291. 55	258 .84	52. 02	308280. 79	279 .33	52. 02	332677. 10
Basin 11 (Wadi Al Dirjati)	4.7 6	115 .89	71. 64	224481 35.23	165 .39	71. 64	320377 09.00	240 .12	71. 64	465119 53.65	260 .26	71. 64	504139 69.25

Discussion:

This section interprets the quantitative spatiohydrological results, evaluating the complex interactions between physical catchment parameters, pedological constraints, and the multi frequency runoff dynamics affecting **the Benghazi plain**:

- The spatial dimensions, channel network hierarchy, and elevation profiles extracted from Table 4 exert a governing control on the surface hydrologic regime across the Benghazi plain. Physical watershed scale, channel slope, and catchment geometry directly dictate the key parameters of the surface runoff and total volumetric yield. The structural heterogeneity among the primary catchments creates two distinctly contrasting mechanisms of runoff generation and hydrodynamic loading upon the receiving municipal area. The primary control on cumulative runoff volume is driven by the spatial extent of the contributing drainage area. Basin2 (Wadi Al Qattara, 1320.87 km²) and Basin 11 (Wadi Al Dirjati, 193.71km²) encompass over 85% of the total regional watershed area. Because total runoff volume scales as a direct function of catchment area, these two large basins receive and process the vast majority of atmospheric precipitation. Once precipitation exceeds the initial abstraction losses, the vast surface area of Basins 2 and 11 yields massive volumes of surface runoff. Consequently, these regional systems represent the dominant source of sustained, high volume hydraulic loading reaching the lower coastal plain and municipal infrastructure during multi day rainfall events.

Conversely, hydrograph timing and peak flow concentration are strongly governed by catchment geometry and stream order development. Basin2 exhibits an elongated configuration, characterized by a main channel length of 86.74km relative to its average width of 15.23km, yielding a low Form Factor. This elongated shape lengthens the hydraulic flow paths for overland and channel flow, extending travel times and broadening the temporal distribution of the runoff hydrograph. While this prolonged response time attenuates localized unit peak discharges along the upper reaches, the presence of a highly developed 9th order stream network provides efficient hydraulic routing once flow concentrates into primary channels. In contrast, Basin11 features a remarkably wide geometry, with a basin width of 16.73km against a channel length of 11.58km. This compact, fan shaped configuration causes runoff from multiple tributaries to reach the primary channel junctions nearly simultaneously, resulting in rapid aerial flow convergence and steeper hydrograph peak discharge rates relative to its drainage area. A critical dynamic occurs along the steep Al Rajma escarpment, where small basins (Basins 3-10) demonstrate an entirely different runoff response.

These small catchments, such as Basin3 (0.36km²) and Basin 10 (1.19km²), possess extremely short main channels (1.07 to 1.70km) combined with steep vertical elevation drops. For instance, Basin 10 drops 98m over a channel distance of 1.70km, resulting in a steep average hydraulic gradient. According to fundamental open channel flow principles, surface flow velocity increases with the square root of channel slope, which drastically reduces travel time across these escarpment streams. As a result, the time of concentration for these small basins drops to under 30 minutes, severely limiting initial abstraction and infiltration losses. These steep gradients convert short duration, high intensity rainfall bursts into immediate, high velocity flash flood surges that impact the eastern perimeter of Benghazi with virtually no lag time, long before the delayed volumetric flows from the larger inland wadis arrive

- The pedological distribution and Hydrologic Soil Group (HSG) classifications detailed in Table 5 provide fundamental insight into the surface infiltration capacity and runoff generation potential across the catchments influencing the Benghazi plain. Under the Soil Conservation Service (SCS) runoff framework, the Curve Number (CN) parameter represents an empirical indicator of potential maximum soil retention (S), directly governing the proportion of precipitation converted into surface runoff. The spatial analysis reveals a dominant prevalence of low permeability soil classes, which significantly impairs infiltration performance and amplifies storm hydrograph volumes across the region.

- Across the eleven evaluated drainage basins, weighted Curve Numbers (CN_w) scale from 0.78 to 0.87, indicating widespread hydrological exposure to low initial abstraction thresholds. This elevated runoff response is primarily driven by the spatial dominance of Hydrologic Soil Groups C and D. Soil units such as Red Ferrisiallitic (Ft, Fcr), Lithosols (Lb, Lfb), Red Rendzina (Rzr), Non-Monolithic Crusted (CRnm) feature fine clay rich textures, shallow profiles over carbonate bedrock, and poor structural permeability. These characteristics severely restrict saturated hydraulic conductivity, promoting rapid surface saturation during high intensity rainfall events. In these steep escarpment basins, the combination of low infiltration capacity and high topographic gradients produces a compounding hydrological effect. The low permeability prevents subsurface storage, forcing immediate surface partitioning, while steep channel slopes rapidly route the resulting surface runoff toward municipal outfalls with minimal transmission losses along wadi beds. However, even a baseline CN_w of 78 reflects a high runoff environment under semi-arid conditions.
Under extreme storm depths, the infiltration intake rates of HSG C and D soils rapidly reach steady state terminal capacity, causing all catchments to convert the vast majority of storm precipitation into high volume surface runoff. Basin2 (Wadi Al Qattara) registers the lowest potential retention depth 37.95mm, physically proof of the widespread dominance of shallow clay rich Terra Rossa and Lithic Regosol soils belonging to Hydrologic Soil Groups C and D. Consequently, the initial abstraction threshold is breached within the earliest stages of any storm event. Once precipitation exceeds 7.59mm, saturated hydraulic conductivity drops, forcing a rapid transition from infiltration to surface runoff. This explains why Basin 2 yields the highest direct runoff depth across all recurrence intervals, scaling from 143.75mm (5-year) to 294.08mm (100-year). (Basins 3, 4, 6, 9, 10), these small catchments share identical Curve Numbers 0.83 and potential retention capacities 52.02mm. This pedological uniformity causes them to generate identical direct runoff depths under uniform storm depths, scaling from 131.23mm (5-year) to 279.33mm (100-year).
- Basin 11 (Wadi Al Dirjati) features the lowest Curve Number 0.78 and the highest retention capacity 71.64mm. Higher proportions of moderately permeable soils allow for greater initial rainfall abstraction. Consequently, Basin11 produces the lowest direct runoff depths among all primary catchments 115.89mm under a 5-year event to 260.26mm under a 100-year event.
- The time of concentration (T_c) acts as the critical temporal parameter governing how rapidly overland flow and channelized discharge converge at the basin outlet. The pronounced variance in T_c across the study region ranging from 15 minutes (0.25hr) to nearly 22 hours (22.13hr) is directly driven by the interaction between principal channel length (L) and vertical elevation drops (ΔH). Small catchment situated along the steep Al Rajma escarpment display rapid response times, led by Basin3 (15min), Basin 9 (22.2min), Basin 10 (22.8min), and Basin 6 (27min). These catchments feature extremely short channel flow paths ($L = 1.07$ to 1.75 km) combined with steep topographic slopes. The high gravitational potential energy along the escarpment accelerates overland velocity, drastically shortening travel time. These short T_c values cause escarpment streams to deliver steep, flash flood, high velocity flood surges strike the eastern municipal boundary of Benghazi almost immediately after high intensity rainfall bursts, offering virtually no lag time for early warning or emergency deployment. In sharp contrast, Basin2 (Wadi Al Qattara) registers a prolonged concentration time of 22.13 hr, while Basin 11 registers 4.76hr. Basin 2 possesses an elongated geometry and an extensive 9th order stream network. The extensive spatial distance over which flow must travel attenuates the peak discharge rate along the main channel, spreading flow delivery over a multi-day temporal window.
- Total volumetric surface runoff (V_r) is the spatial integral of direct runoff depth over contributing drainage area (A). The exponential growth of volumetric discharge across return periods highlights the physical dominance of catchment scale over local infiltration variations. Basin 2 (Wadi Al Qattara) single handedly controls the volumetric water balance of the region, enormous flood volumes $189.87 \times 10^6 m^3$ under a 5year event, scaling to $258.90 \times 10^6 m^3$ (10year), $319.05 \times 10^6 m^3$ (25year), $361.12 \times 10^6 m^3$ (50year), and peaking at $388.44 \times 10^6 m^3$ under a 100-year design storm. Basin 11 (Wadi Al Dirjati) acts as the secondary volumetric contributor, producing $22.45 \times 10^6 m^3$ (5year) up to $50.41 \times 10^6 m^3$ (100year).

Together, these two regional basins account for over 95% of the total runoff volume generated across the entire study area. Across all eleven basins, the total volumetric discharge directed toward the Benghazi plain accumulates from $218.68 \times 10^6 m^3$ during a 5year storm event to $453.30 \times 10^6 m^3$ during a 100year storm event. High intensity rainfall triggers immediate, high velocity flash runoff from the steep escarpment small basins (Basins 3-10) within 15 to 60 minutes. These rapid peak flows exceed the hydraulic conveyance capacity of perimeter drainage ditches and culverts, causing sudden localized flash flooding along eastern suburban road intersections. As the storm progresses over several hours to days, the massive volumetric yields generated by the distant

hinterlands of Wadi Al Qattara (388.44Mm^3) and Wadi Al Dirjati (50.41Mm^3) move down the primary wadi channels. Because downstream urban channels and culverts along major transit corridors are cross section under dimensioned and obstructed by historical channel infill, these massive volumes overflow channel banks, creating widespread backwater ponding across low lying.

- Upstream storage structures including dry detention basins, stepped check dams, and hillside terracing should be constructed along the higher gradient outlets of Al Rajma escarpment catchments (Basins 3-10). By detaining high velocity peak flows and extending the catchment response time, downstream hydrograph peaks can be attenuated, reducing peak flow rates delivered to municipal interception points. High-risk wadi channels, particularly along the lower reaches of Wadi Al Qattara and Wadi Al Dirjati, require structural channel stabilization. Engineered trapezoidal concrete lined or gabion armored channels should be constructed to maintain high Manning's roughness performance, prevent bed erosion, and preserve cross sectional conveyance capacity. Downstream storm water networks must be isolated from regional wadi inflows through the installation of high-capacity flood interceptor channels and automated tide gate/backflow prevention structures. Main outfall points discharging into coastal depressions should be augmented with mechanical storm water lift and pumping stations to force drainage against high sea level or groundwater heads during co-occurring surge events. Non-structural zoning overlays must be integrated alongside structural works to enforce legally binding buffer zones along historical wadi paths. Land use regulations should mandate the preservation of natural drainage easements, prohibiting structural infill and enforcing Sustainable Drainage Systems (SuDS) such as permeable pavements and infiltration trenches within new suburban developments to offset urban runoff amplification.

Conclusion:

This study successfully addresses a critical research gap in semi-arid coastal hydrology by delivering a comprehensive, spatially distributed hydro-geometric assessment of flash flood runoff mechanisms across the eleven ungauged catchments impacting the Benghazi urban plain. By bridging the gap between watershed-scale hydro-morphometry, pedological infiltration constraints (SCS-CN framework), and downstream structural vulnerabilities, this research resolves the complex cause and effect relationships governing regional inundation dynamics under multi frequency design storms (5-to-100-year return periods).

The primary objectives achieved and core empirical findings of this study are synthesized as follows:

- The structural heterogeneity among the catchments creates two distinct, compounding flood hazard mechanisms. Small basins along the steep Al Rajma escarpment (Basins 3-10) are governed by steep hydraulic gradients (ΔH up to 98m) and short main channels ($L = 1.07$ to 1.70km), driving rapid open channel flow velocities that drastically reduce times of concentration ($T_c < 30\text{min}$, led by Basin 3 at 15min). These small catchments convert high intensity rainfall bursts into immediate, steep limbed flash flood surges that strike the eastern perimeter of Benghazi with virtually zero lag time. Conversely, the extensive inland systems Wadi Al Qattara (Basin2, 1320.87km^2) and Wadi Al Dirjati (Basin11, 193.71km^2) encompass over 85% of the total regional watershed area. Driven by catchment scale and high stream order development (up to 9th order), these large basins process the vast majority of atmospheric precipitation, delivering sustained, high volume hydraulic loading (V_r) over multi day temporal windows.
- Fine clay rich textures, shallow profiles over carbonate bedrock, and surface crusting associated with Hydrologic Soil Groups C and D (Terra Rossa, Rendzinas, Lithosols, and CRnm) impose severe restrictions on saturated hydraulic conductivity. Weighted Curve Numbers scale from 0.78 to 0.87, establishing low initial abstraction thresholds. In Basin 2 ($CN_w = 0.87$, $S = 37.95\text{mm}$), initial abstraction is breached after just 7.59mm of rainfall, driving direct runoff depth from 143.75mm (5year) to 294.08mm (100year). Escarpment small basins ($CN_w = 0.83$, $S = 52.02\text{mm}$) yield uniform runoff depths scaling from 131.23mm to 279.33mm, while Basin 11 ($CN_w = 0.78$, $S = 71.64\text{mm}$) yields $R = 115.89\text{mm}$ to 260.26mm . Under extreme storm depths, infiltration intake rates rapidly reach steady state terminal capacity, causing all catchments to convert the vast majority of precipitation into effective surface runoff.
- Cumulative regional volumetric yield (V_r) scales exponentially from $218.68 \times 10^6\text{m}^3$ under a 5year storm event to $453.30 \times 10^6\text{m}^3$ under a 100year storm event. Wadi Al Qattara single handedly controls the regional water balance, generating $189.87 \times 10^6\text{m}^3$ (5year) to $388.44 \times 10^6\text{m}^3$ (100year), while Wadi Al Dirjati contributes $22.45 \times 10^6\text{m}^3$ to $50.41 \times 10^6\text{m}^3$, jointly accounting for over 95% of total regional runoff. The interaction of these two regimes produces a devastating two phase flood impact: rapid flash surges from escarpment small basins instantly overwhelm perimeter culverts within 15 to 60 minutes, followed by multi day volumetric inundation from the inland wadis that

overflows cross sectionally under dimensioned and historically infilled urban channels, causing widespread backwater ponding across low lying coastal plains.

In conclusion, this study provides a scientifically robust, transferable framework that transforms ungauged hydrological modeling into actionable civil engineering solutions, offering a definitive blueprint for flood risk management in semi-arid, rapidly urbanizing coastal plains.

Based on the quantitative hydrological findings and the identified structural vulnerabilities across the drainage catchments, a comprehensive, **multi-tiered engineering and regulatory framework is recommended to mitigate flash flood risks in Benghazi:**

- To bridge the gap between predictive modeling and civil engineering intervention, an integrated mitigation strategy is defined.
- Upstream, stepped gabion check dams, dry detention basins, and hillside terracing must be deployed along the high gradient outlets of Basins 3-10 to attenuate high velocity peak flows and extend hydrograph response times.
- Downstream, high risk reaches of Wadi Al Qattara and Wadi Al Dirjati require engineered trapezoidal concrete lined or gabion armored channels to maintain cross sectional conveyance and prevent bed erosion.
- Municipal storm water networks must be isolated via high-capacity flood interceptor channels, automated tide gate/backflow structures, and mechanical lift stations at coastal outfalls.
- Structurally, nonstructural zoning overlays must mandate legally binding buffer easements along historical wadi paths to ban structural infill, supported by Sustainable Drainage Systems (SuDS) such as permeable pavements and infiltration trenches in new suburban developments to offset urban runoff amplification.
- To enhance long term resilience against climate change induced intensity shifts in extreme storms, a real time Hydro Meteorological Early Warning System (EWS) integrating telemetry rain/stream gauges and predictive modeling should be deployed along high risk escarpment channels (Basins 3-10) to provide a 30 to 60 minute advance evacuation window. Concurrently, eco hydrological restoration via re vegetation with deep rooted native flora along the Al Rajma escarpment must be executed to increase surface roughness (Manning's n) and infiltration, thereby extending times of concentration (T_c) and suppressing peak discharges. Finally, future drainage infrastructure designs must incorporate a 15-25% climate change safety uplift factor on historical IDF curves to ensure operational resilience over their 50-to-100-year design life.

References:

1. Gouda, H. G. (1973). Researches in the geomorphology of Libyan lands. Libyan University Publications. https://archive.org/details/@hassan_ibrahem.
2. Gioti, E., Kazi, M., & Tsakiris, G. (2013). GIS based flash flood runoff modeling using high resolution DEMs and meteorological data for travel time routing and hydrograph derivation. *Water Resources Management*, 27(11), 3901–3915.
3. Maarouf, F., Al Juboury, M., & Hassan, H. (2026). Quantitative morphometric evaluation and stream ordering of the Hasab catchment in the southern Iraqi desert using SRTM DEMs and satellite imagery. *Arabian Journal of Geosciences*, 19(1), www.earth.uomosul.edu.iq.
4. Mohammed, A. (2026). Spatial modeling of surface runoff and flash flood risk in the Zanta Basin, Duhok Governorate, using the SCS-CN model and NASA POWER precipitation data. *Environmental Monitoring and Assessment*, 198(3), <https://wjfh.uowasit.edu.iq>.
5. Ashoor, A. (2022). Estimation of surface runoff depth for the Wadi Derna Basin using integrated GIS and SCS-CN methodologies. *Libyan Journal of Engineering and Applied Sciences*, 14(2), 78–91.
6. Abdel Ani, M., Smith, J., & Rahma, K. (2026). A hybrid hydrological model integrating traditional SCS-CN with Random Forest machine learning for dynamic curve number recalibration: Application to the Wadi Al Rahma basin. *Journal of Hydrologic Engineering*, 31(2), 112–126.
7. Samir, M., El Fadel, M., & Al Haddad, R. (2025). Modeling the hydrodynamic effects of storm kinematics following the Bu Mansour dam failure in Wadi Derna using 2D HEC-RAS simulations. *Natural Hazards*, 125(2), 1450–1468.
8. Tawhal, M., & Nagi, A. (2026). Event based hydrological modeling for the ungauged Wadi Yeshbum basin in Yemen using HEC-HMS, SCS-CN, and CHIRPS rainfall records under GLUE uncertainty estimation. *Hydrological Sciences Journal*, 71(4), 512–528 <https://doi.org/10.47372/ejua-ba.2026.2.541>.
9. Oladosu, O., Adeleke, A., & Babatunde, O. (2026). Urban drainage capacity reengineering in Edaiken, Nigeria, through DEM-based catchment delineation and Rational Method runoff modeling. *African Journal of Environmental Science and Technology*, 20(2), 55–68.

10. Al Dawood, A., Al Shaikh, A., & El Kadi, A. (2020). Slope adjusted SCS-CN formulation for surface runoff evaluation in semi-arid environments: A case study of the Wadi Uranah basin, Saudi Arabia. *Arabian Journal of Geosciences*, 13(18).
11. Al Guhmari, M. (2024). Quantitative assessment of annual runoff volume in the Wadi El Nile drainage basin, Yemen, using SCS-CN and Landsat 8 imagery. *Journal of Spatial Hydrology*, 20(1), 45–59.
12. Bashir, B., Al Salamah, I., & Youssef, A. M. (2026). Flash flood susceptibility modeling in Wadi Al Disah, Saudi Arabia: Reconciling the scale dependent Morphometric Ranking Method with the scale independent El Shamy approach using ALOS PALSAR DEMs. *Geomatics, Natural Hazards and Risk*, 17(1).
13. Dawood, J. M. (2012). Fundamentals of spatial analysis within the framework of Geographic Information Systems. Electronic Edition.
14. Al-Dulaimi, K. H. A. (2017). Rivers: An applied geohydromorphometric study. Dar Al Safa for Publishing and Distribution.
15. Ramirez, J. A. (2000). Prediction and modeling of flood. In *Hydrology and hydraulics: Human, riparian and aquatic communities*. Cambridge University Press.
16. United States Geological Survey. (n.d.). Digital elevation model for North East Libya [2024]. EarthExplorer. <https://earthexplorer.usgs.gov/>.
17. National Meteorological Center - Benghazi. (1970–2022). Benina meteorological station precipitation dataset [Unpublished raw data]. National Meteorological Center, Libya.