International Journal for Scientific Research (IJSR)

المجلة الدولية للبحوث العلمية

IJSR

Vol. (5), No. (2) February 2026 الإصدار (5)، العدد (2)

Integrated Hydrological Modeling and Spatial Analysis for Flash Flood Risk Assessment: A Comprehensive Case Study of Aden Governorate, Yemen

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Abstract

This comprehensive study provides an in-depth evaluation of flash flood hazards in Aden Governorate, Yemen, a region characterized by complex volcanic topography and rapid, often unregulated, urban expansion. Utilizing the Watershed Modeling System (WMS 11.0) and Geographic Information Systems (GIS), the research analyzes 15 primary drainage basins across the districts of Sirah, Al-Mualla, Al-Tawahi, and Al-Buraiqa. The study employs the HEC-1 hydrological model to simulate flood hydrographs and estimate peak discharges for return periods ranging from 5 to 100 years. Land Use and Land Cover (LULC) analysis using Sentinel-2 imagery (2017–2023) reveals an 82% increase in built-up areas, significantly altering the hydrological response of the watersheds. The results indicate extreme peak discharges, reaching up to 9,272 m³/s for Wadi Al-Kabir and 257.94 m³/s for Wadi Al-Khasaf during a 100-year event. Spatial inundation mapping identifies critical risk zones in Al-Qati', Souq

Al-Baz, and Al-Haswa, where water levels could reach up to 3 meters. The study proposes a multi-tiered mitigation strategy, integrating structural interventions such as check dams and drainage rehabilitation with non-structural measures like early warning systems and strict zoning enforcement. This research serves as a critical blueprint for sustainable urban flood management in arid coastal cities.

Keywords: Flash Flood Risk, Hydrological Modeling, WMS, HEC-1, GIS, Aden Governorate, Urban Resilience.

1. Introduction

1.1. Background and Rationale:

Flash floods are among the most sudden and devastating natural hazards globally, particularly in arid and semi-arid regions where intense, short-duration rainfall events occur over steep, low-permeability terrain [1,4]. In the context of the Arabian Peninsula, climate change has shifted traditional precipitation patterns, leading to an increased frequency of extreme weather events that overwhelm existing urban infrastructure [6,7,14]. Aden Governorate, the economic hub of Yemen, is uniquely vulnerable due to its geographical position and geological formation [13,14].

Recent regional assessments confirm that extreme rainfall frequency over southern Arabian coastal zones has shown increasing interannual variability linked to regional climate oscillations [6,7]. Flash flood events in arid and semi-arid regions are often characterized by high rainfall intensity, short lag times, and limited infiltration capacity, resulting in rapid surface runoff generation [11,4].

1.2. Problem Statement:

In recent years, Aden has been repeatedly struck by catastrophic flood events, notably in 1967, 1993, 2008, and the most recent disaster on April 21, 2020[2,14]. These events are not merely natural phenomena but are exacerbated by human-induced factors [3,15]. Unplanned urban expansion has encroached upon natural wadi channels, significantly reducing the hydraulic capacity of drainage networks [2,15]. The lack of a comprehensive spatial-hydrological database has hindered effective intervention and risk management [3,5].

Similar patterns of urban encroachment into natural drainage corridors have been identified as a primary driver of flood amplification in rapidly urbanizing coastal cities [3,15].

1.3. Objectives of the Study:

The primary objective of this research is to conduct a multi-scale hydrological assessment of the drainage basins in Aden Governorate to mitigate flood risks [1,2]. Specific sub-objectives include:

- Delineating drainage basins and extracting morphometric parameters using high-resolution Digital Elevation Models (DEM).
- Analyzing long-term rainfall data (1948–2023) to determine design storm depths for various return periods.
- Simulating flood hydrographs and calculating peak discharge and total runoff volumes using the HEC-1 model.
- Evaluating the impact of LULC changes (2017–2023) on the hydrological response.
- Mapping inundation zones and proposing engineering solutions for flood risk reduction.

2. Study Area Description

2.1. Geographical Location:

Aden Governorate is situated at latitude 12.47° N and longitude 44.57° E, at the southwestern tip of the Arabian Peninsula. It is bordered by the Gulf of Aden to the south, Lahj Governorate to the north and west, and Abyan Governorate to the east. The governorate encompasses several distinct districts, including the historic Crater (Sirah), Al-Mualla, Al-Tawahi, and the industrial hub of Al-Buraiqa. Figure 1 illustrates the strategic coastal location of Aden Governorate within the southwestern Arabian Peninsula. The proximity to the Gulf of Aden, combined with its geomorphological enclosure by volcanic highlands, enhances its hydrological sensitivity to short-duration high-intensity rainfall events. This geographic configuration explains the concentration of surface runoff toward the urbanized coastal fringe.

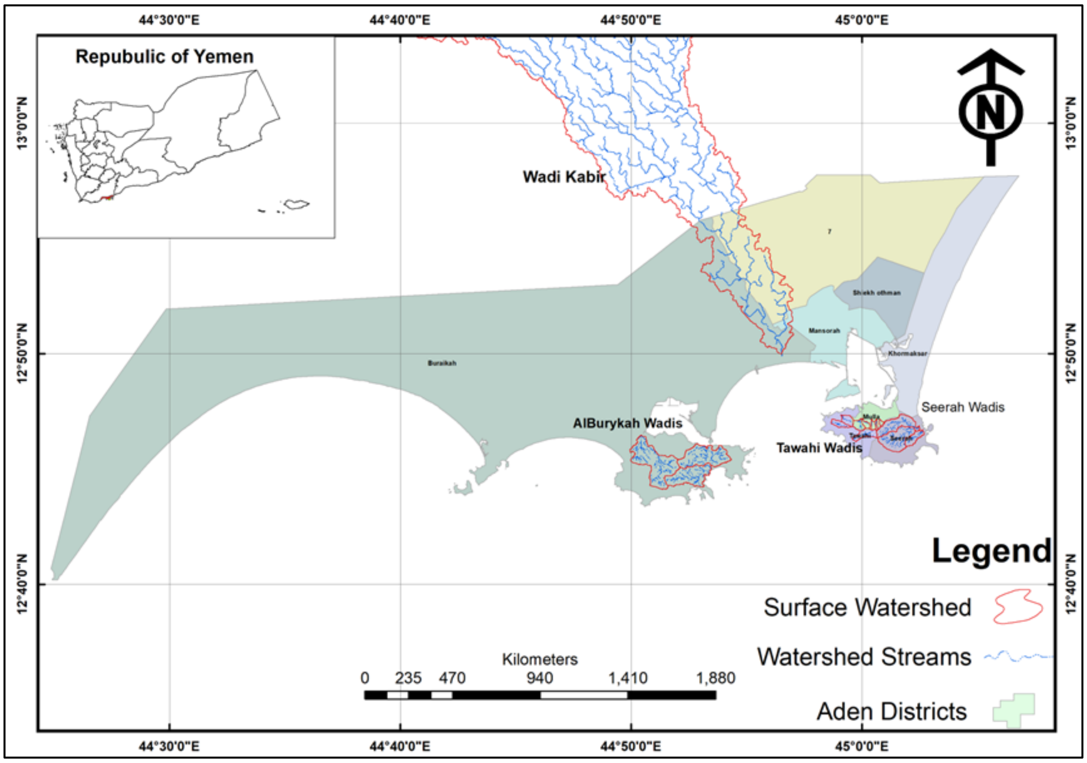

Figure (1): Geographical location of Aden Governorate.

2.2. Geological and Geomorphological Framework:

The geology of Aden is dominated by the Late Tertiary Yemen Volcanics (Yemen Trap Series). The Aden Peninsula is essentially a volcanic complex consisting of:

- **The Tawahi Series:** The oldest rocks, comprising volcanic tuff and rhyolite layers.
- **The Crater Series:** Characterized by rhyolite, trachyte, and basaltic rocks forming the Shamsan Mountain Range.
- **The Al-Buraiqa Series:** Volcanic tuff and basaltic formations in the western part of the governorate.
- **Quaternary Deposits:** Represented by extensive sand dunes, saline flats (sabkhas), and alluvial deposits in the wadi beds.

The topography is characterized by steep volcanic slopes descending from the Shamsan peaks (up to 553m) toward the coastal plains. This "horseshoe" configuration focuses runoff toward the urban centers, creating a natural funnel for flash floods. The topographic gradients shown in Figure 2 demonstrate a rapid elevation drop from the Shamsan volcanic massif toward the coastal plain, with slopes exceeding 0.30 m/m in several upstream catchments. This steep relief significantly reduces lag time and accelerates flood wave propagation toward densely populated districts.

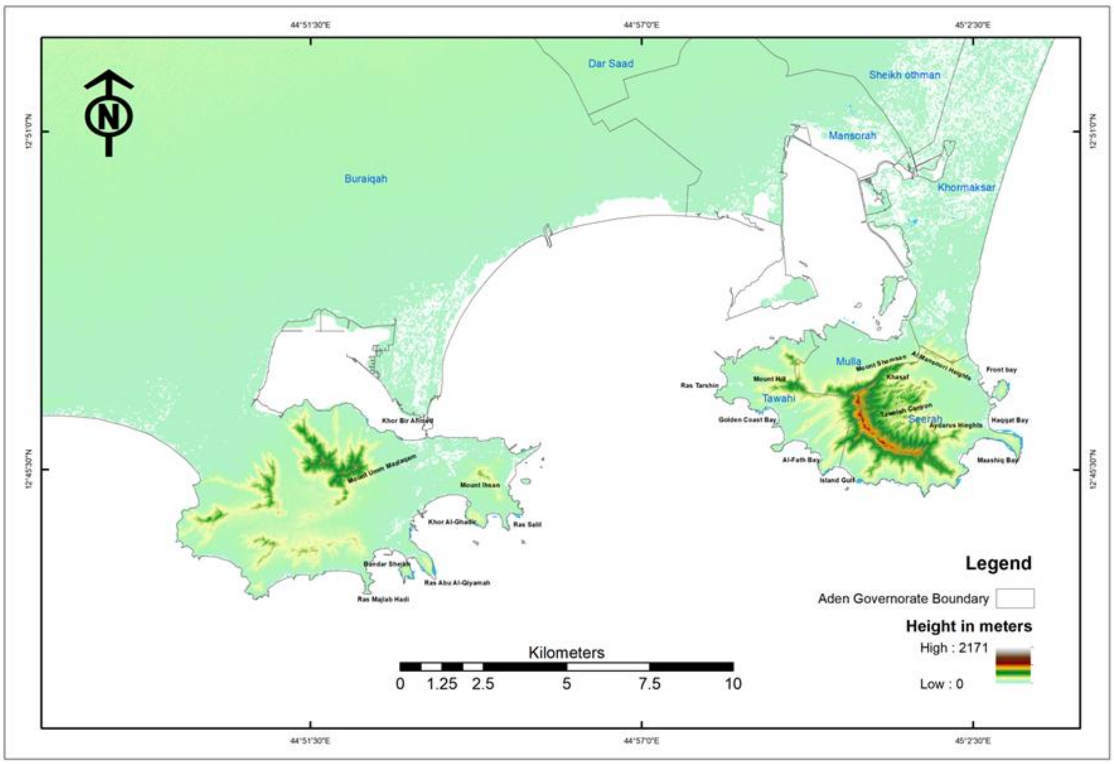

Figure (2): Topographic map of Aden Governorate.

2.3. Climatic and Rainfall Regime:

Aden's climate is arid, with high summer temperatures (up to 37°C) and mild winters. Rainfall is characterized by extreme variability and scarcity, primarily occurring during the summer monsoon and winter cyclonic events. Analysis of 75 years of data (1948–2023) from the Aden International Airport station shows a mean annual maximum rainfall of 25.3 mm, with an absolute maximum of 133 mm recorded in 1983.The General Extreme Value (GEV) distribution was found to be the most appropriate model for predicting extreme rainfall depths. Figure 3 shows the design of rainfall depths for different return periods using (GEV Model).

Table (1): Design Rainfall Depths for Different Return Periods (GEV Model)

Return Period (Years)	**3**	**5**	**10**	**20**	**25**	**50**	**100**
Rainfall Depth (mm)	21.7	33.9	57.3	92.8	108.0	170.0	266.0

The nonlinear increase in rainfall depth from 50-year (170 mm) to 100-year (266 mm) return periods indicates a sharp escalation in extreme rainfall intensity. This exponential growth pattern reinforces the necessity of designing infrastructure based on high-return scenarios rather than historical averages, Table1.

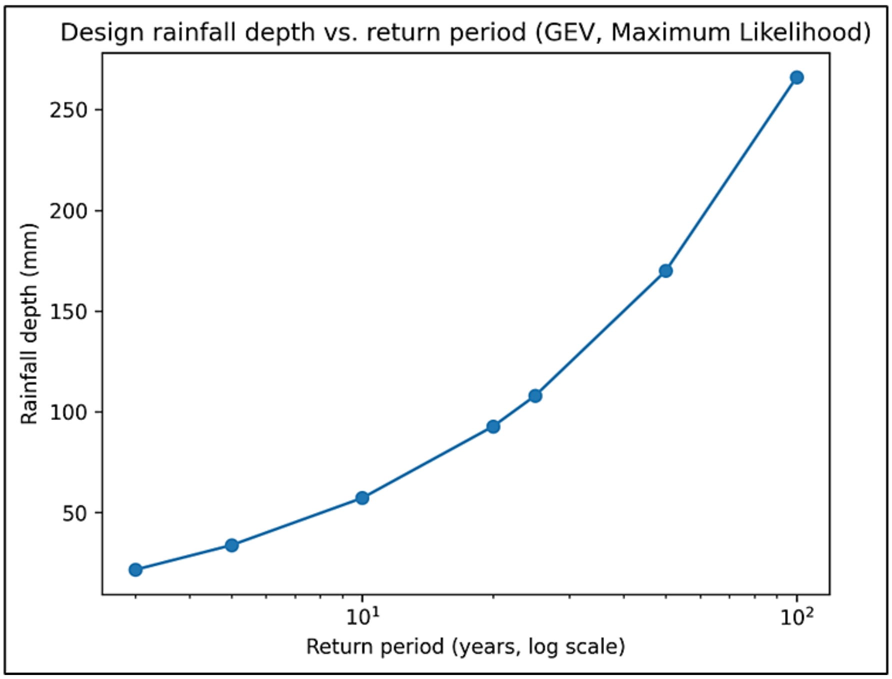

Figure (3): Rainfall Depth Curve for Different Return Periods Using the GEV (Max Likelihood) Model.

Figure 3 illustrates the statistically fitted rainfall–frequency curve derived from the General Extreme Value (GEV) distribution using the Maximum Likelihood estimation method. The curve demonstrates a pronounced nonlinear escalation in rainfall depth as the return period increases, particularly beyond the 25-year threshold. This sharp upward curvature reflects the increasing influence of extreme climatic variability in arid coastal environments. Notably, the transition from the 50-year (170 mm) to the 100-year (266 mm) return period represents a substantial amplification of rainfall magnitude, exceeding 55% growth. Such exponential behavior underscores the inadequacy of designing hydraulic infrastructure based solely on moderate return intervals and justifies the adoption of high-return design standards for flood mitigation planning in Aden Governorate.

3. Methodology

3.1. Data Sources and Integration:

The study integrates multiple data streams:

1 **Topographic Data:** 30m resolution Digital Elevation Model (DEM) from SRTM.
2 **Rainfall Data:** Long-term records from the Civil Aviation and Meteorology Authority.
3 **LULC Data:** Sentinel-2 imagery (10m resolution) processed via the ArcGIS Living Atlas.
4 **Soil Data:** Hydrological soil group classifications obtained from global databases and field verification.

3.2. Hydrological Modeling with WMS and HEC-1:

The Watershed Modeling System (WMS 11.0) was used for automated basin delineation and parameter extraction. The HEC-1 model was selected for its robustness in simulating single-event floods in both simple and complex watersheds. Previous hydrological investigations in comparable arid basins demonstrated satisfactory performance of HEC-based models in simulating peak discharge under extreme rainfall conditions [2,10]. The Soil Conservation Service (SCS) Curve Number (CN) method was applied. CN values were adjusted for moderate antecedent moisture conditions (CN II).

The SCS-CN method is widely recognized for event-based runoff estimation in ungauged and semi-arid catchments due to its adaptability to land use and soil variability [9,11]. The SCS Dimensionless Unit Hydrograph method was used to convert excess rainfall into surface runoff. For basins with multiple sub-catchments, the Muskingum-Cunge method was employed for channel routing.

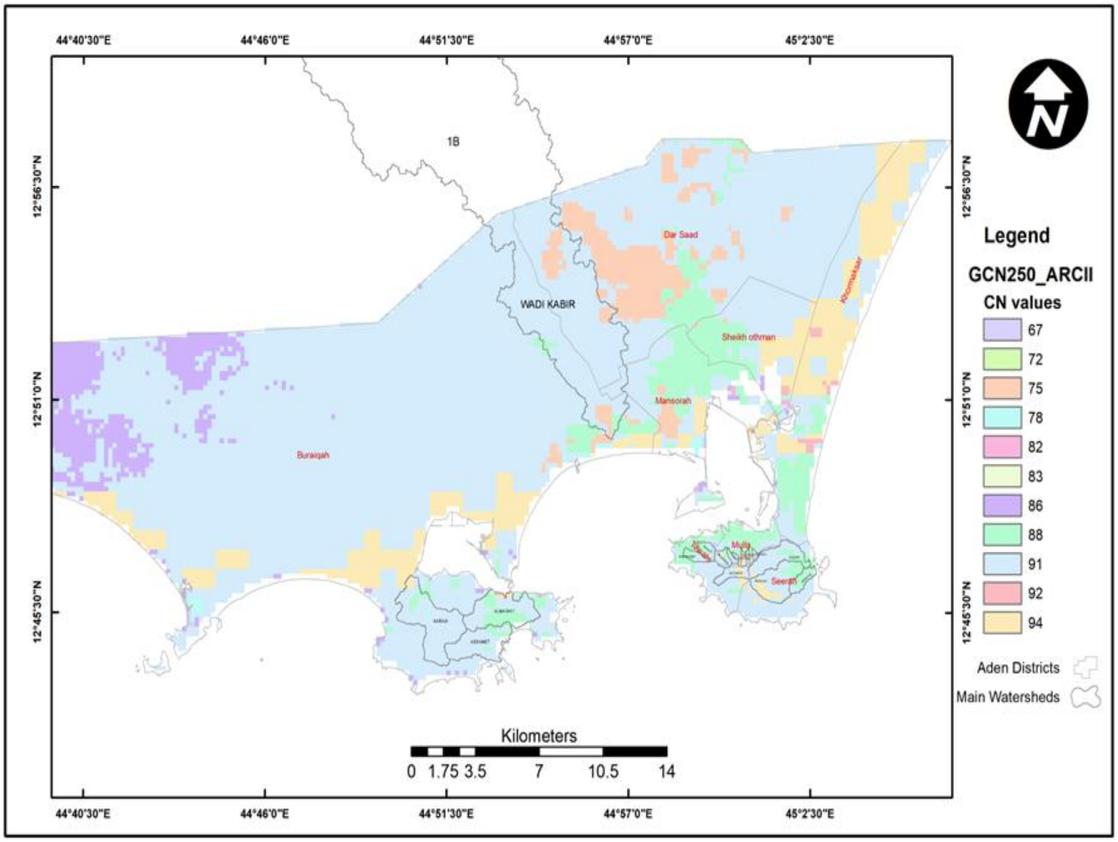

Figure (4): Spatial Distribution of Curve Number (CN II) Values under Average Soil Moisture Conditions.

Figure (4) reveals a spatial increase in Curve Number values within urbanized districts, particularly in Sirah and Al-Mualla, where CN values exceed 85. This indicates limited infiltration capacity and elevated runoff coefficients, directly contributing to higher peak discharge during extreme rainfall events.

3.3. Land Use and Land Cover Analysis (2017–2023):

A comparative analysis of LULC maps was conducted to quantify urban expansion. Seven classes were identified: Built Area, Crops, Trees, Water, Flooded Vegetation, Bare Ground, and Rangeland. The transition from "Bare Ground" to "Built Area" was specifically monitored as it directly impacts the Curve Number and subsequent runoff volume.

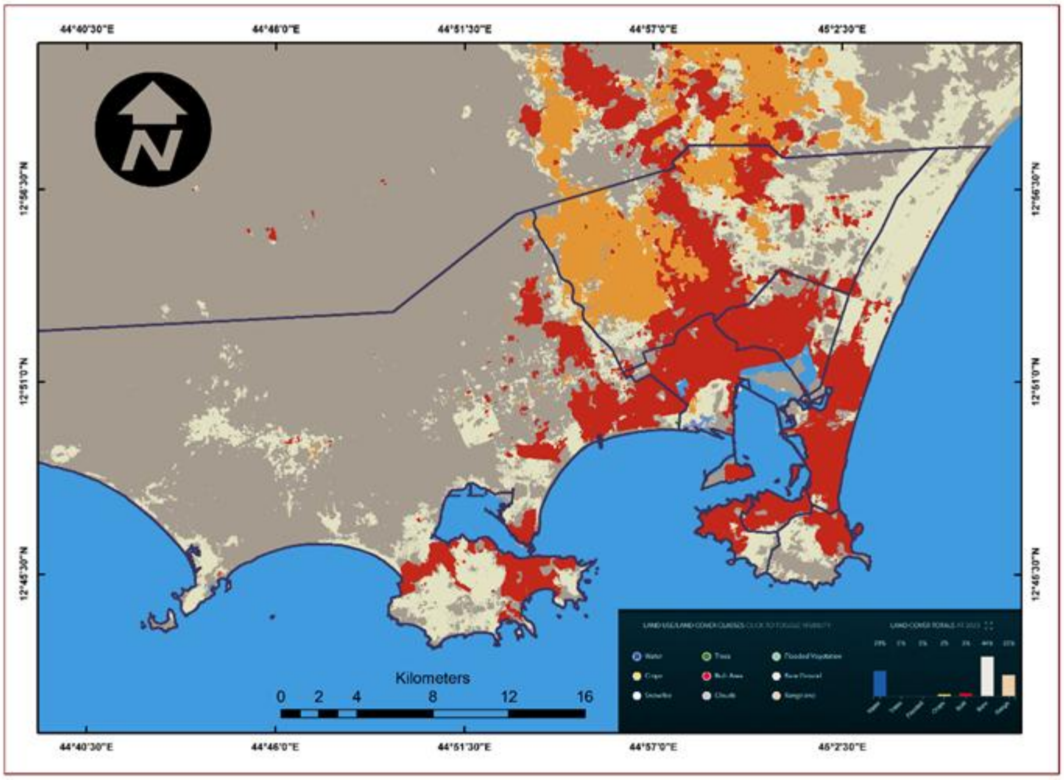

Figure (5): Land Cover and Land Use Classes for the Year 2023 in Aden Governorate.

Figure 5 highlights the spatial transformation of land cover patterns across Aden Governorate between 2017 and 2023. The dominant transition from bare ground to built-up surfaces is concentrated along drainage corridors and coastal urban expansions. This spatial encroachment into natural runoff pathways not only increases the effective Curve Number but also disrupts natural sediment transport processes, thereby intensifying localized flood hazards. The clustering of urban growth near wadi outlets suggests a direct anthropogenic amplification of hydrological risk.

3.4. Model Uncertainty and Sensitivity Analysis:

A sensitivity assessment was conducted to evaluate the influence of Curve Number (CN) and rainfall depth variability on peak discharge outputs. Results indicate that a ±5% variation in CN values could alter peak discharge by up to 12%, highlighting the importance of accurate LULC classification. This finding aligns with established SCS-based hydrological applications in arid environments [9].

4. Results and Discussion

4.1. Morphometric Characterization of Drainage Basins:

The automated delineation using WMS identified 15 primary drainage basins impacting the urban areas of Aden. The morphometric analysis reveals critical insights into the flood potential of these watersheds, as shown in Table 3. Morphometric parameters such as basin slope, drainage density, and shape factor are critical indicators of hydrological response time and flood magnitude [5].

Table (2): Comprehensive Geomorphometric Parameters of Surveyed Basins.

Basin Name	Area (km^2)	Max Flow Length (m)	Basin Slope (m/m)	Shape Factor	Sinuosity	Tc (hr)
Wadi Al-Kabir	1874.61	141,992	0.171	4.12	1.62	13.81
Wadi Al-Khasaf	2.92	3,580	0.330	4.22	1.24	0.58
Wadi Al-Tawilah	3.48	2,967	0.370	2.57	1.08	0.47
Wadi Al-Aidaroos	0.96	973	0.270	3.82	0.97	0.42
Wadi Goldmoor	7.44	5,992	0.220	2.94	1.28	0.92
Wadi Qaroo	5.19	4,140	0.150	1.30	1.59	0.87
Wadi Al-Masafi	4.25	4,645	0.110	3.01	1.30	1.08
Castro-3	0.27	677	0.350	3.03	0.75	0.19

The basins in the Sirah and Al-Mualla districts (e.g., Al-Khasaf, Al-Tawilah, Castro) are characterized by extremely short times of concentration (Tc < 1hour). This indicates that urban areas at the base of these mountains have very little lead time between the start of an intense rainfall event and the arrival of the peak flood wave. The morphometric contrast between Wadi Al-Kabir (area = 1874 km^2) and smaller basins such as Castro-3 (0.27 km^2) highlights the dual nature of flood hazards in Aden: large-scale volumetric flooding from extensive basins and rapid flash responses from steep micro-catchments with Tc < 0.5 hr.

4.2. Hydrological Response and Flood Estimation:

The HEC-1 model outputs provide a quantitative assessment of flood risk across different return periods. The results highlight the catastrophic potential of 50-year and

100-year events. The extreme discharge values observed in Wadi Al-Kabir are consistent with large-scale arid watershed behavior, where expansive catchment areas combined with low infiltration volcanic substrates result in disproportionate runoff amplification during high-return storms [1].

4.2.1. Sirah District (Crater Plateau):

Sirah is the most historically significant and densely populated district. It is impacted by three main basins: Al-Khasaf, Al-Tawilah, and Al-Aidaroos.

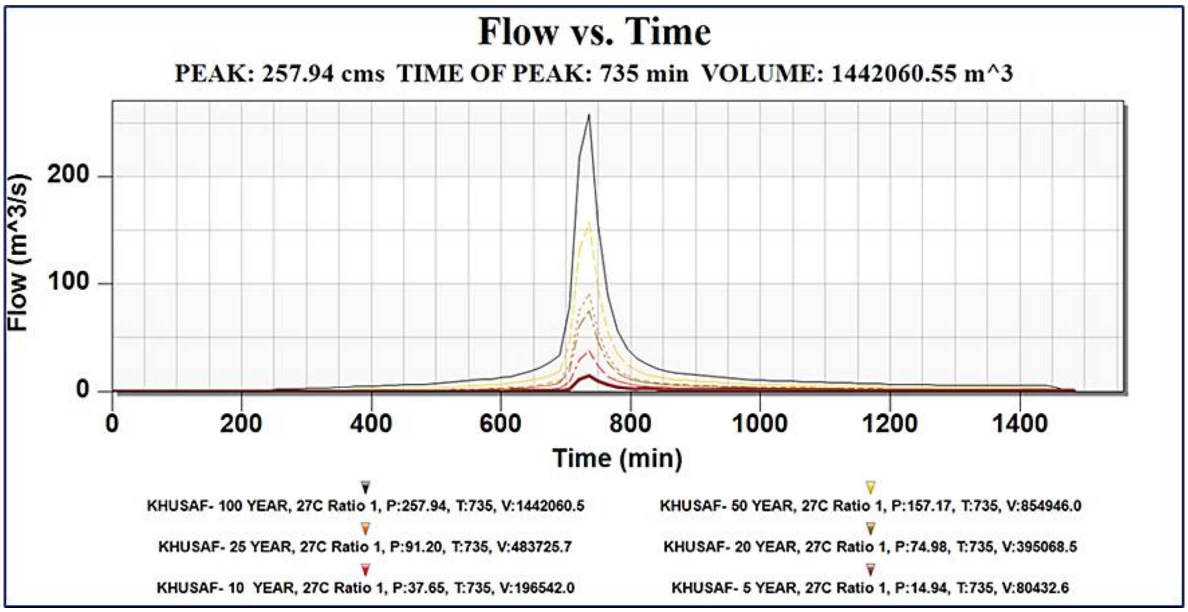

Figure (6): Flood Flow Hydrograph of Wadi Al-Khasaf Basin for Return Periods (5, 10, 20, 25, 50, and 100 years).

Table (3): Flood Characteristics for Sirah District Basins.

Return Period	Parameter	Al-Aidaroos	Al-Tawilah	Al-Khasaf
25 Years	Peak Discharge (m^3/s)	14.02	51.54	91.20
	Volume (m^3)	74,421	270,278	483,725
50 Years	Peak Discharge (m3/s)	24.39	88.63	157.17
	Volume (m^3)	131,533	477,693	856,946
100 Years	Peak Discharge (m^3/s)	40.34	145.26	257.94
	Volume (m^3)	221,861	805,724	1,442,060

The combined 100-year peak discharge from these three basins exceeds 440 m³/s, all converging on the narrow streets of the Crater district, shown in Table 4. The progressive increase in peak discharge and runoff volume across return periods demonstrates a highly sensitive hydrological response. Notably, peak discharge in Al-Khasaf nearly triples between the 25-year and 100-year scenarios, indicating strong nonlinear runoff amplification.

4.2.2. Al-Buraiqa District and Wadi Al-Kabir:

Wadi Al-Kabir represents the largest hydrological threat due to its massive catchment area. The 100-year flood volume of over 434 million m³ poses a significant risk to the industrial facilities and residential areas in Al-Haswa and Bir Ahmed, as shown in Figure 7& Table 5.

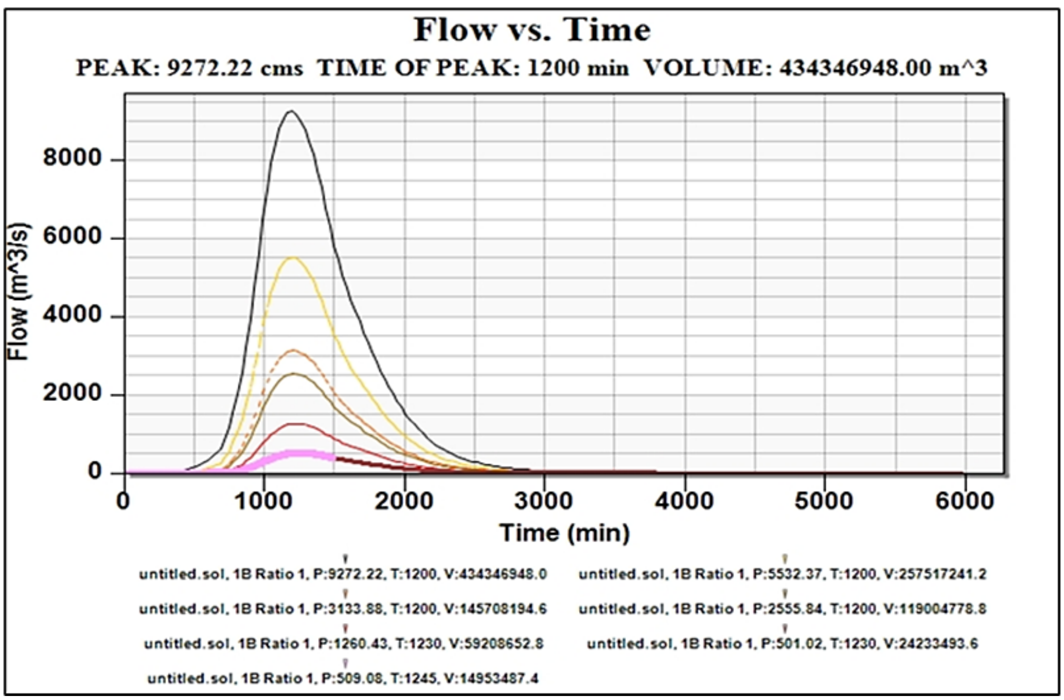

Figure (7): Flood Flow Hydrograph of the Wadi Al-Kabir Basin for Return Periods (5, 10, 20, 25, 50, and 100 years).

The hydrographs exhibit steep rising limbs and short time to peak, characteristic of arid flash flood systems. The sharp peak profile confirms limited natural storage capacity within the upstream basins.

Table (4): Flood Estimation for Wadi Al-Kabir (Al-Buraiqa).

Return Period	Peak Discharge (m^3/s)	Flood Volume (m^3)	Time to Peak (min)
10 Years	1,260	59,208,652	1,230
50 Years	5,532	257,517,241	1,200
100 Years	9,272	434,346,948	1,200

The exceptionally high peak discharge values for Wadi Al-Kabir reflect its extensive catchment area and low infiltration volcanic substrate. The relatively stable time-to-peak (~1200 min) suggests controlled routing dynamics but extreme volumetric loading downstream.

4.3. Spatial Inundation Analysis and Field Observations:

Spatial simulation using Global Mapper Pro 25, calibrated with field observations from the 2020 disaster, identified specific inundation "hotspots."

- **Al-Qati' (Al-Marsaba) Area:** This low-lying depression receives flows from Wadi Al-Aidaroos. Field data confirms that water levels reached 3 meters in 2020, inundating an area of 31,488 m^2. The basin-like morphology prevents natural drainage, leading to prolonged pooling and sediment accumulation, Figure 8, 9.

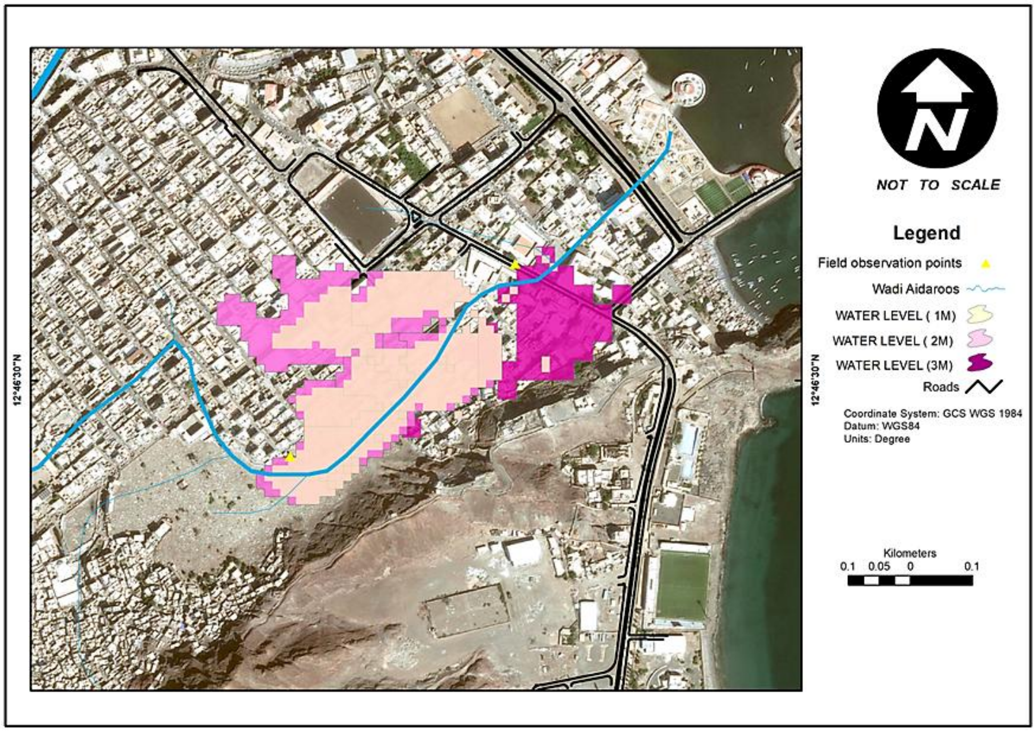

Figure (8): Flood Flow in the Wadi Al-Aidroos Basin, Illustrating Inundation Areas.

Figure (9): Features of the Field Visit During the Flood Disaster of 21 April 2020 in Al-Qati' Area.

- **Souq Al-Baz and Al-Seilah:** This commercial hub receives flows from Wadi Al-Tawilah. The analysis shows that water levels can reach 3 meters near the Al-Qadi passage, inundating 44,453 m², as shown in Figure 10.

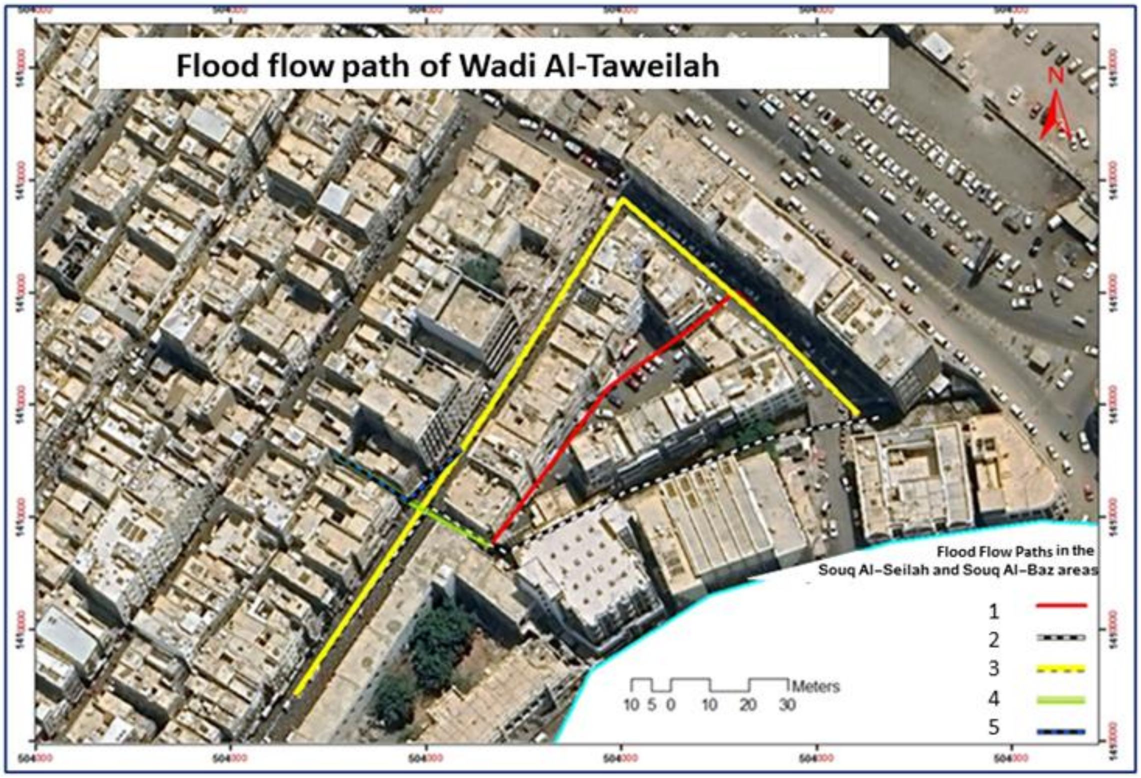

Figure (10): Floodwater accumulation centers and associated water level elevations in the Souq Al-Seilah and Souq Al-Baz areas.

- **Wadi Al-Kabir Outflow Area, Al-Haswa:** The 100-year flood volume of over 434 million m³ poses a significant risk to the industrial facilities and residential areas in Al-Haswa , Flood flow in Al-Wadi Al-Kabir for different rainfall return periods, illustrating inundation areas as shown in Figure 11, [2, 14].

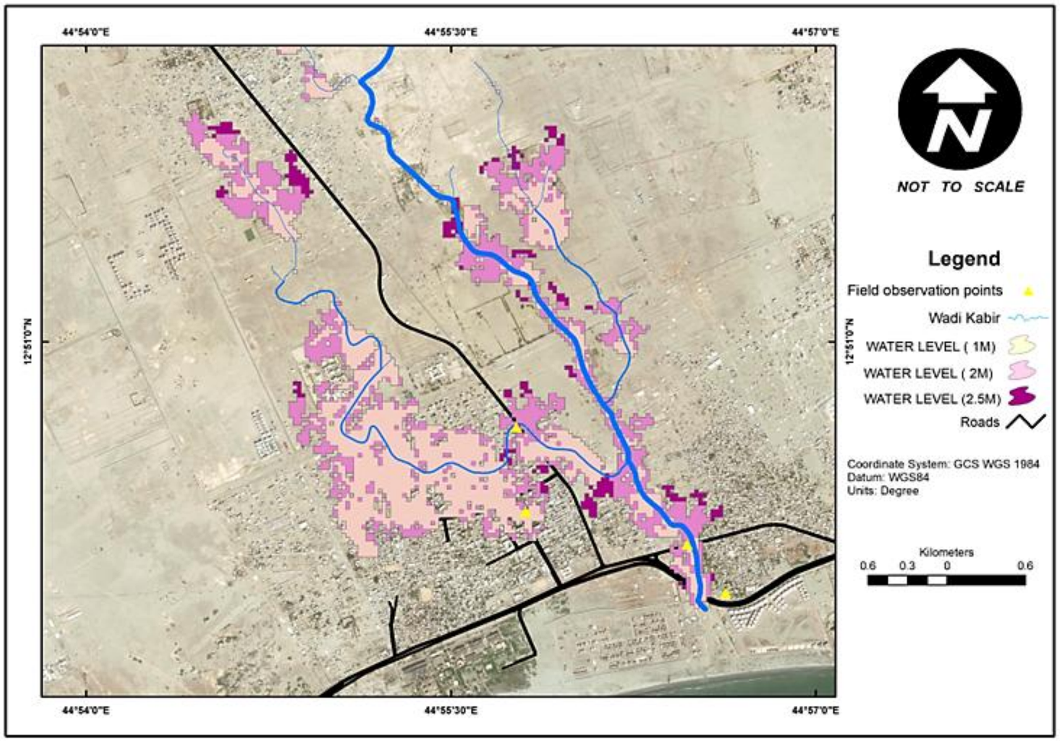

Figure (11): Flood flow in Al-Wadi Al-Kabir for different rainfall return periods, illustrating inundation areas.

The spatial inundation patterns correspond closely with topographic depressions and urban encroachment zones, confirming the reliability of the hydrological model calibration against field observations from the 2020 flood event.

4.4. Land Use Impact (2017–2023):

The transition from natural surfaces to impervious urban cover has significantly increased the Curve Number (CN) values across the governorate. The built-up area increased from 7,168,660 m² (2017) to 13,083,420 m² (2023).

This 82% increase in urban area has led to a corresponding increase in the peak discharge and total runoff volume for the same rainfall events, as the soil's infiltration capacity is replaced by impervious concrete and asphalt, Numerous studies confirm that increased impervious surface coverage directly elevates runoff coefficients and reduces lag time, intensifying flash flood peaks in urban basins [11,15].

The transformation of natural terrain into impervious urban surfaces significantly alters the watershed hydrological equilibrium, shifting the runoff generation mechanism from infiltration-excess to saturation-excess dominated processes.

5. Proposed Flood Risk Mitigation and Management Framework

Based on the hydrological modeling and spatial risk assessment, a multi-faceted strategy is required to protect Aden's population and infrastructure.

5.1. Structural Engineering Interventions:

Structural measures are essential for physically controlling and redirecting floodwaters.

- **Upstream Retention Dams:** It is proposed to construct new check dams in Wadi Al-Aidaroos and Wadi Al-Khasaf. These structures will attenuate peak flows and trap heavy sediments (boulders and gravel) before they reach the urban centers.

Figure (12): One of the dams in the Crater Plateau and the accumulated water behind it after rainfall.

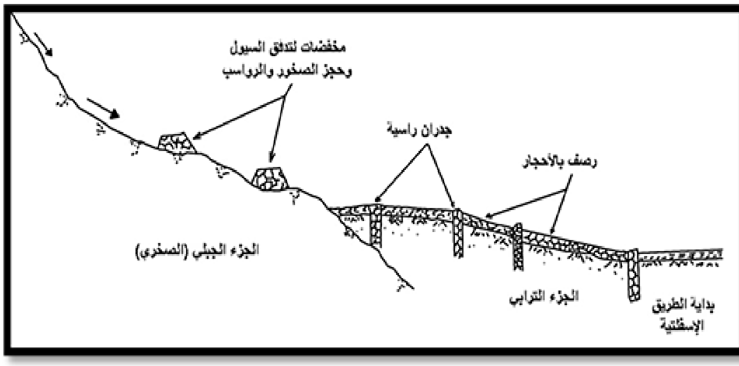

Figure (13): Proposed flow dissipators at 31 outlets of Wadi Al-Aidroos.

- **Rehabilitation of Historic Infrastructure:** The historic Tawilah cisterns and their associated channels must be regularly maintained. Removal of accumulated silt and debris is critical to restoring their original flood-mitigation capacity.

Figure (14): Channels of the Tawelah cisterns.

- **Design of High-Capacity Drainage Channels:** Existing urban drainage networks must be upgraded. Based on 100-year flow estimates, specific dimensions are proposed for key locations:

Table (5): Calculation of design dimensions for hydrological structures at selected sites.

Location	Rainfall Amount (mm) – 100-year Return Period	Calculated Discharge q (m^3/s)	Design Dimensions of Culvert		Remarks
			Width (m)	Height (m)	
Gold Moor Tunnel Opening	266	36.00	2.0	2.0	—
Al-Bank Culvert, Crater	266	132.89	3.5	2.0	—
Al-Kabir Wadi	266	9,272.00	50.0	3.0	Requires a ground bridge with a minimum width of 50 m

- **Wadi Al-Kabir Outlet:** Requires a ground bridge with a minimum width of 50m and height of 3m.
- **Al-Bank Culvert (Crater):** Requires a width of 3.5m and height of 2m.
- **Goldmoor Tunnel:** Opening should be maintained at 2.0m x 2.0m.

5.2. Non-Structural and Policy Measures:

Non-structural measures provide a cost-effective way to reduce vulnerability and enhance resilience.

- **Early Warning Systems (EWS):** Implementation of a real-time hydrological monitoring network. Automated rain gauges and water level sensors in the upper catchments can provide critical lead time (30-60 minutes) for the evacuation of high-risk areas like Al-Qati'.
- **Strict Zoning and Land-Use Regulations:** The "Protection Zone" of Wadi Al-Kabir and other major wadis must be legally enforced. All unplanned construction within the 100-year floodplain must be prohibited.

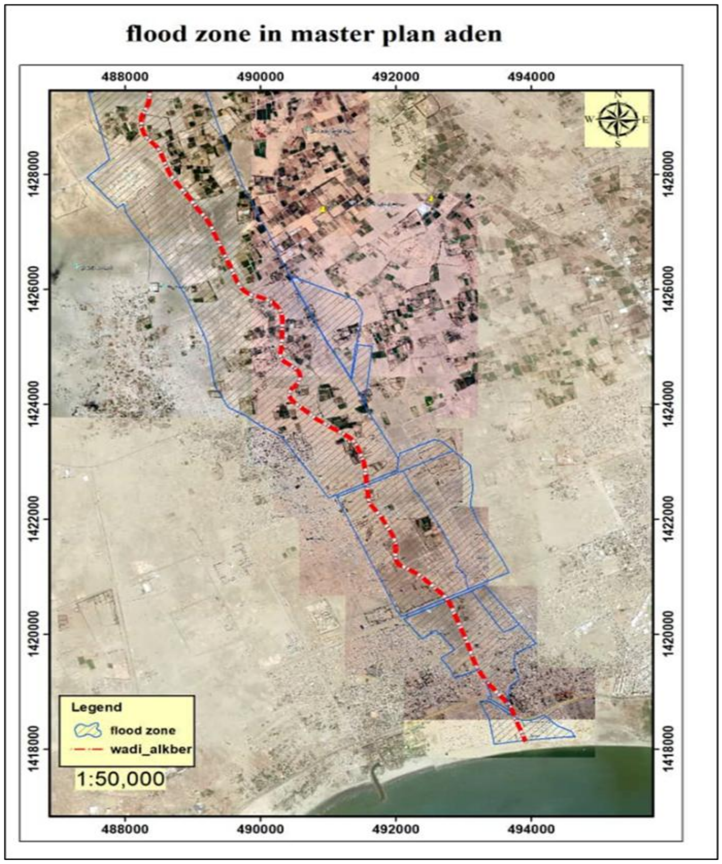

Figure (15): Protection zone of Wadi Al-Kabir & the boundaries of the safe floodplain area.

Figure 15 delineates the proposed 100-year floodplain protection boundary. The overlay with existing urban infrastructure reveals multiple conflict zones where enforcement of zoning regulations is critically required to prevent recurrent disaster exposure.

- **Community Awareness and Preparedness:** Educational campaigns are necessary to inform residents of flood-prone zones and emergency evacuation routes.

5.3. Sediment and Debris Management:

Flash floods in Aden transport significant volumes of sediment. Estimated sediment volumes range from 17 m^3/year for Wadi Al-Aidaroos to over 33,000 m^3/year for Wadi Al-Kabir.

Regular post-flood cleaning of culverts and channels is mandatory to prevent blockage during subsequent events.

6. Conclusions and Recommendations

6.1. Key Findings:

This study has successfully integrated hydrological modeling (WMS/HEC-1) and spatial analysis (GIS) to provide a comprehensive assessment of flash flood risks in Aden Governorate.

1 **High Vulnerability:** The combination of steep volcanic terrain and short concentration times ($T_c < 1$ hr) makes the districts of Sirah, Al-Mualla, and Al-Tawahi highly susceptible to rapid-onset flash floods.

2 **Catastrophic Potential:** 100-year peak discharges for major wadis (e.g., Wadi Al-Kabir at 9,272 m^3/s) far exceed the capacity of current urban infrastructure.

3 **Urban Impact:** Rapid urban expansion (82% increase in built area since 2017) has significantly exacerbated flood risks by obstructing natural drainage and increasing runoff volumes.

4 **Critical Hotspots:** Spatial mapping identified Al-Qati', Souq Al-Baz, and Al-Haswa as the most vulnerable inundation zones.

6.2. Strategic Recommendations:

To ensure the long-term safety and sustainability of Aden, the following actions are recommended:

- **Integrate Hydrology into Urban Planning:** Future urban development plans must be based on the 100-year floodplain maps generated in this study.
- **Invest in Infrastructure:** Prioritize the construction of the proposed check dams and high-capacity culverts.
- **Establish a National Hydrological Authority:** A unified agency is needed to manage monitoring stations, EWS, and flood response strategies.
- **Continuous Monitoring:** Regular updates to the LULC and hydrological models are necessary to account for ongoing urban growth and climate change impacts.

https://doi.org/10.59992/IJSR.2026.v5n2p16 E-ISSN 2755-3418

The integrated modeling framework presented in this study demonstrates the necessity of coupling hydrological simulation with spatial planning tools to achieve climate-resilient urban development in coastal arid environments. The methodology is transferable to other rapidly urbanizing cities facing similar geomorphological constraints.

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