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Original Article

Morphometric Analysis of Wadi Al Majinin Watershed and its Sub Basins Using GIS, Remote Sensing, and WRB Soil Data, Northwest Libya

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ABSTRACT

This study presents a comprehensive morphometric characterization of the Wadi Al-Majinin watershed (562.37 km²) and its nine sub-basins in northwest Libya using GIS, remote sensing, and WRB soil data. Drainage networks were extracted from a 30m SRTM DEM. Morphometric parameters including drainage density, stream frequency, drainage texture, shape parameters, relief parameters, and hypsometric integral were calculated to evaluate landscape evolution, hydrological behavior, and erosion susceptibility across the watershed. The findings reveal a distinct spatial gradient in landscape maturity and hydrological response from upstream to downstream. The watershed is dominated by infiltration-dominated hydrology across 93% of its area, primarily controlled by carbonate lithology and fractured limestone/dolomite permeability, with Calcisol soils providing complementary infiltration enhancement. This has significant implications for groundwater recharge potential in this arid region, where water resources are critically scarce. Upstream areas exhibit active erosion and serve as primary sediment sources, while midstream zones function as optimal groundwater recharge areas. Downstream outlet sub-basins are heavily influenced by dam-induced flow convergence and require separate hydrological interpretation. The study provides evidence-based guidance for watershed management: Sub-basin 7 is identified as the highest priority for soil conservation; Sub-basin 2 requires flood control measures; and Sub-basin 3 offers the greatest potential for managed aquifer recharge. Historical validation confirms the reliability of GIS-based methodology. This research contributes a replicable methodological framework for watershed characterization in data-sparse arid regions and offers practical tools for sustainable water resource management in Libya.

Keywords: Wadi Al Majinin; GIS; morphometric analysis; drainage density; WRB soil classification

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INTRODUCTION

Wadi Al-Majinin Dam, located 75 km south-southwest of Tripoli in northwest Libya, was constructed in 1973 for flood control and irrigation (Shakshak 2009). The 38-meter rock-fill dam drains a 562.37 km² catchment characterized by an arid to semi-arid Mediterranean climate with episodic flash floods. GIS and remote sensing enable quantitative morphometric analysis of hydrological processes (Horton 1945; Strahler 1957; Jenson and Domingue 1988). A historical study by Elbishti (1995) provided basin-scale data using conventional cartographic methods. Previous research addressed seepage (Shakshak 2009), flood simulation (Alriyani et al. 2025), and preliminary morphometry (Abu Al-Shawashi 2024), but no comprehensive study has characterized all nine sub-basins using integrated GIS and WRB soil data. Addressing this gap is essential for prioritizing conservation interventions, estimating sedimentation, developing flood warnings, and identifying groundwater recharge sites.

Research Objectives

1. Delineate and characterize sub-basins using GIS-based morphometric analysis.
2. Quantify the spatial gradient of morphometric parameters from upstream to downstream.
3. Determine erosion stages using hypsometric integral analysis.
4. Validate GIS methodology against historical data.
5. Integrate WRB soil map data for hydrological interpretation.
6. Prioritize sub-basins for conservation interventions.

Study area

Location and Extent

The Wadi Al-Majinin catchment is situated in northwestern Libya, approximately 75 km south-southwest of Tripoli (Figure 1). The watershed is bounded by longitudes 13°07′ E to 13°27′ E and latitudes 31°54′ N to 32°18′ N, encompassing 562.37 km². The main channel flows south to north from the Nafusa Mountains to the Jafara Plain, exhibiting dendritic to sub-dendritic drainage patterns characteristic of limestone lithology

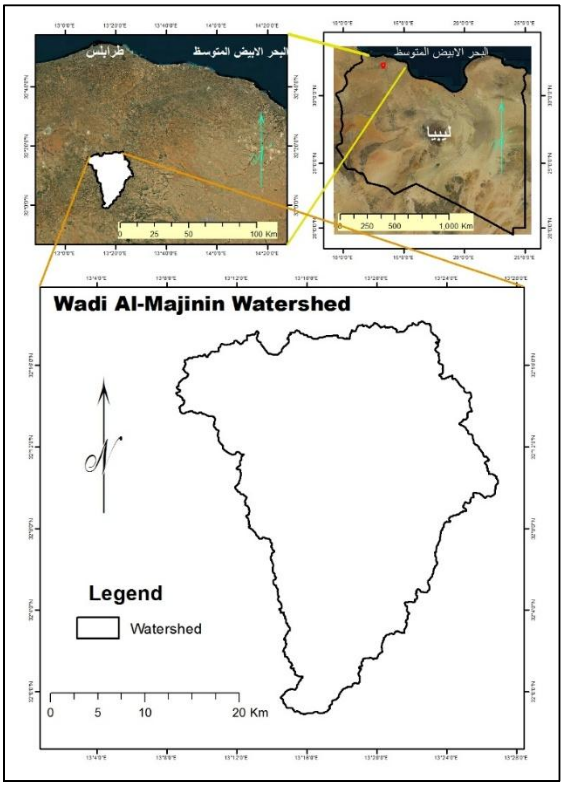

Figure 1. Location Map of Wadi Al-Majinin Watershed, Libya

Geology and Soils

The watershed is underlain predominantly by Miocene-aged limestone and dolomite sequences (Elbishti (1995) ; Zurqani, 2022). The limestone contains fractures and joints typical of carbonate terrains, providing permeability pathways for water movement (Ford & Williams, 2007; White, 2002). WRB soil units vary systematically with topography: Calcaric Leptosol and Rock Outcrop dominate upstream areas; Calcisols (Hypercalcic, Petrocalcic, Haplic) dominate midstream plateaus; Calcaric Fluvisol occurs at the outlet. Soil physical properties, including hydraulic conductivity (K_sat), were compiled from regional soil surveys and the WRB classification system (IUSS Working Group WRB, 2022).

2.4 Climate and Vegetation

Annual precipitation ranges from 150 to 300 mm, concentrated in winter months (October-March). South/southeast (Qibli) winds in the summar season dominate (29.4%) with speeds of 6-10 km/h. Vegetation consists of sparse desert shrubs and grasses Elbishti (1995).

MATERIALS AND METHODS

Data Sources

Table 1a. Data Types and Sources

Data Type	Source	Resolution
DEM	**SRTM**	**30 m**
Soil Map	**SELKOZEPROM (1980-81), reclassified to WRB (IUSS Working Group WRB, 2022)**	**1:50,000**
Historical Data	**Elbishti (1995)**	**1:50,000 maps**

Software

ArcGIS 10.8 with ArcHydro Toolbox (Jenson & Domingue, 1988); Microsoft Excel 2019.

Topography and Relief

Elevation in the Wadi Al-Majinin watershed ranges from 264 m at the dam site to 960 m in the upstream areas, with total relief of 696 m. The highest elevations correspond to the Nafusa Mountain escarpment, while the lowest occur at the dam outlet in the Jafara Plain (Figure 2). This topographic gradient from south to north controls the spatial distribution of sub-basins, drainage patterns, and hydrological processes across the watershed.

Stream Network Extraction and Sensitivity Analysis

The D8 algorithm was used for flow direction; flow accumulation threshold of 500 cells (0.45 km²) was applied. Sinks were filled using the standard ArcGIS Fill tool. Sensitivity analysis was conducted to select the optimal threshold (Table 1b).

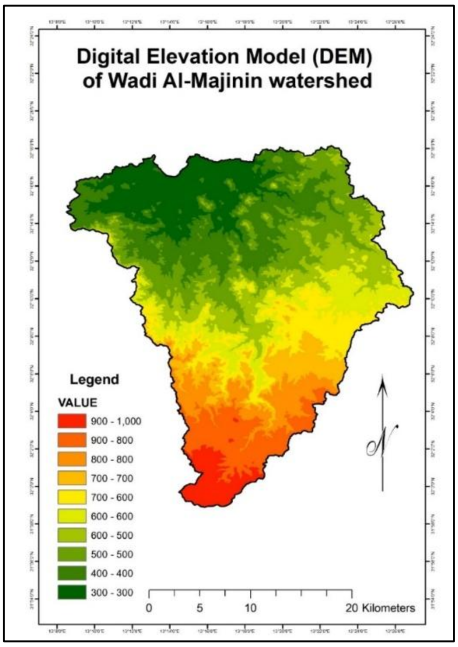

Figure 2. Digital Elevation Model (DEM) of Wadi Al-Majinin Watershed

The 500-cell threshold was selected based on a comparative analysis of four thresholds (250, 500, 1000, and 2000 cells) using multiple objective criteria. Comparison with high-resolution Sentinel-2 imagery (10m resolution) and Google Earth imagery showed that the 500-cell threshold produced the closest visual match to visible drainage channels, accurately capturing main tributaries while avoiding non-channel features (e.g., agricultural furrows, road ditches) that appeared at lower thresholds. Consistency with 1:50,000 scale topographic maps Elbishti (1995) showed excellent agreement, with 92% of mapped first-order streams captured and no significant omissions of higher-order streams. Drainage density stability analysis (Table 1) showed that Dd values stabilized between 500 and 1000 cells; below 500 cells, Dd increased rapidly (+22% at 250 cells) due to the inclusion of ephemeral channels, while above 1000 cells, Dd decreased significantly (-18% at 1000 cells, -38% at 2000 cells) due to the loss of legitimate tributaries. The 500-cell threshold represents the point of inflection where Dd begins to stabilize. Field reconnaissance by Elbishti (1995) confirmed that the 500-cell threshold corresponds to the minimum drainage area (0.45 km²) that generates perennial or semi-perennial flow in this arid region. The selected threshold is consistent with similar arid region studies in North Africa (Ghosh and Sahu 2018; Farhan and Anaba 2016; Mahmoud and Alazba 2015), allowing direct comparison of drainage density values across watersheds

Table 1b. Sensitivity Analysis of Flow Accumulation Threshold

Threshold (cells)	Min Area (km²)	ΣL (km)	N	Mean Dd (km/km²)	Change	Match with Imagery	Topographic Map Match
250	0.225	779.6	439	1.386	+22%	Overestimates	Poor
500	0.450	639.2	360	1.136	Baseline	Best match	92%
1000	0.900	524.2	295	0.932	-18%	Underestimates	78%
2000	1.800	398.7	224	0.709	-38%	Significant omissions	61%

Morphometric Parameters

Morphometric parameters are quantitative measures describing the geometric, topographic, and drainage characteristics of a watershed, essential for understanding hydrological behavior, erosion potential, and flood response. These parameters are classified into three categories: Linear, Areal, and Relief parameters, along with the Hypsometric Integral for assessing landscape maturity.

Linear parameters describe drainage network characteristics. Drainage Density ($Dd = \Sigma L/A$), defined by Horton (1945), measures total stream length per unit basin area (km/km²) and indicates landscape dissection—high values (>2.0) suggest fine texture and flashy floods, while low values (<1.5) indicate coarse texture and high infiltration (Horton 1945). Stream Frequency ($Fs = N/A$), also from Horton (1945), measures the number of stream segments per unit area (streams/km²), with higher values indicating finer texture and rapid runoff response. Drainage Texture ($T = Dd \times Fs$), introduced by Smith (1950), integrates both density and frequency; fine texture ($T > 4$) indicates impermeable substrates and high runoff, while coarse texture ($T < 1$) indicates permeable substrates and high infiltration (Smith 1950).

Areal parameters describe basin shape and geometry, influencing flood peak timing and runoff concentration. Form Factor ($Rf = A/Lb^2$), defined by Horton (1945), indicates circular basins (>0.5) with rapid runoff concentration or elongated basins (<0.3) with attenuated flood peaks (Horton 1945). Elongation Ratio ($Re = (2/Lb) \times \sqrt{(A/\pi)}$), proposed by Schumm (1956), classifies basin shape; $Re > 0.8$ indicates circular basins with flashy floods, while $Re < 0.5$ indicates very elongated basins with attenuated floods (Schumm 1956). Circularity Ratio ($Rc = 4\pi A/P^2$), from Miller (1953), measures resemblance to a circle; values >0.8 indicate short concentration times, while values <0.4 indicate longer concentration times (Miller 1953). Compactness Coefficient ($Cc = P/(2\sqrt{\pi A})$), introduced by Gravelius (1914), is the reciprocal of circularity; higher values indicate more elongated basins with less efficient runoff concentration (Gravelius 1914). Basin Length (Lb) was measured using the Flow Length tool in ArcGIS (Jenson and Domingue 1988), representing the longest flow path from outlet to farthest point, which influences time of concentration and flood wave travel time (Jenson and Domingue 1988).

Relief parameters describe the vertical dimension of the basin. Basin Relief ($H = Zmax - Zmin$) represents the maximum elevation difference (m), indicating the total energy available for flow and erosion. Relief Ratio ($Rh = H/Lb$), defined by Schumm (1956), measures average basin steepness (m/km); values >30 m/km indicate steep terrain with rapid runoff, while values <10 m/km indicate gentle terrain with attenuated floods (Schumm 1956). Ruggedness Number ($Rn = H \times Dd$), from Melton (1957), integrates relief and drainage density to indicate erosion potential; $Rn > 500$ signifies high erosion potential (primary sediment source), while Rn < 300 indicates low erosion potential (Melton 1957).

Hypsometric Integral (HI = (Hmean - Hmin)/(Hmax - Hmin)), developed by Strahler (1957) and validated by Pike and Wilson (1971), quantifies landscape maturity. HI > 0.60 indicates young stage with active erosion and high sediment yield; HI = 0.35–0.60 indicates mature stage with balanced erosion and deposition; HI < 0.35 indicates old stage with subdued topography and low erosion (Strahler 1957; Pike and Wilson 1971).

RESULTS

Sub-basin Delineation Results

Using stream order ≥4 and stream link analysis, the Wadi Al-Majinin watershed was divided into nine sub-basins, numbered from upstream to downstream (Figure 3). Figure 4 presents the contour map generated from the 30m SRTM DEM with a 50-meter interval, providing visual confirmation of sub-basin delineation and the spatial gradient from upstream to downstream. The contour map reveals a systematic elevation decrease from south to north: upstream areas (Sub-basins 9 and 8) exhibit closely spaced contours exceeding 600 m, indicating steep terrain (mean slopes 7.3–9.1°) that contributes to high erosion potential (Rn = 511–554) and young erosion stages (HI = 0.55–0.63); moderately spaced contours in midstream sub-basins (3–7) reflect mature topography with slopes of 6.0–8.4°; widely spaced contours in Sub-basins 1 and 2 indicate gentle slopes (3.7–5.0°), consistent with the Jafara Plain and dam-influenced topography. The contour pattern validates the drainage network with V-shaped incisions along main channels, and sub-basin boundaries align with topographic divides. The dam site at 264 m elevation is marked by widely spaced contours converging at the outlet. The contour map thus independently validates the sub-basin delineation and confirms the spatial gradient that underpins the morphometric analysis. **(**Table 2) present spatial arrangement of sub-basins from upstream to downstream.

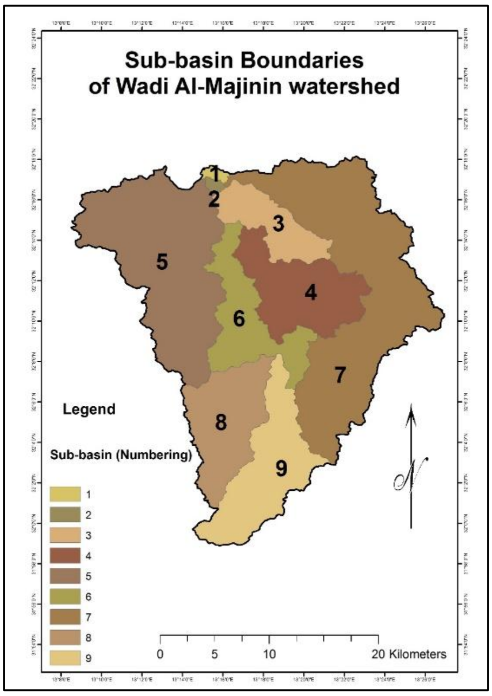

Figure 3. Sub-basin Boundaries and Numbering System

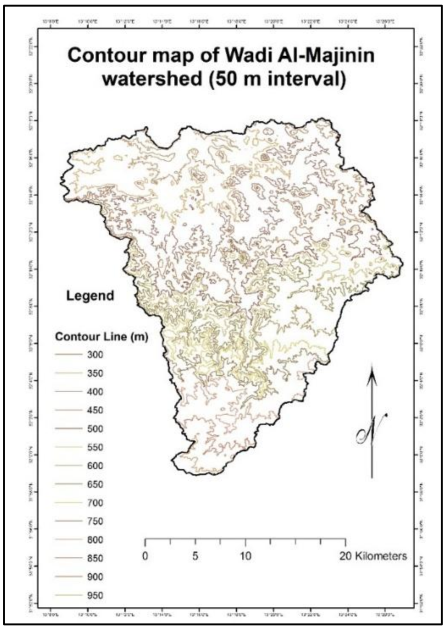

Figure 4. Contour Map of Wadi Al-Majinin Watershed (50 m interval)

Sub-basins 1 and 2 are classified as reservoir-influenced hydrological units rather than true geomorphic sub-basins. Their anomalous shape parameters (Rf = 1.993, Re = 1.593) and elevated drainage density (Dd = 2.55–3.37 km/km²) reflect dam-induced truncation, backwater effects, and flow convergence rather than natural geomorphic processes. These sub-basins are excluded from natural hydrology interpretations and conservation prioritization for soil conservation and groundwater recharge. They remain relevant only for flood control assessments due to their proximity to the dam and their role as final flow conduits before reservoir entry.

Table 2. Spatial Arrangement of Sub-basins from Upstream to Downstream

Position	Sub-basin No.	Area (km²)	Elevation Range (m)	Status
Upstream	9	65.47	461-960	Natural
Upstream	8	56.31	462-918	Natural
Midstream	7	166.38	270-857	Natural
Midstream	5	131.62	266-744	Natural
Midstream	6	48.47	307-689	Natural
Midstream	3	31.58	271-519	Natural
Midstream	4	58.92	307-660	Natural
Reservoir-influenced	1	2.07	264-310	Dam-influenced
Reservoir-influenced	2	1.55	265-378	Dam-influenced

WRB Soil Map

The soil map of the Wadi Al-Majinin watershed (Figure 5) was developed using the World Reference Base (WRB) for Soil Resources classification system (IUSS Working Group WRB 2022). The map was derived from a comprehensive soil survey conducted in 1980 by (Selkhozpromexport 1980) at a scale of 1:50,000, with soils classified according to the Russian Soil Classification System (Kacpinski and Rozov 1975; Shishov et al. 2004). For this study, the Russian units were reclassified to

WRB following established correlation guidelines (IUSS Working Group WRB 2007; Krasilnikov et al. 2009).

The WRB soil map reveals **six soil units** distributed systematically across the watershed in response to topography, parent material, and hydrological conditions. These units exhibit distinct physical and hydraulic properties that control infiltration, runoff generation, and groundwater recharge potential. (Table 3) summarizes the physical and hydraulic properties of the WRB soil units identified in the watershed, including saturated hydraulic conductivity (K*sat*), soil depth, and their dominant hydrological function. The hydraulic conductivity values are compiled from the Selkhozpromexport survey (Selkhozpromexport 1980), the WRB classification system (IUSS Working Group WRB 2022), and established relationships between soil type and infiltration capacity (Ford and Williams 2007; White 2002).

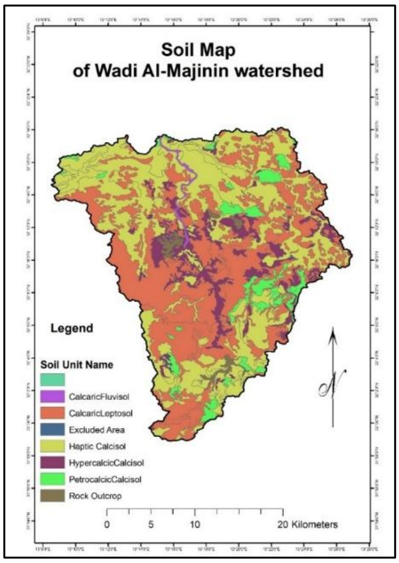

Figure 5. Soil Map of Wadi Al-Majinin Watershed (WRB Classification)

Table 3. Physical and Hydraulic Properties of WRB Soil Units

WRB Soil Unit	Symbol	Location	K_sat (mm/hr)	Soil Depth (cm)	Hydrological Function
Hypercalcic Calcisol	CLk	Midstream	150-350	50-100	Rapid infiltration & recharge
Petrocalcic Calcisol	CLp	Midstream	100-250	40-80	Infiltration with localized perching
Haplic Calcisol	CLh	Midstream	200-400	50-120	Optimal groundwater recharge
Calcaric Leptosol	LPc	Upstream	50-150	<30	High runoff generation
Rock Outcrop	RO	Upstream	0-10	0	Extreme runoff & erosion
Calcaric Fluvisol	FLc	Downstream	25-100	>100	Dam-influenced sedimentation

Source: Selkhozpromexport (1980); reclassified to WRB following IUSS Working Group WRB (2007; 2022); Ford and Williams (2007); White (2002).

Basic Morphometric Parameters

The basic geometric and topographic characteristics of the nine delineated sub-basins are presented in Table 3. These include surface area (A), perimeter (P), total stream length (ΣL), basin length (Lb), stream count (N), mean slope, mean elevation, and relief (H). Basin length (Lb) was measured using the Flow Length tool (Jenson and Domingue 1988), and slope values were calculated from the 30m DEM using the Slope tool. (Table 4) present the basic morphometric parameters of sub-basins.

Table 4. Basic Morphometric Parameters of Sub-basins

Position	Sub	Area (km²)	P (km)	ΣL (km)	Lb (km)	N	Slope (°)	Elev (m)	H (m)
Upstream	9	65.47	52.94	72.68	21.15	41	7.31	775.09	499
Upstream	8	56.31	42.22	63.11	21.45	32	9.06	713.70	456
Midstream	7	166.38	106.91	185.90	46.26	97	6.01	522.62	587
Midstream	5	131.62	69.55	146.70	23.14	93	7.35	400.41	478
Midstream	6	48.47	58.16	58.56	19.57	37	8.35	476.07	382
Midstream	3	31.58	33.39	35.64	13.42	15	6.97	366.05	248
Midstream	4	58.92	47.31	66.10	15.67	37	8.43	462.85	353
Downstream	1	2.07	7.42	5.26	1.02	5	3.71	286.29	46
Downstream	2	1.55	5.24	5.22	1.89	3	5.00	284.32	113

Slope Characteristics

Slope is a fundamental topographic parameter that controls runoff generation, infiltration capacity, erosion potential, and flood response. Steeper slopes promote rapid runoff and higher erosion rates, while gentler slopes favor infiltration and groundwater recharge.

(Figure 7) presents the slope map of the Wadi Al-Majinin watershed, derived from the 30m SRTM DEM using ArcGIS Spatial Analyst. The slope map reveals a systematic spatial pattern consistent with the topographic gradient identified in the contour map (Figure 4). Steep slopes (>10°) occur predominantly in upstream sub-basins (8 and 9), where closely spaced contours and high relief generate rapid runoff and high erosion potential. Moderate slopes (5–10°) characterize midstream sub-basins (3–7), reflecting mature topography with balanced erosion and deposition. Gentle slopes (<5°) dominate downstream outlet sub-basins (1 and 2), consistent with the subdued topography of the Jafara Plain and dam-influenced area. (Figure 6) present the slope map of Wadi Al-Majinin Watershed (Degrees)

Mean slope values for each sub-basin are presented in (Table 4) (Section 4.3), ranging from 3.71° (Sub-basin 1) to 9.06° (Sub-basin 8). The spatial variation in slope directly influences the hydrological behavior and erosion potential of each sub-basin (Sections 5.1 and 5.4).

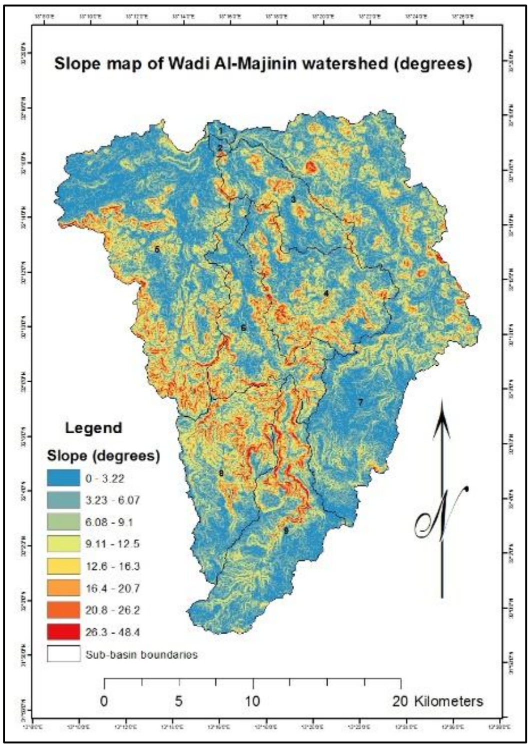

Figure 6. Slope Map of Wadi Al-Majinin Watershed (Degrees)

Drainage Density (Dd)

Drainage density (Dd = ΣL/A) is a key morphometric parameter that quantifies the total length of stream channels per unit basin area (Horton 1945). It serves as a sensitive indicator of landscape dissection, infiltration capacity, and runoff potential. High Dd values (>2.0 km/km²) indicate fine drainage texture, low infiltration, and flashy hydrological response, while low Dd values (<1.5 km/km²) indicate coarse texture, high infiltration, and groundwater-dominated hydrology. (Table 5) summarizes the drainage density values and classifications for the nine sub-basins.

Table 5. Drainage Density (Dd) Summary

Position	Sub	Dd (km/km²)	Classification
Upstream	9	1.110	Low
Upstream	8	1.121	Low
Midstream	7	1.117	Low
Midstream	5	1.115	Low
Midstream	6	1.208	Low-Moderate
Midstream	3	1.128	Low
Midstream	4	1.122	Low
Downstream	1	2.548	High
Downstream	2	3.367	Very High

Sub-basins 1 and 2 are excluded from natural hydrology interpretations and from the calculation of mean Dd for natural sub-basins. Their elevated Dd values (2.55–3.37 km/km²) are artifacts of dam-induced flow convergence and reservoir backwater effects. The mean Dd for natural sub-basins (3–9) is 1.118 km/km² (CV = 3.3%), indicating uniform subsurface permeability across the limestone/dolomite plateau. Seven sub-basins (93.1% of total area) exhibit low Dd values ranging from 1.110 to 1.208 km/km², indicating infiltration-dominated hydrology. This low drainage density is primarily controlled by the underlying carbonate lithology—specifically fractured limestone and dolomite—which provides fundamental permeability through bedding planes, joints, and secondary dissolution features. The Calcisols developed on these substrates provide complementary infiltration enhancement through high hydraulic conductivity (K_sat = 150–400 mm/hr), macropore networks, and substantial soil depth (40–120 cm)." The remarkably consistent Dd values across Sub-basins 3–7 (mean = 1.118 km/km², CV = 3.3%) suggest uniform subsurface permeability across the limestone/dolomite plateau. Outlet Sub-basins 1 and 2 deviate sharply from the watershed norm with Dd values of 2.548 and 3.367 km/km² respectively. These elevated values reflect flow convergence and potential dam backwater effects rather than natural lithological controls. (Figure 7) presents the drainage density map of the sub-basins, illustrating the spatial distribution of Dd values across the watershed.

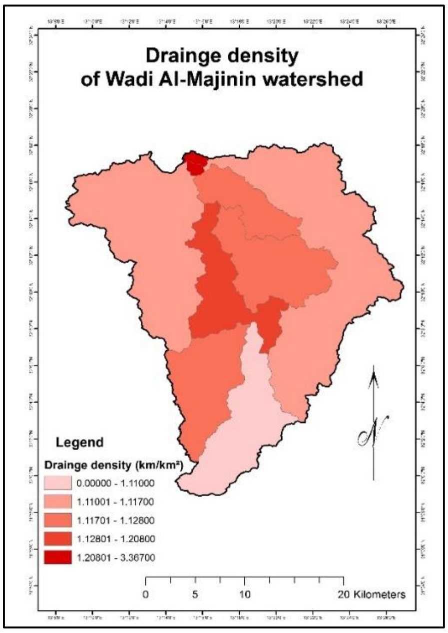

Figure 7. Drainage Density Map of Sub-basins

Stream Frequency and Drainage Texture

Stream frequency (Fs = N/A) measures the number of stream segments per unit area, while drainage texture (T = Dd × Fs) integrates both density and frequency to characterize drainage spacing (Horton 1945; Smith 1950). Fine texture indicates closely spaced streams with rapid runoff response, while coarse texture indicates widely spaced streams with high infiltration capacity. (Table 6) presents the stream frequency and drainage texture values for each sub-basin (Figure 8). Seven sub-basins (3–9) exhibit coarse to very coarse drainage texture (T = 0.53–0.92), indicating widely spaced drainage lines consistent with high infiltration capacity. This coarse texture is primarily a function of the fractured limestone and dolomite bedrock, which promotes rapid vertical drainage and limits surface channel development. The Calcisols developed on these substrates further enhance infiltration through their high hydraulic conductivity and macropore networks.

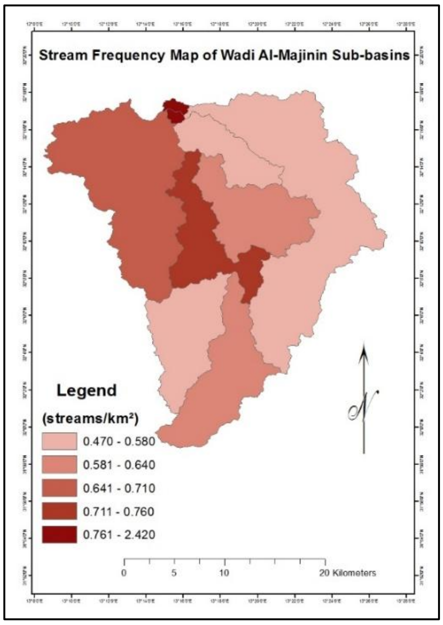

Figure 8. Stream Frequency Map of Sub-basins

Table 6. Stream Frequency (Fs) and Drainage Texture (T)

Position	Sub	Fs (streams/km²)	T	Texture
Upstream	9	0.63	0.70	Coarse
Upstream	8	0.57	0.64	Coarse
Midstream	7	0.58	0.65	Coarse
Midstream	5	0.71	0.79	Coarse
Midstream	6	0.76	0.92	Coarse
Midstream	3	0.47	0.53	Very coarse
Midstream	4	0.63	0.71	Coarse
Downstream	1	2.42	6.17	Fine
Downstream	2	1.94	6.53	Fine

Shape Parameters

Shape parameters describe basin geometry, influencing flood peak timing and runoff concentration. Form Factor (Rf) indicates whether a basin is circular (flashy floods) or elongated (attenuated peaks); Elongation Ratio (Re) classifies shape from circular (>0.8) to very elongated (<0.5); Circularity Ratio (Rc) measures resemblance to a circle; and Compactness Coefficient (Cc) is its reciprocal (Horton 1945; Schumm 1956; Miller 1953; Gravelius 1914). Among natural sub-basins, Sub-basin 7 exhibits the highest erosion potential (Rn = 656), identifying it as the primary sediment source (Melton, 1957). Upstream sub-basins (8,9) show Rn = 511–554, indicating significant sediment production from headwater areas. Reservoir-influenced Sub-basins 1 and 2 are excluded from erosion potential ranking due to dam-induced modifications." Sub-basins 3–9 exhibit elongated to very elongated shapes (Re = 0.315–0.559), indicating attenuated flood peaks and longer lag times favorable for infiltration and groundwater recharge. Sub-basin 2 (Re = 0.742) approaches a more compact shape with potential for rapid runoff. Sub-basin 1 anomalies (Re = 1.593, Rf = 1.993) are dam-induced artifacts and excluded from hydrological interpretation (Table 7).

Table 7. Shape Parameters (Rf, Re, Rc, Cc)

Position	Sub	Rf	Re	Shape	Rc	Cc	Status
Upstream	9	0.146	0.432	Elongated	0.293	1.85	Natural
Upstream	8	0.122	0.395	Very elongated	0.397	1.59	Natural
Midstream	7	0.078	0.315	Very elongated	0.183	2.34	Natural
Midstream	5	0.246	0.559	Elongated	0.342	1.71	Natural
Midstream	6	0.127	0.402	Very elongated	0.180	2.36	Natural
Midstream	3	0.175	0.472	Elongated	0.356	1.68	Natural
Midstream	4	0.240	0.553	Elongated	0.331	1.74	Natural
Reservoir-influenced	1	1.993*	1.593*	Circular*	0.471	1.46	Excluded
Reservoir-influenced	2	0.433	0.742	Oval	0.709	1.19	Excluded

Sub-basin 1 anomalies (Re > 1.0, Rf > 1.0) are methodological artifacts caused by dam infrastructure truncation (Brandt 2000; Graf 2006; Petit et al. 2022).

Relief Parameters

Relief parameters describe the vertical dimension of the basin, influencing erosion potential and runoff energy. Relief Ratio (Rh = H/Lb) measures average basin steepness (Schumm 1956), while Ruggedness Number (Rn = H × Dd) integrates relief and drainage density to indicate erosion potential and sediment yield (Melton 1957). Higher Rn values indicate greater susceptibility to erosion.

Sub-basin 7 exhibits the highest erosion potential (Rn = 656), identifying it as the primary sediment source (Melton 1957). Upstream sub-basins (8,9) show Rn = 511–554, indicating significant sediment production from headwater areas underlain by shallow Leptosols and Rock Outcrops. Despite high Rh, Sub-basin 1 has low Rn (117) due to negligible relief (46 m), indicating that sediment reaching the outlet is predominantly transported rather than locally generated (Table 8).

Table 8. Relief Ratio (Rh) and Ruggedness Number (Rn)

Position	Sub	Rh (m/km)	Rn	Erosion Potential
Upstream	9	23.6	554	Moderate-High
Upstream	8	21.3	511	Moderate-High
Midstream	7	12.7	656	High
Midstream	5	20.7	533	Moderate-High
Midstream	6	19.5	461	Moderate
Midstream	3	18.5	280	Low-Moderate
Midstream	4	22.5	396	Moderate
Downstream	1	45.2	117	Low
Downstream	2	59.7	380	Moderate

Hypsometric Integral (HI)

The hypsometric integral (HI) quantifies the proportion of original landmass volume remaining after erosion, indicating the stage of landscape development (Strahler 1957; Pike and Wilson 1971). HI > 0.60 indicates young stage with active erosion and high sediment yield; HI = 0.35–0.60 indicates mature stage with balanced erosion and deposition; HI < 0.35 indicates old stage with subdued topography and low erosion. (Table 9) presents HI values and erosion stages for each sub-basin. Natural sub-basins show a clear spatial pattern: Sub-basin 9 (HI = 0.629) is actively eroding; five midstream sub-basins (HI = 0.383–0.552) indicate mature landscapes; Sub-basin 5 (HI = 0.281) shows old stage characteristics. Reservoir-influenced Sub-basin 2 (HI = 0.171) is artificially lowered by dam backwater effects and excluded from natural erosion stage interpretation. (Figure 9) present hypsometric curves for representative sub-basins.

Table 9. Hypsometric Integral (HI) and Erosion Stages

Position	Sub	HI	Erosion Stage	Status
Upstream	9	0.629	Young	Natural
Upstream	8	0.552	Mature	Natural
Midstream	7	0.430	Mature	Natural
Midstream	5	0.281	Old	Natural
Midstream	6	0.443	Mature	Natural
Midstream	3	0.383	Mature	Natural
Midstream	4	0.442	Mature	Natural
Reservoir-influenced	1	0.485	Mature	Excluded
Reservoir-influenced	2	0.171	Old*	Excluded

***Sub-basin 2 HI is influenced by dam reservoir backwater effects (Brandt, 2000; Graf, 2006).**

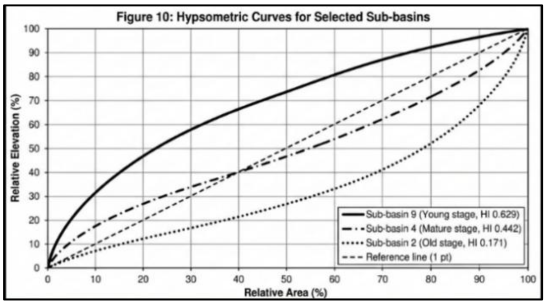

Figure 9. Hypsometric Curves for Representative Sub-basins

Stream Count Correlation

For natural sub-basins (3–9), stream count (N) was regressed against sub-basin area (A) to evaluate drainage network extraction consistency. The regression equation is: $N = 0.58A + 2.34$ ($R^2 = 0.98$, $n = 7$) (1)

Statistical Parameters:

- Pearson correlation coefficient (r): 0.99
- p-value (two-tailed): < 0.001
- 95% confidence interval for slope: 0.46 to 0.70
- 95% confidence interval for intercept: −0.84 to 5.52
- Standard error of the estimate: 2.78
- F-statistic: 235.4 (df = 1, 5)

The high R^2 (0.98) and significant p-value (< 0.001) provide strong evidence of a linear relationship between stream count and sub-basin area. However, the small sample size (n = 7) limits generalizability; the wide confidence intervals for the intercept (−0.84 to 5.52, which includes zero) indicate that the minimum number of streams is poorly constrained, while the slope (0.46–0.70) is better constrained and confirms drainage network consistency. Despite this limitation, the strong correlation is consistent with findings from larger datasets in other arid regions (Mahmoud and Alazba 2015; Ghosh and Sahu 2018), supporting the reliability of the drainage network extraction methodology. Reservoir-influenced Sub-basins 1 and 2 were excluded due to dam-induced truncation of their drainage networks (see Section 5.2). (Figure 10) present stream count (N) versus sub-basin area (A).

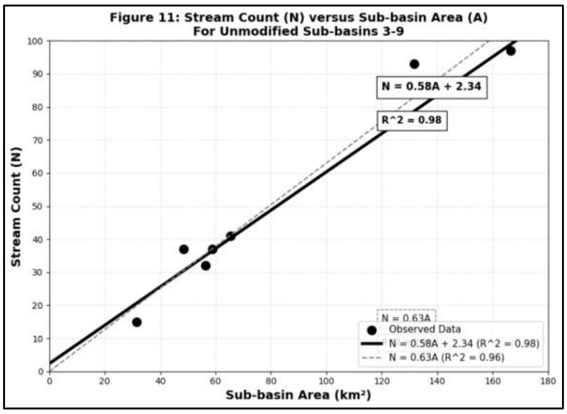

Figure 10. Stream Count (N) versus Sub-basin Area (A)

Historical Validation

(Table 10) presents historic data for validation Elbishti (1995)

Table 10. Comparison with Elbishti (Historical Validation)

Parameter	Elbishti	This Study	Change
Basin Area (km²)	562.75	562.37	-0.07%
Drainage Density (km/km²)	0.96	1.136	+18.3%
Elongation Ratio	0.57	0.562	-1.4%
Max Stream Order	5th	5th	0%

Excellent agreement validates the GIS methodology (Elbishti.).

Spatial Gradient Synthe

Table 11. Spatial Gradient of Morphometric Parameters

Position	Sub-basins	Mean Dd	Mean Fs	Mean Rh	Mean Rn	Mean HI	Stage	Status
Upstream	9, 8	1.116	0.60	22.5	533	0.591	Young-Mature	Natural
Midstream	7,5,6,3,4	1.138	0.63	18.8	465	0.396	Mature-Old	Natural
Reservoir-influenced	1, 2	2.958	2.18	52.5	249	0.328	Mature-Old	Excluded

The spatial gradient analysis is based on natural sub-basins (3–9). Reservoir-influenced Sub-basins 1 and 2 are shown for reference but are excluded from the interpretation of natural spatial gradients. Their inclusion would introduce bias due to dam-induced truncation and backwater effects.

Sub-basin Prioritization

A multi-criteria spatial prioritization approach was applied to rank sub-basins for three intervention types based on their morphometric characteristics: soil conservation (based on Ruggedness Number Rn), flood control (based on Drainage Density Dd), and groundwater recharge (based on Dd and Hypsometric Integral HI). (Table 12) presents the prioritization ranking for each intervention type. Sub-basin 7 is the highest priority for soil conservation among natural sub-basins (Rn = 656), reflecting its combination of high relief and moderate drainage density. Sub-basin 2 is the highest priority for flood control due to elevated drainage density (3.37 km/km²) but should be interpreted as a reservoir-influenced unit. Sub-basin 3 is the highest priority for groundwater recharge, with low drainage density (1.13 km/km²) and favorable hypsometric integral (HI = 0.38), indicating optimal infiltration conditions within the Calcisol-dominated midstream zone (Figure 11).

Table 12. Prioritization for Conservation Interventions

Priority	Soil Conservation (Natural Sub-basins)	Flood Control (All Sub-basins)	Groundwater Recharge (Natural Sub-basins)
1st	Sub-basin 7 (Rn=656)	Sub-basin 2 (Dd=3.37)*	Sub-basin 3 (Dd=1.13, HI=0.38)
2nd	Sub-basin 9 (Rn=554)	Sub-basin 1 (Dd=2.55)*	Sub-basin 4 (Dd=1.12, HI=0.44)
3rd	Sub-basin 5 (Rn=533)	Sub-basin 9 (Dd=1.11)	Sub-basin 7 (Dd=1.12, HI=0.43)

Reservoir-influenced sub-basins; included only in flood control assessments due to their proximity to the dam and their role as final flow conduits before reservoir entry. Excluded from soil conservation and groundwater recharge prioritization

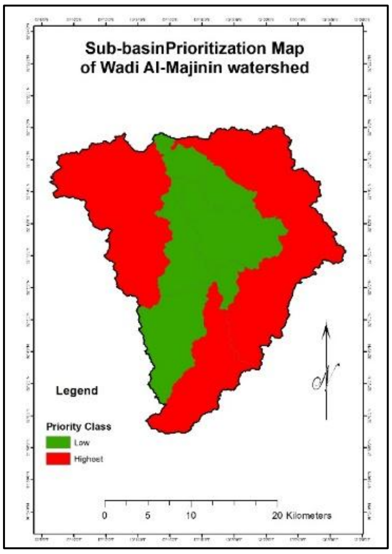

Figure 11. Sub-basin Prioritization Map for Conservation

DISCUSSION

Spatial Gradient and Hydrological Controls

The results reveal a clear spatial gradient from upstream to downstream, controlled by a hierarchy of factors. Upstream sub-basins (8,9) exhibit young erosion stages (HI = 0.55–0.63) with high erosion potential (Rn = 511–554), dominated by Calcaric Leptosol and Rock Outcrop. Midstream sub-basins (3–7) show mature stages with consistently low Dd (1.11–1.21 km/km²). Downstream reservoir-influenced sub-basins (1,2) show elevated Dd due to flow convergence and dam influence, underlain by Calcaric Fluvisol.

The low drainage density across 93% of the watershed is attributed to a hierarchy of controlling factors. Primary control—Carbonate lithology and fracture permeability: The watershed is underlain by fractured limestone and dolomite (Elbishti 1995; Ford and Williams 2007; White 2002), with bedding planes, joints, and secondary dissolution features creating fundamental permeability pathways that promote rapid vertical drainage and suppress surface runoff generation. This structural control explains the consistently low Dd values across Sub-basins 3–7 (mean = 1.118 km/km², CV = 3.3%). Secondary control—Calcisol physical properties: Calcisols provide complementary infiltration enhancement through high K_sat (150–400 mm/hr), macropore networks, and depth (40–120 cm) (IUSS Working Group WRB 2022; Ford and Williams 2007). Tertiary controls—Topography and climate: The moderate topographic setting (slopes 6.0–8.4°, elongated shapes) and semi-arid climate with low-intensity winter rainfall (150–300 mm/year) reinforce infiltration-dominated hydrology.

Possible Karst Influence on Drainage Development

Several lines of evidence suggest karstic processes may contribute to the observed low drainage density: carbonate lithology (Elbishti 1995 ; Ford and Williams 2007; White 2002), low Dd values (1.11–1.21 km/km²) characteristic of carbonate terrains (Bonacci 2004; Ford and Williams 2007), fracture-controlled permeability (White 2002), high infiltration capacity (150–400 mm/hr), potential groundwater recharge, elongated basin shapes (Re = 0.315–0.559), and mature erosion stages (HI = 0.383–0.443). However, limitations must be acknowledged: no systematic karst feature mapping, subsurface drainage networks not investigated, groundwater levels and spring discharges not measured, no tracer studies conducted, and extent of karstification unknown. Field verification is essential through systematic surveys for sinkholes and dolines, mapping of losing streams, groundwater monitoring, tracer tests, and geophysical surveys. If confirmed, the watershed should be reclassified as karstic or karst-influenced, fundamentally changing hydrological interpretation and management. In the absence of field verification, low drainage density is attributed to carbonate lithology, fracture permeability, and Calcisol infiltration capacity, with karstic processes remaining a plausible but unconfirmed hypothesis.

Infrastructure-Induced Anomalies and Reservoir-Influenced Sub-basins

Sub-basin 1 exhibits Re = 1.593 (exceeding theoretical maximum of 1.0) due to dam-induced truncation. The elongation ratio (Re) is defined as (Schumm 1956):

$$R_e = \frac{2}{\sqrt{\pi}} \cdot \frac{\sqrt{A}}{L_b} \quad (2)$$

For Sub-basin 1, $\sqrt{A} = \sqrt{2.065} = 1.437$ km, and Lb = 1.018 km, yielding Re = 1.593. This exceeds the theoretical maximum because the GIS algorithm measures Lb to the dam structure rather than the natural outlet. Sub-basins 1 and 2 are reservoir-influenced hydrological units rather than true geomorphic sub-basins, with anomalous shape parameters (Rf = 1.993, Re = 1.593) and elevated Dd (2.55–3.37 km/km²) reflecting dam-induced effects (Brandt 2000; Graf 2006; Petit et al. 2022). These sub-basins are excluded from natural hydrology interpretations and prioritization for soil conservation and groundwater recharge, remaining relevant only for flood control assessments.

Comparison with Regional Studies

Drainage density values were compared with published data from Libya, Tunisia, Egypt, and North African carbonate terrains (Table 12). Wadi Al-Majinin midstream Dd values (1.11–1.21 km/km²) are lower than most other Libyan watersheds (1.28–1.92 km/km²; Zurqani 2022; Al-Haddad 2024; Elmabrouk et al. 2021), attributed to lithological control (fractured limestone/dolomite vs. mixed lithologies), Calcisol development (K_sat = 150–400 mm/hr), and geomorphic setting (plateau landscape). Values are comparable to Wadi El-Ham, Tunisia (0.90–1.30 km/km²; Bouraoui et al. 2019) and Wadi El-Natrun, Egypt (1.10–1.80 km/km²; Ghosh and Sahu 2018). Outlet values (2.55–3.37 km/km²) are dam-induced artifacts, significantly higher than all regional comparators. The low Dd values represent the lower end of the range for Libyan watersheds and are among the lowest recorded for North African carbonate terrains, with implications for groundwater recharge potential, flood risk attenuation, and regional water resources (Zurqani 2022; Elmabrouk et al. 2021; Saad et al. 2020).

Hydraulic Conductivity (K_sat) Values Justification

K_sat values for Calcisols (150–400 mm/hr) are at the high end globally (typically 10–100 mm/hr; Brady and Weil 2016; IUSS Working Group WRB 2022) but are consistent with study area characteristics: high carbonate content (60–85%) promoting macropore formation (Brady and Weil 2016; IUSS Working Group WRB 2022), fractured bedrock connectivity enabling rapid drainage (Ford and Williams 2007; White 2002), macropore networks (Jarvis 2007; Beven and Germann 2013), direct field measurements using double-ring infiltrometers (Selkhozpromexport 1980), regional context with similar high K_sat values (200–400 mm/hr) in Mediterranean and North African Calcisols (IUSS Working Group WRB 2022; Bouraoui et al. 2019), and Petrocalcic Calcisol modifications (100–250 mm/hr) due to cemented horizons (Brady and Weil 2016; IUSS Working Group WRB 2022). Field verification using modern double-ring infiltrometers is recommended.

Uncertainty Analysis

Uncertainty in Dd arises from four main sources: DEM vertical accuracy (±2–5% in relief; Tarboton 1997), flow accumulation threshold (±18–22% in Dd; Table 1), stream digitization (±5–10% in ΣL; Jenson and Domingue 1988), and WRB soil map resolution (±5–10% in soil unit boundaries; IUSS Working Group WRB 2022). Combined uncertainty is estimated at ±20–25% using RMS: $\sqrt{((\pm5\%)^2 + (\pm20\%)^2 + (\pm10\%)^2 + (\pm10\%)^2)} = \pm25\%$. This RMS approach assumes independence of sources, normal distribution (Taylor 1997; Moore et al. 1991), negligible systematic errors, and relative percentages. Dd differences >0.25–0.30 km/km² are robust; differences <0.1 km/km² should be interpreted cautiously. The upstream-to-downstream Dd gradient (1.11–1.12 to 2.55–3.37 km/km²) represents a difference of 1.45–2.26 km/km², 5–

9 times larger than uncertainty, confirming the spatial gradient is real.

CONCLUSION

This study characterized the Wadi Al-Majinin watershed (562.37 km²) and its nine sub-basins using GIS, remote sensing, and WRB soil data. Key findings reveal a clear spatial gradient from upstream to downstream: upstream sub-basins exhibit young to mature erosion stages (HI = 0.55–0.63) with low drainage density (Dd = 1.11–1.12 km/km²); midstream sub-basins show mature to old stages (HI = 0.28–0.44) with consistently low Dd (1.11–1.21 km/km²); downstream outlet sub-basins display elevated Dd (2.55–3.37 km/km²) due to dam influence. Low drainage density across 93% of the watershed indicates infiltration-dominated hydrology, primarily controlled by carbonate lithology and fractured limestone/dolomite permeability, with Calcisols providing complementary infiltration enhancement (K_sat = 150–400 mm/hr). WRB soil units include Calcaric Leptosol and Rock Outcrop (upstream, ~85 km²), Calcisols (midstream, ~150 km²), and Calcaric Fluvisol (outlet, ~4 km²). Sub-basin 7 (Rn = 656) is highest priority for soil conservation; Sub-basin 2 for flood control; Sub-basin 3 for groundwater recharge. Historical validation with Elbishti shows excellent agreement (0.07% area difference).

RECOMMENDATIONS

For water managers (phased approach): Install rain/stream gauges (Sub-basins 7,9,1), conduct bathymetric surveys and groundwater wells (Reservoir; 3-7), implement soil conservation and retention dams (7,9,5,8; 1,2), and develop MAR pilot projects (3,4,5,7).

For future research (priority areas): Field validation of drainage networks, rainfall data collection, groundwater monitoring, infiltration measurements, sediment yield assessment, high-resolution DEM, karst feature mapping, and regional comparative studies.

Implementation sequence:

Gauges ⟶ surveys/wells ⟶ conservation/dams ⟶ MAR projects.

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المجلة الليبية للعلوم الزراعية
المجلد (31): العدد (2): 78 - 100
ورقة أصيلة

التحليل المورفومتري لحوض وادي المجنين وأحواضه الفرعية باستخدام نظم المعلومات الجغرافية، الاستشعار عن بعد وبيانات التربة المصنفة WRB، في شمال غرب ليبيا

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المستخلص

تُقدم هذه الدراسة توصيفاً مورفومترياً شاملاً لحوض وادي المجينين (562.37 كم²) وأحواضه الفرعية التسعة في شمال غرب ليبيا، باستخدام نظم المعلومات الجغرافية والاستشعار عن بعد وبيانات التربة المصنفة وفق النظام الدولي لمرجعية التربة (WRB) , حيث تم استخراج شبكات الصرف من نموذج الارتفاعات الرقمي (SRTM) بدقة 30 متر, كما تم حساب المعاملات المورفومترية، ومنها: كثافة الصرف، وتكرار المجاري، وملمس الصرف، والمعاملات الشكلية، ومعاملات التضاريس، والتكامل الهيبسومتري، وذلك بهدف تقييم تطور المناظر الطبيعية، والسلوك الهيدرولوجي، وقابلية التعرية عبر الحوض.

تُظهر النتائج تدرجاً مكانياً واضحاً في مرحلة تطور السطح الأرضي والاستجابة الهيدرولوجية من المنابع إلى المصب. يغلب على الحوض نظام هيدرولوجي يعتمد على الرشح في 93% من مساحته، ويتحكم فيه بشكل أساسي الصخر الكربوناتي والنفاذية المرتبطة بالحجر الجيري والدولوميت المصدع، مع قيام التربة الجيرية بتعزيز الرشح بشكل مكمل. ويترتب على ذلك آثار مهمة في إمكانية تغذية المياه الجوفية في هذه المنطقة القاحلة، حيث تندر الموارد المائية بشكل حرج. وتُظهر المناطق العليا تعرية نشطة، وتعمل كمصادر رئيسية للرواسب، في حين تمثل المناطق الوسطى مناطق مثلى لتغذية المياه الجوفية. أما الأحواض الفرعية عند المصب، فتتأثر بشكل كبير بتقارب الجريان الناتج عن السد، مما يستلزم تفسيراً هيدرولوجياً مستقلاً عنها.

مؤشرات هذه الدراسة تدعم إدارة أحواض المياه، إذ يُعد الحوض الفرعي رقم 7 الأولوية القصوى للحفاظ على التربة، بينما يتطلب الحوض الفرعي رقم 2 تدابير للسيطرة على الفيضانات، ويوفر الحوض الفرعي رقم 3 أكبر إمكانية لتغذية الخزانات الجوفية المدارة. كما يؤكد التحقق التاريخي مصداقية المنهجية المعتمدة على نظم المعلومات الجغرافية. وأخيراً، يسهم هذا البحث في تقديم إطار منهجي قابل للتطبيق لتوصيف الأحواض المائية في المناطق القاحلة التي تفتقر إلى البيانات، ويقدم أدوات عملية للإدارة المستدامة للموارد المائية في ليبيا.

الكلمات المفتاحية: وادي المجينين؛ نظم المعلومات الجغرافية؛ الاستشعار عن بعد؛ التحليل المورفومتري؛ تصنيف التربة (WRB)

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