

Topo-Hydrological Evaluation of Check Dams in the Al-Mujib Basin, Jordan

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Abstract

In arid and semi-arid regions (ASARs), the effectiveness of rainwater harvesting (RWH) structures such as check dams is largely governed by terrain and hydrological dynamics. However, many existing structures are sited empirically, often neglecting systematic spatial evaluations. This study conducts a retrospective topo-hydrological assessment of 18 check dams in the Al-Mujib Basin, southern Jordan, to evaluate their siting efficiency. Five key indices Topographic Wetness Index (TWI), Stream Power Index (SPI), Topographic Position Index (TPI), Sediment Transport Index (STI), and Terrain Roughness Index (TRI) were derived from ASTER 30 m DEM and standardized to assess spatial suitability. The Receiver Operating Characteristic (ROC) curve and Area Under the Curve (AUC) metrics were employed to quantify the discriminatory power of each index. TPI and SPI demonstrated the highest predictive capacity (AUC = 0.850 and 0.822, respectively), confirming the significance of concave landforms and concentrated runoff zones an outcome that underscores the fact that most check dams were indeed located within geomorphologically favorable depressions and areas of high flow concentration. Composite suitability scores revealed that only 2 out of the 18 evaluated check dams (~11%) were classified within the high suitability category, while others exhibited suboptimal terrain-hydrology alignment. Correlation analysis indicated strong synergy between SPI and TWI ($r = 0.94$) and the statistical independence of TPI, reinforcing its unique value in capturing geomorphological depressions. This study highlights the critical need to validate dam placement through empirical spatial diagnostics, particularly in water-scarce landscapes increasingly vulnerable to climatic variability. The study underscores the significance of post-construction evaluations to monitor and maintain RWH structures for ensuring their efficacy and sustainability.

Keywords: Al-Mujib Basin, Check Dams, Rainwater Harvesting, ROC-AUC, Topo-Hydrological Indices

1. Introduction

Water scarcity poses a substantial threat to agricultural productivity, ecological stability, and rural livelihoods in arid and semi-arid regions (ASARs) [1]. Consequently, check dams, which are small-scale rainwater harvesting (RWH) structures constructed across ephemeral streams, have been widely adopted as cost-effective solutions to capture runoff, mitigate erosion, and enhance groundwater recharge [1] and [2]. For instance, the Hamoud Check Dam (Figure 1), constructed in 2013 in Wadi Al-Mujib with a storage capacity of 70,000 m³, was primarily designed to support livestock watering and mitigate flash floods in the region [3]. It serves as a representative example of small-scale RWH infrastructure in Jordan. However, despite their

growing importance, the placement of these structures frequently relies on local needs, societal considerations, or empirical experience rather than rigorous spatial analysis [4]. This practice raises concerns regarding the functional sustainability of many existing dams, particularly in complex terrains characterized by highly variable hydrological conditions [5].

Advancements in geospatial techniques have facilitated the use of topo-hydrological indices to assess sites suitability for RWH structures [6]. Topo-hydrological indices are quantitative metrics derived from Digital Elevation Models (DEMs) data that assess landscape characteristics influencing water movement, accumulation, and erosion [2].



Figure 1: Hamoud check dam in the Al-Mujib Basin

Indices such as the Topographic Position Index (TPI) classify landscape positions (e.g., valleys, ridges), guiding optimal dam locations to intercept runoff [7]. The Sediment Transport Index (STI) predicts erosion susceptibility and sediment deposition patterns, essential for designing dams to mitigate siltation [8]. Topographic Wetness Index (TWI) identifies areas prone to water retention, indicating suitable zones for check dam placement to enhance water retention [9]. The Stream Power Index (SPI) estimates erosion risk by measuring the erosive force of flowing water [10]. Lastly, the Terrain Roughness Index (TRI) assesses surface complexity, influencing runoff velocity and erosion potential [11]. These indices have been widely integrated into multi-criteria decision analysis (MCDA) models for prospective RWH site selection [2] and [6]. However, their application for retrospective evaluation of already-constructed check dams remains limited, particularly in ASARs where data scarcity often hinders systematic post-construction assessment.

A further limitation in the current literature is the lack of objective validation methods for evaluating the relevance and discriminatory power of individual indices in existing RWH structure placement. While several studies have qualitatively assessed RWH structure performance, they have not employed statistical tools to quantify the relationship between RWH structure sites and factors selected. For example, the study in [5] assessed 38 structures in Mozambique using GIS-based MCDA and found most to be in moderately suitable zones. Similarly, a GIS-AHP approach was applied in [13] to evaluate 58 RWH systems in arid regions, with over 95% rated as low to moderate suitability. However, such approaches often lack empirical rigor due to their dependence on expert judgment without validating

spatial associations through statistical metrics. In this context, Receiver Operating Characteristic (ROC) analysis and the Area Under the Curve (AUC) metric offer model-independent tools to evaluate the spatial association between dam locations and topohydrological indices. High AUC values indicate a strong spatial association between a given index and dam presence, providing an empirical basis for assessing topo-hydrological suitability [9].

This study addresses these gaps by conducting a topo-hydrological evaluation of 18 existing check dams in the Al Mujib Basin, southern Jordan an arid basin where check dams are critical for water security. The objectives are (1) to extract SPI, TWI, TPI, STI, and TRI values at check dam sites; (2) to assess each index's ability to explain check dam placement using ROC-AUC analysis; and (3) to derive a normalized index-based suitability score for each check dam. By combining terrain diagnostics with statistical evaluation, this study introduces a transferable framework for evaluating the siting efficiency of RWH structures and supports evidence-based planning in ASARs that are similarly water-scarce regions.

2. Material and Methods

2.1 Study Area

The Al-Mujib Basin, a critical hydrological system in central Jordan, spans 6,769 km² and comprises two principal sub-basins: the southern Wadi Al-Mujib Basin (~4,297 km²) and the northern Wadi Al-Walla Basin (~2,472 km²). The southern sub-basin, characterized by its complex drainage network, takes over the basin's primary perennial tributaries, Wadi Al-Nakhila and Wadi Al-Suwayda, which converge to form the core hydrological axis of the basin [14].

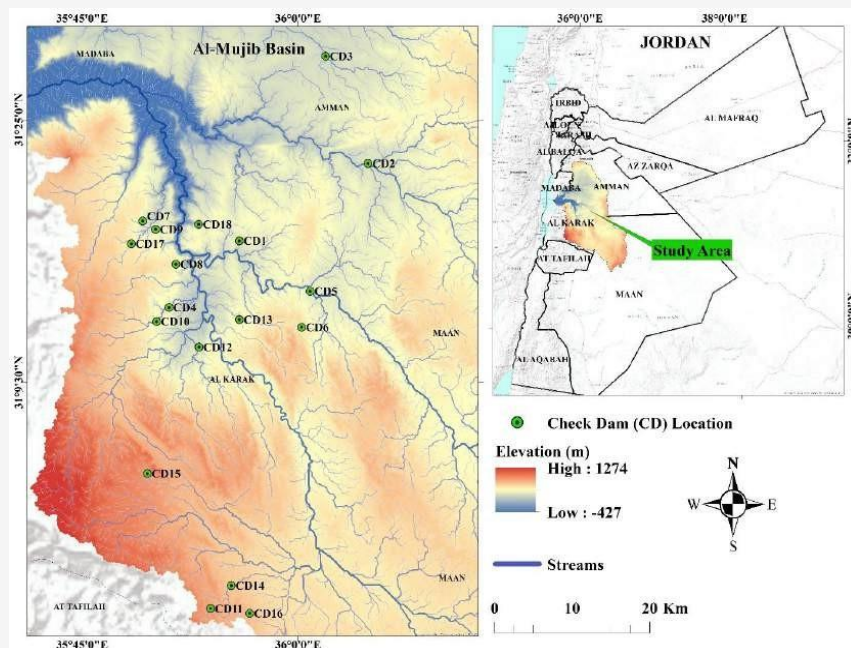


Figure 2: Distribution of check dams across the Al-Mujib Basin, highlighting elevation variation and main stream

Climatically, the basin transitions from hyper-arid conditions in the southeast (mean annual rainfall: ~50 mm) to semi-arid highlands in the northwest and southwest, where precipitation exceeds 500 mm annually [15]. This steep precipitation gradient, coupled with pronounced elevational variations, drives heterogeneous hydrological processes and water availability patterns. The basin's strategic importance for water resource management is underscored by its extensive network of check dams (Figure 2), engineered to mitigate flash floods, enhance groundwater recharge, support emerging agricultural projects, and stabilize sediment transport in this water-stressed region.

2.2 Methods

2.2.1 Conceptual framework

The role of topo-hydrological indices in RWH site identification necessitates further empirical investigation, particularly in ASARs. Figure 3 illustrates the overall methodological framework adopted in this study to evaluate the spatial suitability of existing check dams a widely implemented RWH strategy aimed at enhancing water security in water-scarce regions [1]. A DEM with a spatial resolution of 1 arc-second (~30 m), derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), was utilized to generate five key topo-hydrological indices. ASTER-derived DEMs are particularly suitable for medium- to large-scale hydrological modeling due to their reliable

spatial resolution and periodic data updates, which support temporal analyses of terrain evolution [15] and [16]. Given the spatial extent of the study area (~6,769 km²), ASTER DEM data provide an adequate basis for deriving topographic and hydrologic parameters with sufficient accuracy.

Google Earth Pro images were utilized to discover the sites and constructions of the check dams. The raster calculator tool was employed to derive the selected topo-hydrological indices through a series of spatially integrated geoprocessing operations. The analytical workflow was subsequently divided into two main phases. In the first phase, all indices were standardized and reclassified into five suitability classes to ensure uniform scaling and enhance result interpretability. Each index was assigned a suitability score ranging from 1 (very low suitability/non-optimal) to 5 (very high suitability/optimal), based on hydrological and geomorphological relevance to check dam placement. The predictive performance of each index in delineating suitable dam sites was then evaluated using the ROC-AUC curve, implemented via the Arc Spatial Data Modeller (ArcSDM) extension in ArcGIS. Although ROC-AUC is conventionally used to evaluate classification model performance, in this study it was repurposed to assess the spatial suitability of existing check dams based on reclassified topo- hydrological indices across the entire basin.

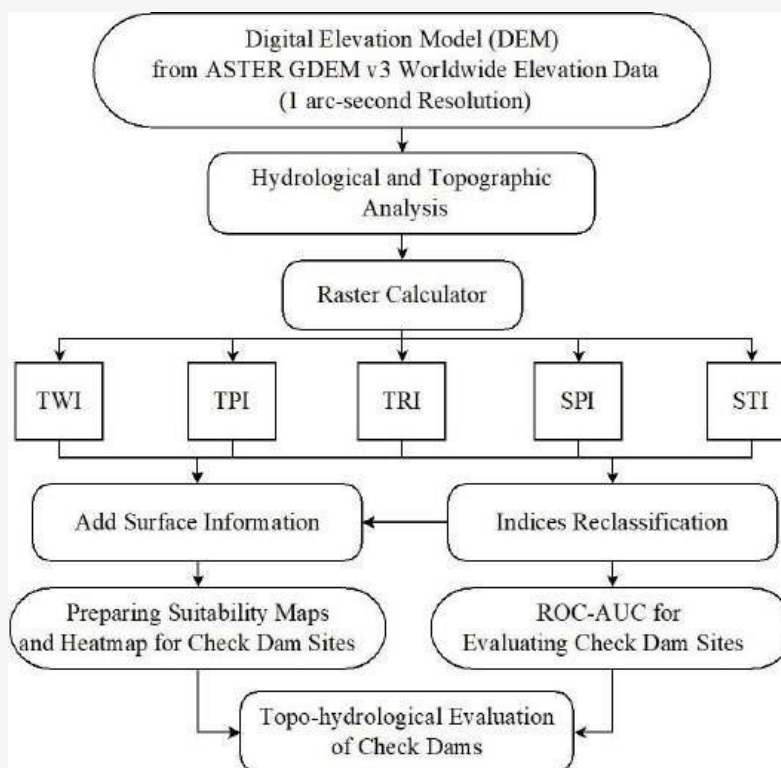


Figure 3: Conceptual framework, indices and processes for assessing check dams

Rather than validating a predictive model, the ROC-AUC here quantifies the degree to which each index TPI, TWI, TRI, STI, and SPI successfully distinguishes check dam sites from other locations, thus reflecting their spatial association with terrain features favourable for runoff retention and erosion control.

In the second phase, each check dam site was spatially analyzed in relation to the reclassified topo-hydrological indices using the "Add Surface Information" tool from the ArcGIS 3D Analyst toolbox. This tool enabled the direct extraction of check dam-related attributes such as TWI, TRI, TPI, STI, and SPI values from the underlying topo-hydrological indices, ensuring objective and consistent assignment of values to each check dam site. To synthesize the spatial diagnostics, a composite suitability score was calculated for each site by averaging its five standardized index scores. This aggregated metric captures the integrated hydrological and topographical favorability of each dam site and aligns with established MCDA methods in spatial planning. To further support the analysis, a correlation heatmap was developed using the ggplot2 package, applying conditional formatting to visually depict the strength and direction of relationships among the topo-hydrological indices.

This visualization provided an intuitive diagnostic tool for identifying both interdependent and statistically independent variables, thereby enhancing the robustness and transparency of the spatial assessment framework.

2.2.2 Topo-hydrological indices

This section offers a comprehensive elucidation of each index and supporting maps that illustrate the index values (Figure 4). Each topo-hydrological index was classified into five standardized categories (Table 1) using the natural breaks (Jenks) method, which optimizes class boundaries to reflect inherent data distributions and minimize intra-class variance. The classification into five scores (1 to 5) was adopted to standardize the evaluation of index values, allowing for a consistent and comparable assessment of site suitability, with score 5 denoting optimal conditions based on the specific topo-hydrological behavior of each index. This framework harmonizes heterogeneous spatial criteria by aligning index thresholds with hydrological principles prioritizing gentle slopes (low SPI/STI), moisture-rich depressions (high TWI/low TPI), and stable terrain (low TRI) while ensuring statistical rigor through data-driven class intervals.

Table 1: Rates indices on a scale of 1–5 (5 = very high/optimal for check dams). Suitability varies based on whether higher or lower values are preferable, aiding in the evaluation of optimal sites

Topo-hydrological indices	Class Range	Normalized Suitability Score
STI	0 – 1,013.2	5
	1,013.3 – 4,728.4	4
	4,728.5 – 11,483	3
	11,484 – 22,629	2
	22,630 – 43,062	1
SPI	0 – 0.854	1
	0.855 – 2.41	2
	2.42 – 4.58	3
	4.59 – 7.99	4
	8 – 19.8	5
TRI	0.00999 – 0.238	5
	0.239 – 0.362	4
	0.363 – 0.465	3
	0.466 – 0.568	2
	0.569 – 0.917	1
TWI	3.57 – 7.03	1
	7.04 – 8.81	2
	8.82 – 11.3	3
	11.4 – 15	4
	15.1 – 26.2	5
	4.57 – 29.3	2
	29.4 – 147	1

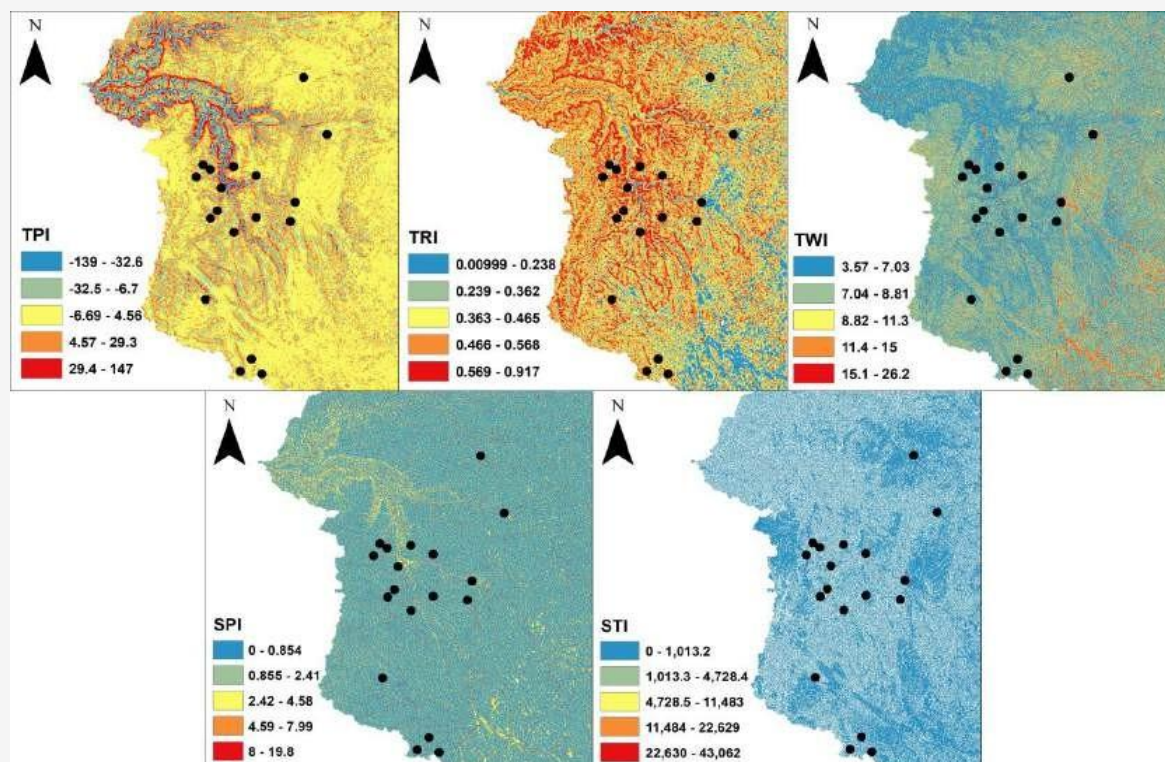


Figure 4: Thematic maps of topo-hydrological indices supporting the spatial assessment of check dam sites

It is worth noting that no universal consensus exists regarding the optimal threshold values for each topo-hydrological index, as their suitability often varies across different geographic contexts, data resolutions, and methodological frameworks. The result is a replicable, spatially explicit model that balances water availability, retention potential, and infrastructure sustainability for RWH planning. The reclassification of each index into five suitability classes facilitated the generation of a continuous suitability surface, which was essential for deriving threshold-dependent performance metrics such as the ROC-AUC curve. This standardized classification enabled a more nuanced evaluation of the model's predictive capability by allowing for the calculation of true positive and false positive scores across varying suitability thresholds. It also facilitated the computation of a composite suitability score for each check dam site by averaging the reclassified values of the five topo-hydrological indices, thereby providing an integrated measure of site favorability.

2.2.2.1 Topographic Wetness Index (TWI)

The TWI is a terrain-based hydrological indicator that quantifies the spatial variability of soil moisture and identifies areas with a high potential for flow accumulation [18]. Derived from a DEM, the index integrates the upslope contributing area and local slope to reflect the extent of topographic control over hydrological responses within a catchment [19]. In the context of evaluating sites for check dam construction, TWI provides critical insights into the natural convergence of surface runoff. High TWI values typically indicate locations where water is likely to accumulate, which are ideal for enhancing water retention, reducing downstream peak flows, and promoting groundwater recharge [9] and [18]. Therefore, incorporating TWI into the topo-hydrological evaluation framework allows for the systematic identification of favorable sites for check dams [19][20] and [21]. This enhances the reliability of spatial planning and ensures that selected dam locations align with natural hydrological patterns [22]. TWI is calculated using the following Equation 1:

$$TWI = \ln \left(\frac{A}{\tan(\beta)} \right)$$

Equation 1

Where:

- A = The area contributing to flow
- β = Slope angle at the given point

2.2.2.2 Topographic Position Index (TPI)

The TPI is widely used in geography and geomorphology to assess terrain characteristics and their relation to the surrounding landscape [23]. It also aids in understanding surface water flow dynamics [24]. TPI is calculated based on elevation differences within a defined window of surrounding pixels or grid points, helping to determine whether a location is situated on a ridge, in a valley, or on relatively flat terrain [25] and [26]. Specifically, a positive TPI value indicates a ridge, a negative value indicates a valley, and a value close to zero denotes flat terrain [7]. In the context of check dam site selection, TPI is particularly useful in identifying valley bottoms areas with negative TPI values where surface runoff tends to accumulate. These geomorphological depressions are ideal for water retention, making TPI an essential factor in evaluating the topographic and hydrological suitability of potential check dam sites. TPI is calculated according to the following Equation 2:

$$TPI = Z_0 - Z$$

Equation 2

Where:

- Z_0 = Elevation of the central point (focal point)
- Z = Elevation of the surrounding points within a defined radius or neighborhood

2.2.2.3 Terrain Ruggedness Index (TRI)

The TRI is a valuable index for characterizing terrain heterogeneity and identifying zones of surface water flow and runoff concentration [27]. It plays a critical role in delineating suitable sites for RWH structures, particularly check dams [2]. By quantifying the variability in elevation within a defined neighborhood, TRI effectively captures micro-topographic features that influence hydrological processes. Low TRI values approaching zero are indicative of relatively flat and low-lying areas where surface water tends to accumulate [27]. Such areas are well-suited for check dam placement, as they facilitate runoff retention and contribute to the reduction of downstream erosion [10]. Incorporating TRI into the site selection framework enhances the spatial assessment of terrain roughness and its hydrological implications. The TRI is computed using Equation 3:

$$TRI = Y \sqrt{[Z_{ij} - Z_{00}]^2}$$

Equation 3

Where:

- Z_{00} = The elevation value of the center cell in a moving window

Z_{ij} = The elevation values of each neighboring cell in that window

Y = A constant or weighting factor

2.2.2.4 Stream Power Index (SPI)

SPI is a widely recognized topo-hydrological indicator used to evaluate the potential for water flow concentration within a watershed. It integrates the effects of upstream contributing area and local slope to quantify the erosive power of surface runoff [28] and [29]. Higher SPI values are generally associated with steep slopes and extensive contributing areas, indicating zones of elevated flow energy and increased erosion potential [27]. These characteristics make SPI particularly valuable in the planning and management of RWH structures, such as check dams. Specifically, SPI helps identify locations that not only receive concentrated surface runoff but also require erosion control measures [30]. Conversely, low SPI values typically correspond to gently sloping or poorly drained areas with limited flow accumulation, which are generally unsuitable for effective check dam placement due to insufficient hydraulic energy. By incorporating SPI into the site selection framework, practitioners can more accurately assess hydrological dynamics and target interventions in areas where they are most likely to enhance water retention and mitigate soil loss. The SPI is commonly computed using Equation 4, which combines terrain slope with upstream drainage area.

$$SPI = A \cdot \tan(\beta)$$

Equation 4

Where:

A = the contributing area (catchment area) in m^2 or Km^2

β = the slope (angle of inclination) at a given point on the surface

2.2.2.5 Sediment Transport Index (STI)

The STI is a widely adopted metric for quantifying an area's potential to transport eroded material, integrating both topo-hydrological characteristics, particularly slope and contributing area [31]. The underlying rationale of STI lies in the assumption that larger contributing areas are likely to experience greater erosion, while steeper slopes intensify the kinetic energy of surface runoff, thereby enhancing sediment transport capacity [32]. Consequently, areas with elevated STI values are more susceptible to erosion and sediment conveyance, which may lead to siltation in downstream infrastructures such as RWH structures [2]. In the context of assessing potential dam and RWH sites, incorporating STI provides critical insight into sediment dynamics [8].

Sites characterized by high STI values may face accelerated sediment deposition, reducing the functional lifespan and storage capacity of the dam. Therefore, identifying and excluding such locations from potential dam siting improves the long-term sustainability and operational efficiency of RWH systems. The STI is computed using a dimensionally consistent formulation that includes the constants 22.13 and 0.0896 for unit correction, while the exponents 0.6 and 1.3 introduce non-linear sensitivity to flow accumulation and slope, respectively [33]. This non-linear modeling better reflects the complex nature of sediment mobilization and transport across varied landscapes. The STI is calculated using Equation 5, as follows:

$$STI = (m + 1) \cdot \left(\frac{A_s}{22.13} \right)^{0.4} \cdot \sin \left(\frac{\beta}{0.0896} \right)^{1.4}$$

Equation 5

Where:

A_s = The area affected by erosion

β = the slope angle (measured in degrees)

2.2.3 Accuracy assessment

The ROC-AUC curve is a widely accepted statistical measure used to evaluate the predictive performance of binary classification models [34]. AUC values range between 0.5 and 1, where values closer to 1 signify higher predictive accuracy [35]. The classification of AUC values typically follows five performance tiers: 0.5–0.6 (poor), 0.6–0.7 (moderate), 0.7–0.8 (good), 0.8–0.9 (very good), and 0.9–1.0 (excellent) [8][34] and [36]. The ROC-AUC curve assesses the model's ability to distinguish between two classes suitable and unsuitable sites making it particularly valuable in spatial decision-making contexts [37]. In this study, the ROC-AUC method was employed to evaluate the reliability of check dam site suitability derived from topo-hydrological indices. To evaluate the spatial performance of each topo-hydrological index, ROC curve analysis was conducted using the ArcSDM extension in ArcGIS. The point shapefile representing the actual check dam locations was used as the true positive input, while the reclassified raster layers of each index standardized into five suitability classes were supplied as classification models. The tool compares the values of each index at dam locations with those across the broader landscape and automatically computes classification metrics across a range of thresholds. In this context, True Positives (TP) denote check dam locations correctly identified within high-suitability index classes, while False Positives (FP) refer to non-dam areas erroneously classified as suitable.

Conversely, True Negatives (TN) represent non-dam areas accurately recognised as unsuitable, and False Negatives (FN) indicate check dam sites falling within low-suitability classes. Based on these classifications, three diagnostic metrics were computed: sensitivity (Equation 6), specificity (Equation 7), and overall accuracy (Equation 8). Sensitivity reflects the index's ability to correctly detect suitable dam sites, whereas specificity assesses its effectiveness in excluding unsuitable areas. Accuracy measures the proportion of all correctly classified pixels across the study domain. In parallel, the AUC curve was calculated using the trapezoidal method to evaluate the overall discriminatory capacity of each index [7]. Collectively, these metrics offer a complementary validation framework that enhances the interpretability of the AUC results and provides a more nuanced appraisal of index performance.

$$\text{Sensitivity} = \frac{TP}{TP + FN}$$

Equation 6

$$\text{Specificity} = \frac{TN}{TN + FP}$$

Equation 7

$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN}$$

Equation 8

Where:

TP = true positive
 FP = false positives
 TN = true negatives
 FN = false negatives

2.2.4 Add surface information tool for setting check dam value

The Add Surface Information tool, available within the 3D Analyst toolbox in ArcGIS, was a critical component in the spatial evaluation workflow of this study (Figure 5). It was employed to accurately extract both classified and unclassified values of the topo-hydrological indices (TWI, TPI, TRI, SPI, and STI) at the precise sites of the 18 existing check dams. By overlaying the dam point features on each of the five standard raster index layers, the tool interpolates the underlying values and appends them directly to the attribute table of the point layer. This operation ensured a consistent and objective assignment of index values to each check dam site. Beyond value extraction, the outputs from this tool served as the foundation for the computation of individual suitability scores. The suitability scores of the check dams were extracted from the five indices using standardised classification layers ranging from 1 to 5, based on predefined threshold intervals. These reclassified scores for all five indices were then averaged to derive a composite suitability score for each check dam, offering an integrated indicator of spatial favourability. This average score allowed for ranking dam sites based on their alignment with optimal topo-hydrological conditions. Moreover, the extracted values and corresponding suitability scores were used to generate the final spatial suitability map, which visualizes how well each dam is situated within the broader hydrological and terrain context of the basin. Thus, the Add Surface Information tool not only supported the analytical rigour of the evaluation process but also enabled the development of a replicable, GIS-based framework for multi-index suitability analysis and visualisation. These extracted values served as the primary input for constructing the correlation matrix and visualising interrelationships through a heatmap.

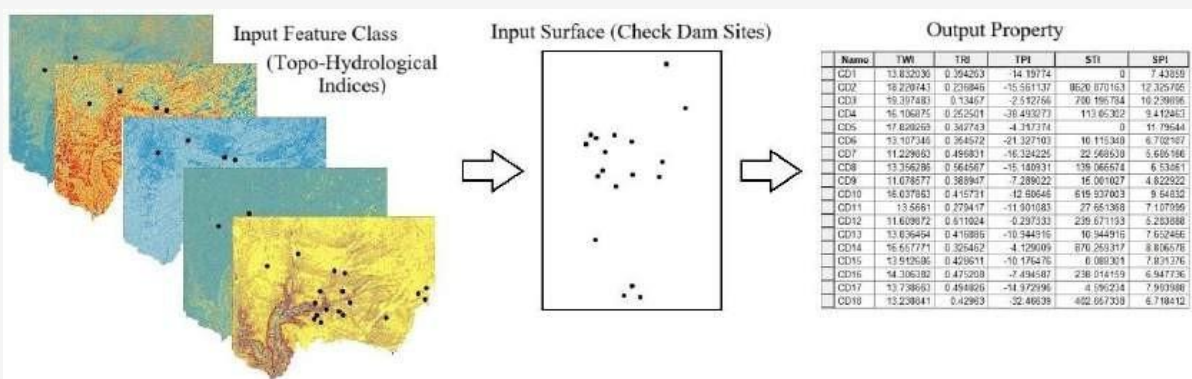


Figure 5: Workflow of the "Add Surface Information" tool showing the extraction of topo-hydrological index values from raster layers to check dam point features

2.3 Diagnostic Evaluation of Check Dam Performance Using ROC-AUC Curve

To contextualize and support the ROC-AUC curve, each topo-hydrological index was first reclassified into five standardized suitability classes. This preliminary step established a consistent evaluation framework that allowed the continuous indices to be meaningfully compared and assessed in relation to check dam performance. The resulting classification formed the basis for generating binary suitability thresholds, which were then used to calculate true and false positive rates across varying index levels in the ROC-AUC procedure. Figure 6 illustrates the ROC-AUC curves for five topo-hydrological indices TPI, SPI, TWI, STI, and TRI used to evaluate their ability to distinguish between suitable and unsuitable check dam sites.

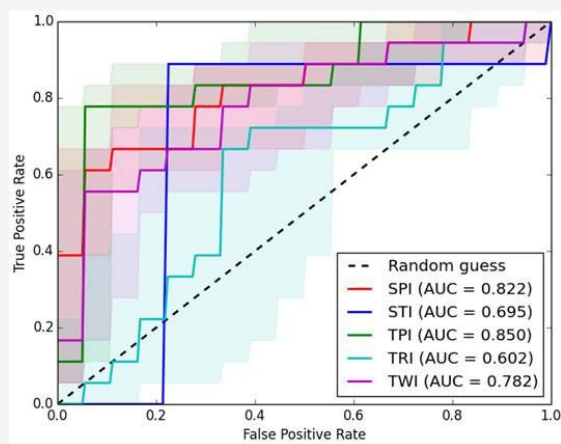


Figure 6: ROC-AUC curves for five topo-hydrological indices (SPI, STI, TPI, TRI, and TWI) used in evaluating the suitability of existing check dam sites

Among them, TPI (AUC = 0.850) and SPI (AUC = 0.822) emerged as the most effective indices, reflecting their strong alignment with the spatial distribution of high-performing check dams. These results affirm the importance of terrain morphology and stream dynamics in shaping site suitability. TWI (AUC = 0.782) demonstrated moderate predictive capability, suggesting a secondary yet relevant role in capturing moisture-related site characteristics. In contrast, STI (AUC = 0.695) and particularly TRI (AUC = 0.602) exhibited lower discriminatory power, implying a limited standalone utility in differentiating dam performance across the study area. While the ROC-AUC curve is traditionally reserved for categorical classification models, its application here serves a diagnostic and comparative purpose: to objectively quantify the degree of

association between each continuous index and the spatial occurrence of suitable check dam sites. This model-independent metric complements spatial reasoning and enhances the reproducibility of the evaluation. To further substantiate these findings, subsequent sections provide detailed index values for each dam site, enabling a more granular examination of site-specific performance. This integrated evaluation framework, which couples statistical metrics with localized data, offers a comprehensive and transparent approach for assessing the role of each index in existing check dam functionality.

2.4 Assessment of Check Dams Based on Topo-Hydrological Indices

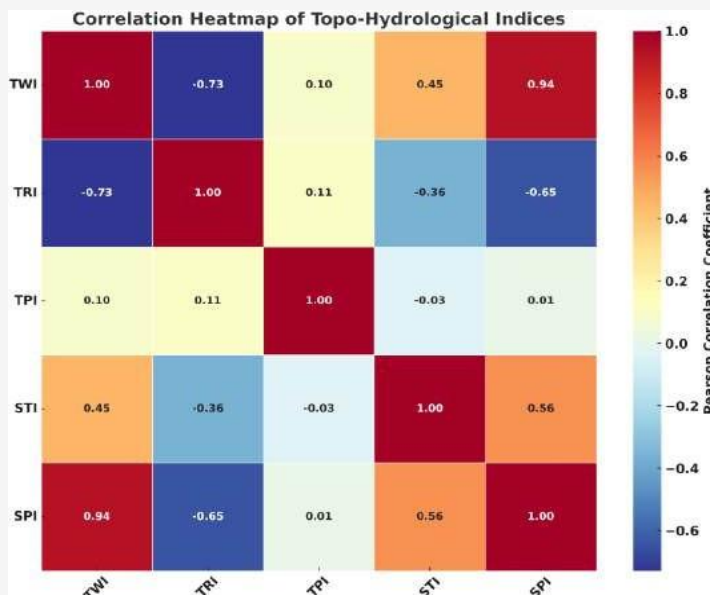
Table 2 summarizes the characteristics of 18 existing check dams, assessed using key topo-hydrological indices: TWI, TRI, TPI, SPI, and STI. The TWI values, ranging from 11.08 to 19.39, reflect varying capacities of the sites to retain surface runoff, with higher values indicating zones of greater water accumulation potential. TRI values show relatively low variation (0.13–0.61), suggesting moderate surface roughness across most dam sites. The predominance of negative TPI values (reaching as low as -38.49) indicates that the majority of the dams were constructed in concave landforms, such as valleys or depressions, which are generally more suitable for water impoundment. STI and SPI values vary markedly among the sites, with STI ranging from 0 to 870.26 and SPI from 4.82 to 12.32, signifying a broad spectrum of hydrological energy and sediment transport conditions. Notably, sites such as CD2 and CD14 exhibit high values for both STI and SPI, implying strong erosional forces and elevated sediment yield. These findings provide a quantitative basis for evaluating the performance and geomorphological appropriateness of existing check dams, and they offer insights for optimizing future site selection in similar ASARs.

2.5 Interrelationships of Topo-Hydrological Indices in Assessing Check Dam Performance

The correlation heatmap (Figure 7) offers key insights into how topo-hydrological indices interact and contribute to evaluating the suitability of existing check dam sites. The exceptionally strong positive correlation between the TWI and the SPI ($r = 0.94$) indicates that sites exhibiting greater potential for water accumulation also tend to experience higher stream energy. This relationship emphasizes the importance of jointly considering both indices when assessing a dam site's capacity for sustained water retention and its exposure to erosive forces.

Table 2: Topo-hydrological indices of existing check dams, used to evaluate their suitability for RWH

Check Dam	TWI	TRI	TPI	STI	SPI
CD1	13.83	0.39	-14.20	0.00	7.44
CD2	18.22	0.24	-15.56	8620.87	12.33
CD3	19.40	0.13	-2.51	700.20	10.24
CD4	16.11	0.25	-38.49	113.05	9.41
CD5	17.82	0.34	-4.32	0.00	11.80
CD6	13.11	0.35	-21.33	10.12	6.70
CD7	11.23	0.50	-16.32	22.57	5.69
CD8	13.36	0.56	-15.14	139.07	6.53
CD9	11.08	0.39	-7.29	15.00	4.82
CD10	16.04	0.42	-12.61	619.94	9.65
CD11	13.57	0.28	-11.90	27.65	7.11
CD12	11.61	0.61	-0.30	239.67	5.28
CD13	13.84	0.42	-10.94	10.94	7.65
CD14	16.56	0.33	-4.13	870.26	8.81
CD15	13.91	0.43	-10.18	0.09	7.83
CD16	14.31	0.48	-7.49	238.01	6.95
CD17	13.74	0.49	-14.97	4.60	7.99
CD18	13.24	0.43	-32.47	402.66	6.72

**Figure 7:** Correlation heatmap of topo-hydrological indices, highlighting strong associations (e.g., TWI–SPI) and the statistical independence of TPI

Conversely, a strong negative correlation between TWI and TRI ($r = -0.73$) highlights that smoother terrains, which typically facilitate water stagnation, are more favorable for check dam placement compared to rugged landscapes that promote rapid surface runoff. This is further supported by the inverse relationship between TRI and SPI ($r = -0.65$), implying that complex topography tends to dissipate stream energy, thus reducing sediment transport potential downstream. Interestingly, TPI displayed negligible correlations with all other variables ($|r| <$

0.11), indicating its statistical independence. This confirms TPI's unique role in identifying depressional or valley-bottom areas regardless of flow intensity or terrain complexity an essential factor in locating geomorphologically optimal dam sites. Meanwhile, the STI showed moderate correlations with both TWI ($r = 0.45$) and SPI ($r = 0.56$), suggesting that sediment dynamics are influenced by both water accumulation and flow power, but also shaped by site-specific topographic and edaphic characteristics.

Together, these findings underscore the value of a multi-index assessment framework for evaluating the suitability of existing check dams. While some indices like TWI and SPI capture overlapping hydrological dynamics, others such as TPI offer complementary spatial insights. Recognizing these distinctions ensures a robust and non-redundant basis for improving check dam functionality and guiding future site selection strategies.

2.6. Spatial Evaluation of Check Dams

The composite suitability scores, calculated as the mean of the standardized classifications of TWI, TRI, TPI, SPI, and STI, unveil significant disparities in the spatial suitability performance of the 18 evaluated check dams (Table 3) according to the reclassified index layers. The highest scores were recorded for CD4 (4.8) and CD3 (4.6), indicating their placement in highly favorable topographic settings characterized by strong runoff convergence, low to moderate terrain roughness, and concave landforms suitable for water retention. CD10, CD5, and CD14 followed closely, each attaining a score of 4.4, further reflecting optimal alignment with hydrological and topographical suitability criteria. In contrast, dams such as CD9 (mean score = 2.6) and CD7 (mean score = 2.8) ranked lowest, suggesting suboptimal

conditions including limited water accumulation potential and higher surface complexity. Figure 8 provides a spatially explicit visualization of the classified index values across the study area, offering additional insights into the topo-hydrological context of each check dam. Together, the numerical rankings and spatial patterns provide a coherent and comprehensive evaluation of existing check dam performance. This approach not only elucidates site-specific advantages and constraints but also underscores the practical utility of multi-index spatial analysis in optimizing the placement, design, and long-term functionality of RWH structures in ASARs. The final suitability map of existing check dams (Figure 9), generated by aggregating the standardized scores of the five topo-hydrological indices (TWI, TRI, TPI, SPI, and STI), provides a spatially integrated representation of overall site favorability across the study area. This map delineates zones of very low to very high suitability, enabling a clear visual assessment of each dam's performance in relation to its surrounding terrain and hydrological context. Figure 10 presents a comparative satellite image (dated August 2023) of two check dams exhibiting contrasting suitability levels for RWH: Al-Lajjun (CD4) on the left, and Wadi Al-Khabra (CD12) on the right.

Table 3: Normalized topo-hydrological class scores and composite suitability for existing check dams in the Al- Mujib Basin

Check Dam	TWI class	TRI class	TPI class	STI class	SPI class	Mean score
CD4	5	4	5	5	5	4.8
CD3	5	5	3	5	5	4.6
CD10	5	3	4	5	5	4.4
CD5	5	4	3	5	5	4.4
CD14	5	4	3	5	5	4.4
CD2	5	5	4	3	5	4.4
CD6	4	4	4	5	4	4.2
CD11	4	4	4	5	4	4.2
CD13	4	3	4	5	4	4.0
CD17	4	2	4	5	5	4.0
CD15	4	3	4	5	4	4.0
CD1	4	3	4	5	4	4.0
CD18	4	3	4	5	4	4.0
CD9	3	3	4	5	4	3.8
CD8	4	2	4	5	4	3.8
CD16	4	2	4	5	4	3.8
CD7	3	2	4	5	4	3.6
CD12	4	1	3	5	4	3.4

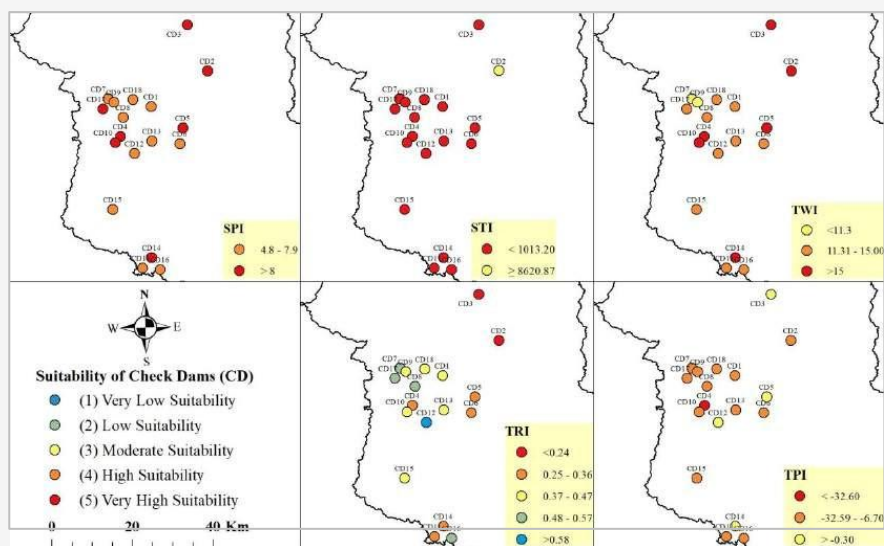


Figure 8: Spatial distribution of check dam suitability based on topo-hydrological indices (SPI, STI, TWI, TRI, TPI) in the Wadi Al-Mujib Basin

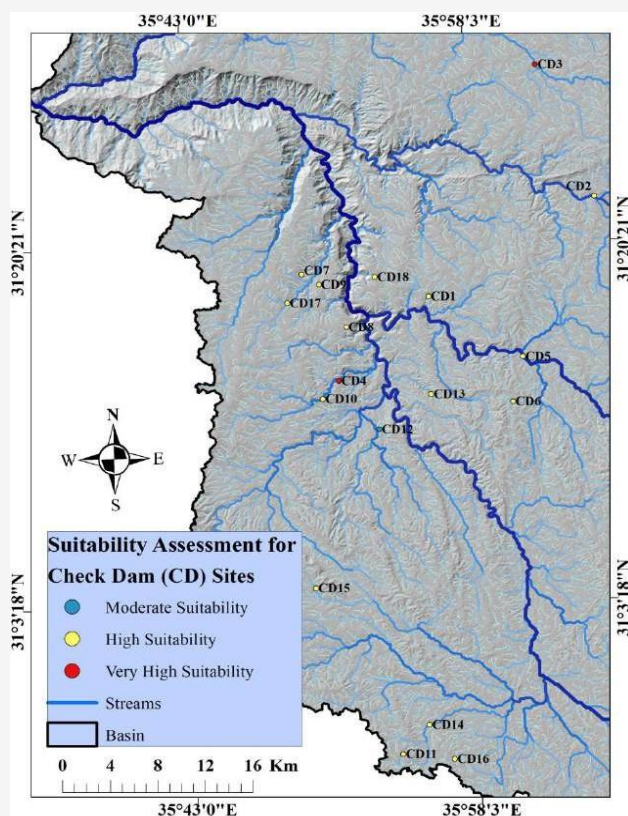


Figure 9: Suitability assessment map of existing check dams in the Al-Mujib Basin



Figure 10: Comparison of Al-Lajjun (CD4) and Wadi Al-Khabra (CD12) check dams showing differences in RWH suitability

Al-Lajjun/CD4, categorized as highly suitable, is strategically located at a well-defined valley junction where converging drainage lines enable efficient runoff capture. The check dam impounds a substantial reservoir with a total storage capacity of approximately 1,000,000 m³ [3], reflecting its ability to intercept significant surface flows. The geomorphological setting characterized by steep surrounding slopes, a narrow valley cross-section, and pronounced flow accumulation corresponds to high values of topo-hydrologic indices (e.g., TWI, SPI), confirming the site's optimal hydrological performance. Conversely, (Wadi Al-Khabra/CD12) is classified as moderately suitable. Although it plays a role in runoff retention, its geomorphological context limits its effectiveness. The dam is situated in a more subdued terrain with less concentrated flow paths, resulting in a relatively modest impoundment capacity of only 18,000 m³ [3]. The narrow and shallow reservoir, along with visible sedimentation patterns and vegetative growth, suggests suboptimal runoff accumulation and a reduced hydrological catchment response. This visual and quantitative comparison reinforces the necessity of multi-criteria spatial analysis in prioritizing dam locations, highlighting how terrain configuration and catchment dynamics critically influence the success of RWH structures.

3. Discussion

This study retrospectively evaluated the spatial suitability of 18 existing check dams in the Al-Mujib Basin using five key topo-hydrological indices. The results demonstrate that most dams were sited in locations characterized by favorable terrain features for runoff retention and erosion control, validating their placement despite the absence of prior GIS-based spatial planning. The ROC-AUC analysis has been widely used in previous studies to validate

suitability models based on topo-hydrological indices. For instance, a study conducted in Morocco [7] evaluated the accuracy of suitability maps by comparing them with depression maps derived from DEM analysis, showing improved accuracy with greater depression depths, and reaching an AUC of 0.875 at a 5 m threshold.

In another study [2], a comparison between model outputs and historical flood observations yielded an AUC of 0.948, indicating a strong model performance. Although ROC-AUC is typically used for evaluating predictive models, this study employed it diagnostically to measure how well each topo-hydrological index aligns spatially with existing check dam locations. A higher AUC (closer to 1) indicates that an index effectively distinguishes dam sites presumed suitable from other areas. For example, an AUC of 0.850 for TPI confirms the prevalence of concave landforms at dam locations, reinforcing its relevance. The STI and TRI demonstrated lower standalone performance (AUC = 0.695 and 0.602, respectively) yet contributed complementary insights.

Most check dams in this study showed TPI values between -0.3 and -38.5, with many below -20, indicating concave landforms. This aligns with prior studies suggesting TPI < -20 or -50 as highly suitable for check dams due to enhanced surface flow accumulation [2] and [7]. Similarly, SPI values ranged from 4.8 to 12.3, with all sites exceeding the 2.0 threshold, highlighting zones of high flow energy potential further supporting their suitability for check dams [2] and [10]. In the same vein, most TWI values ranged from 11.1 to 19.4, with several above 15, indicating strong moisture accumulation potential. Although TWI demonstrated moderate performance overall, values above 15 have been consistently linked to suitable RWH zones in previous studies. [9] and [24].

Compared to other TRI classes, values between $0.41 < \text{TRI} < 0.49$ demonstrated the highest suitability for RWH [10], whereas TRI values outside this range showed reduced effectiveness in identifying optimal sites.

While [8] identified the range $4.9 < \text{STI} < 412$ as optimal for RWH suitability, our findings similarly showed that most effective sites fell within this range, whereas extreme values (e.g., 870.3 or 8620.9) were associated with lower suitability. Despite the consistently high suitability scores assigned to the check dams based on the STI with 17 out of 18 check dams classified as Class 5 the index demonstrated only moderate discriminatory power in ROC-AUC analysis ($\text{AUC} = 0.695$). This discrepancy suggests that STI, while relevant to sediment dynamics, lacks sufficient spatial contrast to effectively distinguish suitable dam sites at the basin scale. The near-uniformity in suitability scores implies that low STI values are not exclusive to optimal sites, thus reducing the index's diagnostic reliability. This raises concerns about overestimating site favourability when relying on STI alone. More critically, several sites were assigned high suitability despite having implausibly low STI values for instance, as low as 0, which is hydrologically unrealistic in the context of active sediment transport zones. This anomaly indicates a need to revisit the calculation method or parameterisation of STI, particularly in ASARs where sediment processes are highly variable. Consequently, STI should be applied cautiously, and only in combination with more spatially robust indicators such as SPI and TWI, to ensure reliable assessment of check dam site suitability.

Correlation analysis among the indices underscores the value of an integrated evaluation framework. The strong positive correlation between TWI and SPI ($r = 0.94$) suggests that zones with high runoff accumulation often coincide with areas of high stream power, necessitating a careful balance between water retention and erosion risk. Conversely, the strong negative correlations between TRI and both TWI ($r = -0.73$) and SPI ($r = -0.65$) indicate that smoother terrain supports moisture retention while reducing erosive energy. Notably, TPI showed minimal correlation with the other indices ($|r| < 0.11$), affirming its unique role in detecting depression features independently of slope or flow intensity. Composite suitability scores reinforced these findings. Check dams such as CD3 and CD4 were located in geomorphologically optimal sites—marked by high TWI and SPI and low TPI and TRI values. In contrast, check dams like CD12 and CD7, situated in flatter or more rugged areas, scored lower, suggesting less favorable terrain-hydrology interactions.

However, the use of 30 m ASTER DEMs presents inherent limitations, as finer-resolution data (< 10 m) could enhance the accuracy of topo-hydrological indices. Additionally, the absence of other key factors such as soil texture, land cover, and socio-economic constraints may oversimplify the suitability evaluation, despite their recognized influence on RWH success [5] and [13]. Future research should integrate these variables, alongside post-construction performance data (e.g., storage efficiency, maintenance history), using machine learning or hybrid decision-support frameworks to enhance spatial accuracy and operational planning. Ultimately, the integration of topo-hydrological indices in this study not only validated the spatial logic behind existing check dam placements but also established a transferable, data-driven framework for evaluating RWH structures in arid basins. Such approaches are essential in regions where empirical data are limited and water resource planning must increasingly rely on geospatial intelligence.

4. Conclusion

This study proposed a spatially explicit, diagnostic framework for evaluating the topo-hydrological suitability of existing check dam sites in arid environments. By integrating five key indices TWI, TPI, TRI, SPI, and STI with ROC-AUC analysis, the spatial alignment of 18 check dams in the Al-Mujib Basin was assessed retrospectively. The findings revealed that TPI and SPI had the highest discriminatory power ($\text{AUC} = 0.850$ and 0.822), affirming their effectiveness in identifying geomorphologically and hydrologically favourable sites. Composite suitability scores highlighted several optimally located dams (e.g., CD3 and CD4), while others exhibited weaker alignment with topo-hydrological dynamics. The study reinforces the value of terrain-based diagnostics in post-construction evaluation and site validation, particularly in data-scarce, topographically complex basins. However, the generalisability of the framework is contingent on basin characteristics and DEM resolution; results are most applicable to semi-arid settings with similar terrain configurations. The use of 30 m ASTER data limits micro-scale accuracy, and additional variables such as soil texture, land use, and socio-economic constraints were not incorporated highlighting opportunities for methodological expansion. The results of this study offer practical insights for both practitioners and policymakers. Engineers can utilize the index-based suitability framework to retrospectively evaluate existing RWH structures and prioritise rehabilitation or redesign in cases of spatial misalignment.

Planners and decision-makers may adopt the integrated GIS–topo-hydrological approach to optimise the siting of future check dams, promoting efficient allocation of water-related investments. The spatial variation in composite suitability scores highlights opportunities for tiered interventions. High-scoring dams (≥ 4.6), like CD4 and CD3, should be maintained and used as design references. Medium-performing sites (4.0–4.2) require moderate upgrades, while low-scoring ones (< 4.0), such as CD7 and CD12, need thorough reassessment. This suitability-based framework supports data-driven resource allocation and strategic siting of future RWH structures, promoting more resilient water infrastructure planning. Furthermore, this methodology equips national agencies with a replicable tool for basin-wide suitability mapping within the broader context of sustainable water resource planning.

Future research should explore the integration of finer-resolution datasets, incorporate field-based performance metrics, and expand the index pool with additional biophysical and socio-economic factors. Such efforts will enhance the robustness and applicability of spatial decision-support tools as ASARs are increasingly vulnerable to water insecurity.

5. Future Work Recommendation

Future studies are encouraged to enhance the spatial assessment of RWH structures by incorporating a broader range of variables and methodologies. This includes integrating additional biophysical factors such as slope, rainfall, runoff, soil texture, permeability, land use/land cover, and drainage density to refine suitability analysis. Embedding socio-economic factors such as proximity to settlements and agricultural zones, as well as cost-effectiveness into MCDA frameworks (e.g., AHP, Fuzzy AHP) would ensure more holistic site evaluations. The use of high-resolution DEMs (< 10 m), derived from LiDAR or UAV sources, can significantly improve microtopographic precision. Moreover, validating site performance through post-construction monitoring, including reservoir filling rates, sediment deposition, and maintenance records, would provide valuable feedback for model refinement. Finally, the application of hybrid machine learning algorithms like Random Forest or XGBoost can uncover complex, non-linear relationships in dam siting and performance. Collectively, these advancements would support the development of robust, context-specific models tailored to sustainable and resilient water resource management in ASARs.

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