BILINGUAL PUBLISHING GROUP

Journal of Environmental & Earth Sciences

https://journals.bilpubgroup.com/index.php/jees

ARTICLE

Sub-Watershed Prioritization of Chambal River Basin Using Morphometric and Topo-Hydrological Parameters

Teja Ram Nitharwal [1*], *Vipin Chandra Lal* [2], *Arun Pratap Mishra* [3], *Kaushalendra Kumar Karvendu* [1], *Rashmi Singh* [4], *Geeta Kumari* [5], *Ashvini Kumar* [1]

[1] *Department of Geography, Delhi School of Economics, University of Delhi, New Delhi 110007, India*

[2] *Department of Geography, Dr. Bhim Rao Ambedkar College, University of Delhi, New Delhi 110094, India*

[3] *Office of the Registrar General of India, Ministry of Home Affairs, Government of India, New Delhi 110011, India*

[4] *Department of Geography, Miranda House, University of Delhi, New Delhi 110007, India*

[5] *Department of Geography, Kalindi College, University of Delhi, New Delhi 110008, India*

ABSTRACT

Natural resource management is essential to sustain human well-being and the environment. Water and soil are two of the most important natural resources that require careful management. The western part of India faces multiple challenges, including climatic variability, soil degradation, water scarcity, deforestation, etc. The basin's sub-watersheds are delineated and prioritised using the Soil and Water Assessment Tool (SWAT) and Sub Watershed Prioritization Tool (SWPT), respectively, using morphometric and topo-hydrological characteristics, and the sub-watersheds are further ranked using Weighted Sum Analysis (WSA). The findings indicate that SWS19, SWS18, SWS1, SWS17, SWS16, and SWS15, which are drained by the rivers Chambal, Kali Sindh, Mashi, Parbati, Parwan, and Beradi, are highly vulnerable sub-watersheds. By integrating remote sensing, GIS techniques, and quantitative morphometric analysis, parameters such as drainage density, stream frequency, bifurcation ratio, and slope gradient were evaluated. The analysis revealed critical sub-watersheds characterized by steep slopes, high drainage density, and poor vegetation cover, indicating their susceptibility to erosion and runoff. The findings underscore the necessity for targeted soil conservation measures, such as contour bunding, afforestation,

*CORRESPONDING AUTHOR:

Teja Ram Nitharwal, Department of Geography, Delhi School of Economics, University of Delhi, New Delhi 110007, India;
Email: trnitharwal1@gmail.com

ARTICLE INFO

Received: 19 January 2025 | Revised: 7 March 2025 | Accepted: 11 March 2025 | Published Online: 23 April 2025
DOI: https://doi.org/10.30564/jees.v7i5.8463

CITATION

Nitharwal, T.R., Lal, V.C., Mishra, A.P., et al., 2025. Sub-Watershed Prioritization of Chambal River Basin Using Morphometric and Topo-Hydrological Parameters. Journal of Environmental & Earth Sciences. 7(5): 117–129. DOI: https://doi.org/10.30564/jees.v7i5.8463

and water retention structures. This study highlights the utility of geospatial tools for sustainable watershed management and provides a replicable framework for prioritizing sub-watersheds in similar regions.

Keywords: Morphometric Analysis; Topo-Hydrology; Sub-Watershed Prioritization Tool (SWPT); Natural Resource Management; Soil and Water; Weighted Sum Analysis (WSA); Chambal River Basin

1. Introduction

Natural resources are vital to our daily lives and are crucial to the planet's functioning. However, the increasing demand for natural resources has led to overexploitation and depletion. As a result, sustainable management of natural resources is vital to ensuring their availability for future generations. People and the planet's economic, environmental, social, health, and energy well-being depend on sustainable natural resource management [1]. The global demand for natural resources is increasing, and the depletion and degradation of these resources are becoming significant global issues [2, 3]. Sustainable management requires responsible use, conservation, and management, ensuring we do not exhaust them or cause irreparable environmental harm. Governments, businesses, and individuals worldwide must collaborate to promote sustainable natural resource management and ensure future generations' access to them [4]. According to the United Nations, the world's population is predicted to reach 9.7 billion by 2050, increasing the demand for food, water, energy, and natural resources [2]. However, depletion and deterioration of natural resources are becoming critical global issues. According to the World Wildlife Fund and the Living Planet Report [5], the globe has lost 60% of its biodiversity over the previous 50 years, and one million species are on the verge of extinction. It also states that 80% of the world's forests have been lost or degraded, and the oceans are overfished and contaminated.

Water and soil are the two most critical natural resources that require effective management. Water is essential for ecological function, human livelihood, and economic development [6, 7]. Water management entails ensuring the availability and quality of water resources while providing fair access to water for various purposes [8, 9]. Soil is a valuable natural resource for agriculture, forestry, and other land-based industries. Soil management involves conserving and improving soil quality and productivity, reducing soil erosion and degradation, and promoting soil conservation practices such as crop rotation, agroforestry, and soil nutrient management [10, 11]. Furthermore, effective natural resource management can help to address emerging challenges such as climate change, water scarcity, and soil degradation.

A watershed is a natural hydrological unit that plays a critical role in managing water resources, soil conservation, and ecological sustainability [12, 13]. Watershed management is a critical component of natural resource management, focusing on managing watersheds or drainage basins [14]. Effective watershed management ensures the balanced utilization of water and land resources to maintain hydrological balance, prevent erosion, and enhance agricultural productivity. However, uncontrolled land-use changes, deforestation, and soil erosion have increasingly threatened watersheds, leading to land degradation and reduced water availability [16]. Sub-watershed prioritization is a technique used to assess and rank different sub-watersheds based on various hydrological, topographical, and environmental factors. This process helps to identify areas prone to soil erosion and degradation, develop targeted conservation strategies, optimize water resource management for agricultural and ecological sustainability and support government and community-based interventions for sustainable land use planning [17, 18]. Given the varying geomorphological characteristics across the Chambal River Basin, the prioritization of sub-watersheds enables the implementation of site-specific watershed management strategies. This helps in mitigating environmental degradation, improving groundwater recharge, and enhancing overall hydrological sustainability in the region.

The prioritization of sub-watersheds plays a pivotal role in identifying critical areas prone to soil erosion and managing water resources effectively. Furthermore, morphometric analysis provides valuable insights into the geomorphological and hydrological behavior of river basins [19]. Several studies have emphasized the importance of integrating morphometric parameters with hydrological analysis for watershed management. For instance, Strahler [20] highlighted that morphometric evaluation enables the assessment of drainage network characteristics, which are essential for understanding runoff potential and erosion susceptibility. Similarly, Biswas, Sudhakar and Desai [21] noted that GIS-based morphometric analysis is a powerful tool for prioritizing watersheds, particularly in semi-arid regions like the Chambal Basin. Morphometric and topo-hydrological analysis has emerged as a robust methodology for assessing watershed characteristics and prioritizing intervention areas. Pioneering studies by Horton [19] and Strahler [20] laid the groundwork for understanding drainage networks and their influence on surface runoff and erosion. Recent advancements in geospatial technologies have further enhanced the precision of such analyses, enabling effective prioritization of sub-watersheds for conservation efforts.

Several attempts have been made to analyse and prioritise sub-watersheds at different scales using Multicriteria Decision Analysis (MCDA) [14, 22–24], Weighted Sum Analysis (WSA) [8], Sediment Yield Index) [25, 26], and Principal Component Analysis (PCA) [27]. Watershed management requires developing and implementing land use plans considering the watershed's unique characteristics, including its topography, soil types, vegetation, and water resources. Land use planning aims to balance competing land uses while promoting the sustainable use and conservation of natural resources. By coordinating land use practices and implementing sustainable management strategies, watershed management can help conserve water resources, improve water quality, protect biodiversity, and support sustainable development [18, 28]. Watershed management needs collaboration and engagement from various stakeholders, including government agencies, corporate sector organisations, civil society groups, and local communities. Therefore, the study's objective, in general, is to prioritise the sub-basins of the Chambal River basin in terms of runoff/peak discharge and potential soil erodibility for the sustainable development of natural resources.

The Chambal River Basin, one of the key tributary basins of the Yamuna-Ganga River System, covers parts of Madhya Pradesh, Rajasthan, and Uttar Pradesh. It is characterized by a complex network of sub-watersheds, diverse topography, and a semi-arid climate, making it prone to hydrological variability, soil erosion, and degradation. Prioritization of sub-watersheds within this basin is essential to identify critical zones requiring conservation measures for effective water resource management and sustainable land use. Watershed management plays a pivotal role in ensuring sustainable development, especially in regions prone to environmental challenges such as erosion and water scarcity [29]. The Chambal River Basin exemplifies the need for targeted interventions due to its diverse physiographic features and vulnerability to land degradation. Spanning across Madhya Pradesh, Rajasthan, and Uttar Pradesh, this basin faces issues including extensive ravine formation, deforestation, and erratic rainfall patterns, all of which exacerbate soil erosion and disrupt water availability [18]. The Chambal Basin's distinctive badland topography and socio-economic significance make it a critical area for study. The ravines not only degrade fertile agricultural land but also pose challenges to infrastructure development and biodiversity conservation. Given these complexities, this research integrates morphometric parameters such as drainage density, bifurcation ratio, and stream frequency with topo-hydrological factors like slope gradient and land cover to identify and prioritize vulnerable sub-watersheds. This paper aims to provide a scientific framework for watershed management by leveraging remote sensing and GIS technologies. The findings are intended to guide policymakers and resource managers in designing targeted soil and water conservation strategies, contributing to the broader goals of sustainable land and water resource management in the Chambal Basin. The Chambal River Basin has been subjected to extensive land degradation due to both natural and anthropogenic factors. The ravines along its course are among the most eroded landscapes in India, posing significant challenges to agriculture and water conservation. Prioritizing sub-watersheds based on their morphometric and topo-hydrological parameters allows for targeted intervention strategies that can mitigate these challenges while promoting sustainable development. The main objective of the paper is to evaluate and prioritize the sub-watersheds of the Chambal River Basin using a combination of morphometric and topo-hydrological parameters, leveraging modern geospatial tools. The findings of this research will contribute to formulating effective watershed management practices, supporting regional and national objectives for sustainable water and land resource management.

2. Material and Method

2.1. Study Area

The study area, Chambal Basin, is located in central India. It lies between 23°31′03.91″ to 26°56′03.72″ N latitude and 74°45′15.00” to 78°13’33.86” E longitude and covers an area of 142,877 sq km, encompassing parts of the states of Madhya Pradesh, Rajasthan, and Uttar Pradesh (**Figure 1**). The Chambal River flows through rugged terrain of ravines, gorges, and hills, providing a unique ecosystem supporting diverse flora and fauna. The upper catchment of the Chambal River Basin consists of rugged and forested terrains in Madhya Pradesh, where the river originates. The middle reach is characterized by extensive ravines and badland topography formed by severe gully erosion along the riverbanks, particularly in northern Madhya Pradesh and parts of Rajasthan. The lower reach features broad floodplains and alluvial terraces in Uttar Pradesh. The Chambal River Basin features a dendritic drainage pattern, reflective of its homogenous lithology and relatively uniform slopes. Major tributaries include right bank tributaries such as Kali Sindh, Parbati, and Banas Rivers and left bank tributaries such as Shipra and Kuno Rivers. These tributaries significantly contribute to the hydrological regime and sediment load of the Chambal River [29].

The area has a predominantly dry climate, with the monsoon season running from June to September. The basin's average annual rainfall is between 600 and 800 mm, with the monsoon season being the wettest. The basin experiences a semi-arid to sub-humid climate. Annual rainfall ranges from 600 mm in the western parts (Rajasthan) to 1,200 mm in the eastern parts (Uttar Pradesh). Monsoonal rains dominate between June and September. Summers are hot (35 °C to 48 °C), while winters are mild to cold (5 °C to 20 °C). This climatic variability affects the hydrological behavior of the basin, influencing surface runoff and soil erosion. The basin's geological composition includes Vindhyan sandstones, shales, and limestones, along with Deccan Trap basalts. Soil types vary across the basin. Sandy soils are predominant in Rajasthan. Black cotton soils are found in the Deccan Trap regions of Madhya Pradesh. Alluvial soils occupy the lower reaches in Uttar Pradesh.These soils exhibit varying levels of permeability and fertility, influencing agricultural practices and water infiltration. The region is prone to droughts and water scarcity, and the *Chambal River* is a critical water source for irrigation, drinking, and industrial purposes. The excessive use of groundwater for irrigation and other purposes has led to a decline in the water table in the region, causing wells to dry up and the soil to become saline. This has affected agricultural productivity and the livelihoods of farmers in the area. In the Chambal River basin, the gullies/ravines and arid plains are where the most severe soil erosion occurs, with the gully areas seeing the highest mean soil erosion rates at 13.44 t ha^{-1} yr^{-1}. Estimates of soil loss at the catchment level point to considerable soil loss in the four catchments of *Kali Sindh, Lower Chambal, Upper Chambal,* and *Parbati* [30].

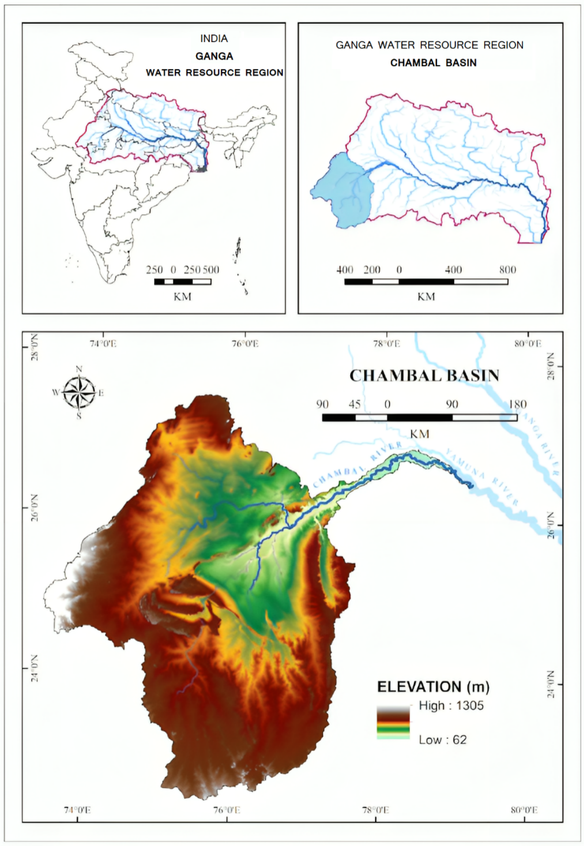

Figure 1. Location of Chambal River Basin in the Ganga River System.

The Chambal basin faces several geohydrological problems that significantly impact the environment and society. The problems of groundwater depletion, waterlogging, salinity, riverbank erosion, water pollution, and climate change require urgent attention and effective management strategies. Hence, sustainable management of water and land resources in the basin is crucial for ensuring the region's ecological, social, and economic well-being. Land use is dominated by agriculture, with wheat, mustard, soybeans, and pulses being the major crops. Sparse vegetation, including thorny scrub and deciduous forests, characterizes much of the region. Protected areas such as the National Chambal Sanctuary are vital for conserving biodiversity, including endangered species like the gharial, Gangetic dolphin, and Indian skimmer [29]. The basin supports a large rural population dependent on agriculture and animal husbandry. However, challenges such as water scarcity, soil erosion, and land degradation impact livelihoods. Sustainable management of the basin's natural resources is critical for improving the socio-economic conditions of the region's inhabitants. The Chambal Basin is one of the most erosion-prone regions in India due to its badland topography and intense monsoonal rains. Unsustainable agricultural expansion and overgrazing have led to significant deforestation, exacerbating erosion. Uneven rainfall distribution and poor water storage infrastructure result in seasonal water shortages. The integration of morphometric and topo-hydrological analysis is essential for addressing these challenges and developing effective watershed management strategies [28].

2.2. Methodology

2.2.1. Data Source

A Cartosat-1 digital elevation model (DEM) version 3R1 of 1 arc-second (~32 m) spatial resolution obtained from the Indian Geo-Platform of ISRO, Bhuvan (https://bhuvan-app3.nrsc.gov.in/data/download/index.php) is used for hydrological analysis (drainage system), relief, slope aspects and other topographical parameters. In this study, topo-hydrological and morphometric parameters were used to rank sub-watersheds. These parameters included: (1) areal aspects (drainage density (D), stream frequency (Fs), drainage texture (Rt), form factor (Rf), circularity ratio (Rc), constant of channel maintenance (C), elongation ratio (Re), and compactness coefficient (Cc); (2) linear aspects (bifurcation ratio (Rb); and (3) topo-hydrological factors (**Table 1**).

Table 1. The methodology adopted for computing morphologic and topo-hydrological parameters.

Parameters	Definition/Formula	References
Stream frequency (F_s)	$F_s = N_u/A$ where N_u is the total number of stream segments of order 'u' and A is the area enclosed within the boundary of the watershed divide (Basin area)	Horton (1932) [31]
Compactness constant (C_c)	$C_c = 0.2821P/A^{0.5}$ where P is the length of the watershed divide that surrounds the basin (Basin perimeter)	Horton (1945) [19]
Constant of channel maintenance (C)	$C = 1/D$ where D is drainage density	Schumm (1956) [32]
Bifurcation ratio (R_b)	$R_b = N_u/N_u + 1$ where $N_u + 1$ is the number of segments of the next higher order	Schumm (1956) [32]
Drainage density (D)	$D = L_u/A$ where L_u is the total stream length of order 'u'	Horton (1932) [31]
Elongation ratio (R_e)	$R_e = \sqrt{4}\times A/P_i/L_b$ where L_b is the distance between the outlet and the farthest point on the basin boundary (Basin length)	Schumm (1956) [32]
Circularity ratio (R_c)	$R_c = 4\times P_i\times A/P^2$ where P is the length of the watershed divide that surrounds the basin (Basin perimeter)	Miller (1953) [33]
Form factor (R_f)	$R_f = A/{L_b}^2$ where L_b is the distance between the outlet and the farthest point on the basin boundary (Basin length)	Horton (1932) [31]
Drainage texture ratio (R_t)	$R_t = N_u/P$	Horton (1945) [19]

Table 1. *Cont.*

Parameters	Definition/Formula	References
Topographic wetness index (TWI)	$TWI = \ln(A_s/\tan\beta)$ where A_s is the local upslope area draining through a certain point per unit contour length and $\tan\beta$ is the local slope	Beven and Kirkby (1979) [34]
Stream power index (SPI)	$A_s \times \tan\beta$	Whipple and Tucker (1999) [35]
Stream transport index (STI)	$STI = (m+1) \times A_s/22.13^m \times \sin\beta/0.0896^n$ where β is the local slope gradient in degrees, *m* is the contributing area exponent, and *n* is the slope exponent	Moore and Burch (1986) [36]

2.2.2. Tools, Techniques and Software

This study uses the Soil and Water Assessment Tool (SWAT) for sub-watershed delineation and Python-written Sub Watershed Prioritization Tool (SWPT) as an extension of the ArcGIS 10.4 program to prioritise the subbasins of the Chambal basin and to reduce the uncertainty around morphometric and topo-hydrological variables [8]. SWAT is a hydrological model used to simulate water quality, sediment, and nutrient transport in watersheds. It helps in managing water resources and assessing the impact of land use changes) [37]. SWPT is a tool used to rank sub-watersheds based on factors like erosion, runoff, and sediment yield to identify critical areas for conservation and management [38]. The SWPT was created to depict how sub-watersheds are prioritised in areas with little or no data. The morphometric and topo-hydrological characteristics are taken into account for the prioritising of micro-watersheds in order to determine the runoff/peak discharge and erosion risk, even without taking critical criteria like soil maps into account [39, 40].

The current study uses the weighted sum analysis (WSA) technique developed by Aher et al. [8] to rank the hydrological units properly. To determine the parameters that needed to be considered in the final analysis combination, the WSA, a rigorous statistical procedure, is combined with geospatial technology. The WSA method estimates the relative significance of each parameter via statistical correlation. Also, it assigns the weight to each parameter concerning its due importance (Equation (1)) in order to avoid the individual bias of several morphometric and topo-hydrological factors associated with weights:

$$\text{Prioritisation} = \sum_{i=1}^{n} Wi * Xi \quad (1)$$

Wi is the weight of each morphometric parameter calculated by the WSA approach, and Xi is the value of morphometric parameters.

3. Result and Discussion

3.1. Drainage Network of Chambal Basin

The Chambal River basin is a vast hydrological system comprising numerous small and large rivers, tributaries, and streams that flow through Rajasthan, Madhya Pradesh, and Uttar Pradesh in India. The Chambal River, the primary river in the basin, originates from the Vindhya Range in Madhya Pradesh and flows northeast for approximately 960 kilometres before joining the Yamuna River in Uttar Pradesh. Based on the Strahler stream order, the Chambal River is the eighth major river outlet, which receives water from tributaries such as the Banas River, the Parvati River, and the Kali Sindh River, among others. The basin is characterised by a dendritic drainage pattern formed when the river and its tributaries resemble the branching pattern of a tree.

The Chambal River Basin is an integral part of the Ganga River System, covering parts of Madhya Pradesh, Rajasthan, and Uttar Pradesh. The Chambal River, a major tributary of the Yamuna River, has a well-developed dendritic drainage pattern and exhibits unique geomorphological characteristics (**Figure 2**). The Chambal River originates from Janapav Hills in the Vindhyan Range (Madhya Pradesh) at an elevation of 854 meters above sea level. It flows in a north-northeast direction through Madhya Pradesh, Rajasthan, and Uttar Pradesh before merging with the Yamuna River near Etawah. The total length of the Chambal River is 1024 km, making it one of the longest rivers in central India. The Chambal Basin has a well-defined tributary system, including both right-bank and left-bank tributaries. Right-bank tributaries include the Parbati River that originates from Madhya Pradesh and joins Chambal in Rajasthan, Kuno River flows through Madhya Pradesh and is an essential tributary for ecological conservation, Sipra River known for its religious significance, originating near Ujjain, and Banas River that is a major tributary from Rajasthan, joining Chambal near Sawai Madhopur. Left-bank tributaries include Kali Sindh River which is one of the largest left-bank tributaries, originating from Madhya Pradesh, Parwan River that is a seasonal river that contributes to Chambal during monsoons, and Mej River which is a minor tributary aiding local irrigation in Rajasthan.

The drainage network of the Chambal Basin is a well-organized fluvial system with varied topography, tributary networks, and hydrological significance. Proper watershed management, soil conservation, and sustainable water resource utilization are essential for maintaining ecological balance and ensuring long-term water security in the region. The Chambal River and its tributaries exhibit a dendritic and sub-dendritic drainage pattern, with a well-integrated network of streams. The basin features deep gorges and ravines, especially in its lower reaches, caused by severe soil erosion. It is an ephemeral river system, with peak flow during the monsoon and reduced discharge in the dry season. The Chambal River Basin plays a crucial role in agriculture, drinking water supply, and hydroelectric power generation. It is home to multiple dams and reservoirs, including Gandhisagar Dam (Madhya Pradesh) for irrigation and hydroelectricity, Rana Pratap Sagar Dam (Rajasthan) important for power generation, and Jawahar Sagar Dam which helps in flood control and water storage. Soil erosion and ravine formation are major issues due to gully erosion in the lower Chambal region. The Chambal River is a National Sanctuary, protecting endangered species like the Gharial (Gavialis gangeticus) and the Gangetic Dolphin.

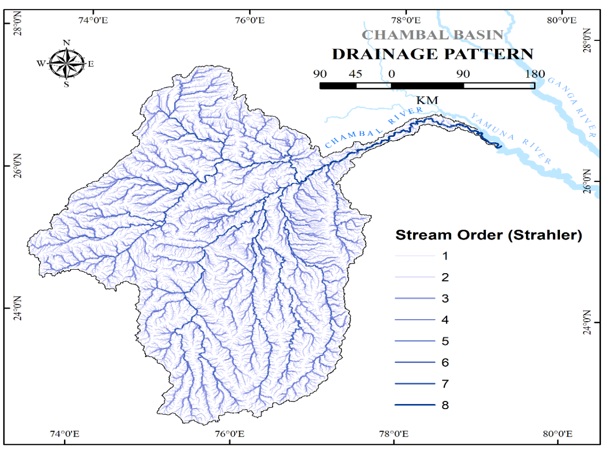

Figure 2. Drainage map of the study area.

3.2. Sub-Watershed Delineation and Codification

The Chambal basin is subdivided into 21 sub-watersheds using the Soil and Water Assessment Tool (SWAT) based on major and minor outlets (**Figure 3**). The object I.D. created by SWAT for all the 21 sub-watersheds is converted into the code of the sub-watershed, such as object ID 1 as Sub-Watershed 1 (SWS1) to object ID 21 as Sub-Watershed 21 (SWS21).

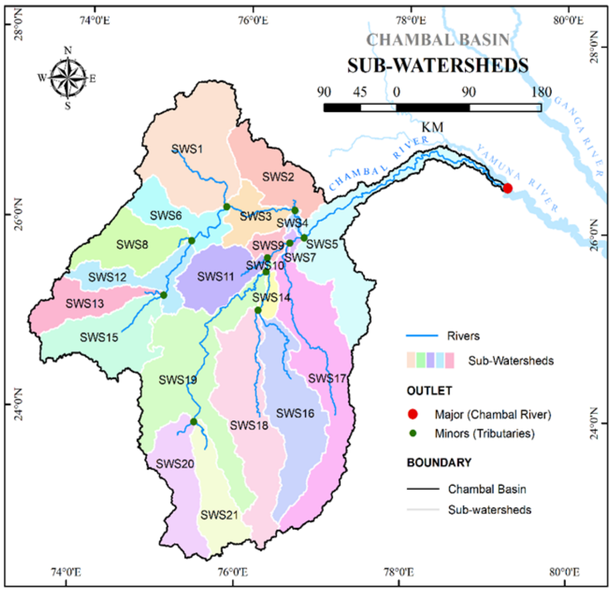

Figure 3. Sub-watershed delineation and codification.

3.3. Prioritization of Chambal Sub-Watersheds

The SWPT tool automatically calculates the correlation coefficients between each pair of morphometric and topo-hydrological factors in the Chambal basin's sub-watersheds to prioritise them. This correlation matrix is then used to determine which factors could and could not impact the prioritisation. The study employed the parameters in this analysis with a correlation coefficient greater than 0.6. The SWPT program also determines the WSA index, prioritising sub-watersheds using the chosen parameters. Based on the data above, the tool may rank sub-watersheds in descending order, starting with the most vulnerable to runoff production and soil erosion and ending with the least susceptible one.

The prioritization of sub-watersheds in the Chambal River Basin is a crucial step toward effective watershed management, soil conservation, and sustainable water resource planning. The study highlights the significant spatial variations in erosion susceptibility, land degradation, and hydrological potential across different sub-watersheds.By applying morphometric, hydrological, and GIS-based techniques, the sub-watersheds have been categorized into high, moderate, and low-priority zones based on erosion vulnerability and conservation needs. High-priority sub-watersheds, mainly in the upper and middle reaches, exhibit severe soil erosion, requiring urgent intervention through afforestation, soil conservation measures, and sustainable agricultural practices. Moderate-priority zones need integrated watershed development, including rainwater harvesting, controlled grazing, and agroforestry. Low-priority zones, though relatively stable, still require monitoring and long-term sustainability strategies to prevent future degradation. The prioritization of sub-watersheds provides a scientific framework for policymakers and stakeholders to implement targeted conservation and management strategies. Integrating community participation, government initiatives, and technological advancements will ensure sustainable water resource utilization, biodiversity conservation, and livelihood security in the Chambal River Basin. This holistic approach will contribute to environmental sustainability and long-term ecological balance in the region.

Table 2 shows the results of morphometric and topo-hydrological parameters using an automated GIS-based tool for prioritising sub-watersheds (SWPT). It can be observed that the frequency of streams (Fs) ranges between 0.0000002581 (SWS7) and 0.0000000046 (SWS17). According to the results of the bifurcation ratio (Rb), the highest value is obtained by SWS12 (2.92), while SWS11 acquired the lowest one (1.36). In terms of Rf, the results of SWPT showed that SWS7 and SWS17 have the most (0.82) and lowest (0.13) values, respectively. The prioritisation of the results of the elongation ratio (Re) is highest in SWS7 (1.02) and lowest in the SWS17 (0.41). Sub-watershed 01, based on the circularity ratio (Rc) factor, obtained the highest value (0.22), and SWS5 had the lowest one (0.05).

Table 2. Morphometric and topo-hydrological parameters of the sub-watersheds.

Name	F2	R	R4	R2	R	D	R	Cc	C	TWI	SPI	STI
SWS1	0.0000000050	1.85	0.62	0.89	0.22	0.00010	0.00008	2.13	9558.74	14.38	6.48	41.48
SWS2	0.0000000125	2.00	0.43	0.74	0.15	0.00015	0.00011	2.62	6505.48	14.05	6.51	38.51
SWS3	0.0000000187	1.83	0.38	0.70	0.15	0.00019	0.00012	2.59	5330.71	14.20	6.37	37.70
SWS4	0.0000001517	2.17	0.38	0.69	0.15	0.00048	0.00037	2.55	2081.13	13.36	7.11	36.81
SWS5	0.0000000067	2.00	0.15	0.43	0.05	0.00013	0.00004	4.66	7670.79	13.85	6.69	44.04
SWS6	0.0000000164	2.30	0.29	0.60	0.13	0.00017	0.00011	2.81	5915.61	14.22	6.35	38.85
SWS7	0.0000002581	2.38	0.82	1.02	0.15	0.00059	0.00060	2.54	1700.77	14.09	6.37	31.87
SWS8	0.0000000107	2.15	0.25	0.57	0.16	0.00017	0.00010	2.50	5931.53	14.15	6.39	39.42
SWS9	0.0000000541	1.92	0.72	0.95	0.17	0.00030	0.00023	2.45	3312.05	13.81	6.70	35.88
SWS10	0.0000013396	2.59	0.43	0.74	0.19	0.00123	0.00170	2.27	812.20	13.89	6.36	28.99
SWS11	0.0000000143	1.36	0.40	0.71	0.21	0.00016	0.00014	2.18	6144.86	13.99	6.59	39.38
SWS12	0.0000000174	2.92	0.17	0.47	0.08	0.00018	0.00009	3.60	5452.39	14.05	6.45	38.74
SWS13	0.0000000153	2.00	0.17	0.46	0.12	0.00018	0.00010	2.92	5415.25	13.74	6.78	41.33
SWS14	0.0000000715	1.87	0.32	0.63	0.20	0.00035	0.00029	2.21	2897.71	14.19	6.30	35.55
SWS15	0.0000000096	2.05	0.29	0.61	0.13	0.00013	0.00009	2.76	7960.77	13.95	6.60	38.69
SWS16	0.0000000084	2.09	0.17	0.46	0.12	0.00012	0.00008	2.93	8389.62	14.05	6.49	40.27
SWS17	0.0000000046	1.87	0.13	0.41	0.08	0.00011	0.00005	3.45	9245.17	14.10	6.45	40.93
SWS18	0.0000000054	1.96	0.17	0.46	0.10	0.00010	0.00006	3.19	10361.38	14.06	6.47	39.75
SWS19	0.0000000040	1.88	0.20	0.51	0.07	0.00008	0.00004	3.87	12138.78	14.19	6.50	41.22
SWS20	0.0000000108	1.58	0.26	0.58	0.15	0.00013	0.00010	2.60	7774.45	14.22	6.31	38.31
SWS21	0.0000000129	2.44	0.21	0.52	0.15	0.00015	0.00011	2.56	6684.24	14.22	6.33	39.13

According to the results of both drainage density (D) and drainage texture (Rt), SWS10 ranks first with the values of 0.00123 and 0.00170, respectively, and drainage density (D) is lowest in SWS19 (0.00008). With the value of 0.00004 in both SWS5 and SWS19, the drainage texture (Rt) is the lowest. The highest and the lowest values of the compactness coefficient (Cc) factor belonged to SWS5 (4.66) and 01 (2.13), respectively. The values of the constant of channel maintenance (C) factor depict that SWS19 (12138.78) and SWS10 (812.20) rank at the first and the last position, respectively. According to TWI, SPI and STI, the prioritisation results conclude that SWS1, 4, and 5 gain the highest values and sub-watersheds 4, 14, and 10 receive the lowest values, respectively.

The correlation matrix obtained by the weighted sum analysis (WSA) approach of morphometric properties for the sub-watersheds is shown in **Table 3**. The reported results are for a correlation coefficient (r) of more than 0.75. Fs has a significant correlation and a positive value of correlation coefficient, with Rt (r = 0.99), D (r = 0.95), and a significant negative correlation with STI (r = –0.76). Rb has no significant correlation with the other morphometric parameters of the sub-watersheds. At the same time, Rf has a high and positive correlation (r = 0.99) with Re. The D and Rt correlation results have a high positive correlation, while D and STI have a negative correlation. The relation between Rt and STI and between TWI and SPI shows a negative correlation of –0.84 and –0.87, respectively.

Table 3. Correlation matrix of morphometric properties for the sub-watersheds.

	Fs	Rb	Rf	Re	Rc	D	Rt	Cc	C	TWI	SPI	STI
Fs	1.00	0.40	0.24	0.27	0.31	0.95	0.99	−0.25	−0.55	−0.22	−0.13	−0.76
Rb	0.40	1.00	−0.03	−0.05	−0.22	0.43	0.40	0.14	−0.38	−0.12	−0.12	0.37
Rf	0.24	−0.03	1.00	0.99	0.62	0.41	0.36	−0.57	−0.50	−0.02	0.03	−0.58
Re	0.27	−0.05	0.99	1.00	0.68	0.42	0.38	−0.63	−0.53	−0.02	0.02	−0.60
Rc	0.31	−0.22	0.62	0.68	1.00	0.38	0.38	−0.94	−0.48	0.12	−0.14	−0.51
D	0.95	0.43	0.41	0.42	0.38	1.00	0.99	−0.34	−0.75	−0.34	−0.02	−0.87
Rt	0.99	0.40	0.36	0.38	0.38	0.99	1.00	−0.33	−0.66	−0.25	−0.11	−0.84
Cc	−0.25	0.14	0.57	−0.63	−0.94	−0.34	−0.33	1.00	0.48	−0.10	0.16	0.56
C	0.55	−0.38	0.50	−0.53	−0.48	−0.75	−0.66	0.48	1.00	0.45	−0.12	0.79
TWI	−0.22	−0.12	−0.02	−0.02	0.12	−0.34	−0.25	−0.10	0.45	1.00	−0.87	0.15
SPI	−0.13	−0.12	0.03	0.02	−0.14	−0.02	−0.11	0.16	−0.12	−0.87	1.00	0.22
STI	−0.76	−0.37	−0.58	−0.60	−0.51	−0.87	−0.84	0.56	0.79	0.15	0.22	1.00

Figure 4 shows the final prioritisation of sub-watersheds is based on the compound parameter values (CPV). A sub-watershed with the lowest CPV value is determined as the priority, and other sub-watersheds will be ranked accordingly [8]. The CPV is estimated using the weights of each morphometric parameter. The results of sub-watershed prioritisation are shown in **Table 4**. SWS19 received the highest priority ranking (figure) with compound parameter value (CPV = −1743.159), followed by SWS18 (CPV = −1488.863), SWS1 (CPV = −1374.264), while the lowest priority ranking with compound parameter value (CPV = −122.098) is of SWS10 followed by SWS7 (CPV= −249.555). The result shows that the confluence region of Parwan River and Kural River (SWS10), and also the confluence region of Parbati River and Banas River (SWS7), Banas River (SWS4), Parwan River (SWS14), (SWS9), (SWS3), and (SWS13) are the lowest vulnerable hydrological units in terms of soil and water resource degradability.

Table 4. Prioritisation and final ranking of sub-watersheds.

Name	Compound Parameter Value (CPV)	Priority Ranking
SWS19	−1743.159	1
SWS18	−1488.863	2
SWS1	−1374.264	3
SWS17	−1329.703	4
SWS16	−1207.238	5
SWS15	−1145.566	6
SWS20	−1118.927	7
SWS5	−1105.523	8
SWS21	−963.261	9
SWS2	−937.556	10
SWS11	−886.259	11
SWS8	−855.797	12
SWS6	−853.403	13
SWS12	−787.264	14
SWS13	−782.539	15
SWS3	−769.597	16
SWS9	−480.663	17
SWS14	−421.544	18
SWS4	−305.111	19
SWS7	−249.555	20
SWS10	−122.098	21

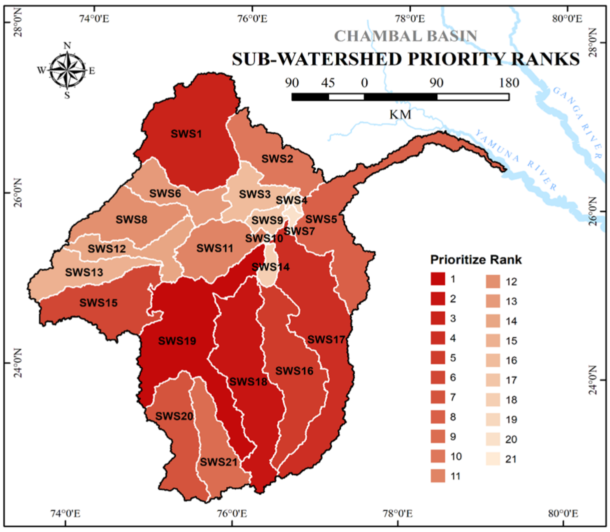

Figure 4. Prioritized ranks of the sub-watersheds.

Whereas the sub-watersheds SWS19 and SWS20, which Chambal River itself drains in its source region, which mainly lies in the state of Madhya Pradesh, SWS18 drained by Kali Sindh River is extended in the state of Rajasthan and Madhya Pradesh, SWS17 and SWS16 are drained by the river Parbati and Parwan respectively, SWAS15 which lies in the state of Rajasthan and drained by the River Beradi, and Mashi sub-watershed coded as SWS1 in the extreme north of the Chambal River basin lies in the highest prioritised zone which needs to be given importance in terms of natural resource management particularly soil and water for the sustenance of the region (**Figure 5**).

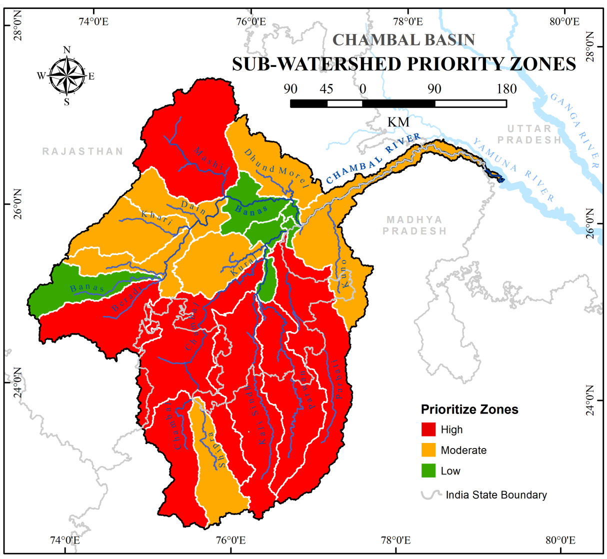

Figure 5. Final sub-watershed priority zones of the Chambal River Basin.

4. Conclusions

The present study prioritizes 21 sub-watersheds in the Chambal River Basin regarding soil erodibility and surface runoff potential based on morphometric and topo-hydrological parameters. Utilizing Cartosat-DEM and advanced geospatial tools such as the Sub-Watershed Prioritization Tool (SWPT) in ArcGIS, this research has successfully identified high-risk sub-watersheds, including SWS19 (Chambal River), SWS18 (Kali Sindh River), SWS1 (Mashi River), SWS17 (Parbati River), SWS16 (Parwan River), SWS15 (Beradi River), and SWS20 (Chambal River). These sub-watersheds exhibit significant hydrological vulnerabilities, necessitating immediate conservation interventions to mitigate erosion risks and enhance water resource sustainability.

This study underscores the importance of integrating morphometric and topo-hydrological parameters in watershed prioritization, providing a robust scientific foundation for targeted management strategies. The analysis revealed that high-priority sub-watersheds are characterized by steep slopes, high drainage density, sparse vegetation cover, and high runoff potential, making them more susceptible to soil erosion and land degradation. Addressing these challenges requires a combination of afforestation, soil conservation techniques, controlled land use, and the construction of water retention structures to enhance water availability and mitigate the risk of land degradation.

The broader applicability of this methodology extends beyond the Chambal River Basin, serving as a replicable model for other regions facing similar hydrological and geomorphological challenges. Policymakers, environmental planners, and stakeholders can utilize the findings of this study to develop evidence-based, region-specific watershed management plans. Furthermore, implementing sustainable agricultural practices, agroforestry models, and watershed restoration programs can help enhance soil moisture retention, increase groundwater recharge, and promote ecological balance in fragile ecosystems.

5. Implications and Future Research

This research highlights the potential of geospatial technologies (GIS and remote sensing) in large-scale watershed analysis, allowing for precise and cost-effective environmental monitoring. The integration of high-resolution remote sensing data with hydrological modeling can further refine prioritization strategies, making them more dynamic and responsive to climate change and anthropogenic pressures.

Future research could explore:

- The dynamic impact of climate change on erosion susceptibility and watershed hydrology, incorporating long-term precipitation and temperature trends in modeling frameworks.
- The role of land-use changes and deforestation in exacerbating watershed vulnerabilities, with a focus on sustainable land-use planning.
- The socio-economic dimensions of watershed management, integrating livelihood assessments, rural development strategies, and community participation to ensure equitable and long-term conservation outcomes.
- Machine learning and artificial intelligence-based models for more accurate predictive analysis of soil erosion and hydrological behavior.

The Chambal River Basin faces complex environmental challenges that demand a scientific and systematic approach to watershed prioritization. The findings of this study serve as a valuable reference for environmental planners and policymakers, enabling them to implement effective conservation strategies that promote sustainable land and water resource utilization. A multi-disciplinary approach, incorporating hydrological, ecological, and socio-economic perspectives, is crucial to achieving long-term ecological stability and regional development.

By addressing soil erosion, water scarcity, and land degradation through scientifically driven watershed management strategies, this study contributes to broader sustainable development goals (SDGs). These efforts will help safeguard the ecological integrity of the Chambal River Basin, ensuring water security, agricultural resilience, and socio-economic stability for the region's communities. As climate change and human activities continue to influence watershed dynamics, periodic reassessment and adaptive management strategies will be crucial for maintaining the sustainability of natural resources in the region and beyond.

Author Contributions

Conceptualization, T.R.N., V.C.L., A.P.M.; methodology, T.R.N., V.C.L., A.P.M.; research, T.R.N., V.C.L., A.P.M., K.K.K., R.S., G.K., A.K.; writing—original draft preparation, T.R.N., K.K.K., R.S., G.K., A.K.; writing—review and editing, T.R.N., K.K.K., R.S., G.K., A.K.; supervision, V.C.L., A.P.M.; project administration, V.C.L., A.P.M.; manuscript submission, T.R.N. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data can be provided based on the request.

Acknowledgements

This research was conducted with minimal external assistance. I acknowledge the academic and professional resources that have contributed to shaping my understanding of the topic. I also appreciate my co-authors for their collaboration and the reviewers and editors for their valuable feedback.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Rockström, J., Steffen, W., Noone, K., et al., 2009. A safe operating space for humanity. Nature, 461(7263), 472–475.

[2] United Nations, 2019. World Population Prospects

2019. Available from: https://www.un.org/development/desa/pd/news/world-population-prospects-2019-0

[3] Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Washington, DC, USA: I. Press. Available from: https://www.millenniumassessment.org/documents/document.356.aspx.pdf

[4] Barnosky, A.D., Hadly, E.A., Bascompte, J., et al., 2012. Approaching a state shift in Earth's biosphere. Nature, 486(7401), 52–58.

[5] World Wildlife Fund, 2018. Living Planet Report - 2018: Aiming Higher. Available from: https://www.worldwildlife.org/pages/living-planet-report-2018

[6] Gleick, P.H., 2003. Global freshwater resources: soft-path solutions for the 21st century. Science, 302(5650), 1524–1528.

[7] Falkenmark, M., Rockström, J., 2004. Balancing water for humans and nature: the new approach in ecohydrology. Earthscan: London, UK.

[8] Aher, P., Adinarayana, J., Gorantiwar, S., 2014. Quantification of morphometric characterization and prioritization for management planning in semi-arid tropics of India: a remote sensing and GIS approach. Journal of Hydrology, 511, 850–860.

[9] Bhattacharya, B., Mazzoleni, M., Ugay, R., 2019. Flood inundation mapping of the sparsely gauged large-scale Brahmaputra basin using remote sensing products. Remote Sensing, 11(5), 501.

[10] Meyer, W.B., Turner, B.L., 1994. Changes in land use and land cover: a global perspective. Cambridge University Press: Cambridge, UK.

[11] Pimentel, D., Burgess, M., 2013. Soil erosion threatens food production. Agriculture, 3(3), 443–463.

[12] Tejwani, K., Gupta, S.K., Mathur, H.N., 1975. Soil and Water Conservation Research in India, 1956-71.

[13] Srinivasan, V., Lambin, E., Gorelick, S., et al., 2012. The nature and causes of the global water crisis: Syndromes from a meta-analysis of coupled human-water studies. Water Resources Research, 48, 10516.

[14] Arabameri, A., Pradhan, B., Pourghasemi, H.R., et al., 2018. Identification of erosion-prone areas using different multi-criteria decision-making techniques and GIS. Geomatics, Natural Hazards and Risk, 9(1), 1129–1155.

[15] Mishra, P., Tripathi, K., 2013. Soil and water conservation research for land management in India. Indian Journal of Dryland Agriculture Research and Development, 28(1), 1–18.

[16] Kale, V.S., 2005. Fluvial hydrology and geomorphology of monsoon-dominated Indian rivers. Revista Brasileira de Geomorfologia, 6(1).

[17] Patel, D.P., Gajjar, C.A., Srivastava, P.K., 2013. Prioritization of Malesari mini-watersheds through morphometric analysis: a remote sensing and GIS perspective. Environmental Earth Sciences, 69(8), 2643–2656.

[18] Singh, P., Gupta, A., Singh, M., 2014. Hydrological inferences from watershed analysis for water resource management using remote sensing and GIS techniques. The Egyptian Journal of Remote Sensing and Space Science, 17(2), 111–121.

[19] Horton, R.E., 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geological Society of America Bulletin, 56(3), 275–370.

[20] Strahler, A.N., 1964. Quantitative geomorphology of drainage basin and channel networks. In: Handbook of Applied Hydrology. McGraw-Hill: New York, NY, USA.

[21] Biswas, S., Sudhakar, S., Desai, V., 1999. Prioritisation of subwatersheds based on morphometric analysis of drainage basin: A remote sensing and GIS approach. Journal of the Indian Society of Remote Sensing, 27, 155–166.

[22] Sinha, R., Bapalu, G., Singh, L., et al., 2008. Flood risk analysis in the Kosi river basin, north Bihar using multi-parametric approach of analytical hierarchy process (AHP). Journal of the Indian Society of Remote Sensing, 36, 335–349.

[23] Meyer, V., Scheuer, S., Haase, D., 2009. A multicriteria approach for flood risk mapping exemplified at the Mulde river, Germany. Natural Hazards, 48, 17–39.

[24] Fernández, D., Lutz, M.A., 2010. Urban flood hazard zoning in Tucumán Province, Argentina, using GIS and multicriteria decision analysis. Engineering Geology, 111(1–4), 90–98.

[25] Samal, D.R., Gedam, S.S., Nagarajan, R., 2015. GIS based drainage morphometry and its influence on hydrology in parts of Western Ghats region, Maharashtra, India. Geocarto International, 30(7), 755–778.

[26] Ayele, G.T., Teshale, E.Z., Yu, B., et al., 2017. Streamflow and sediment yield prediction for watershed prioritization in the Upper Blue Nile River Basin, Ethiopia. Water, 9(10), 782.

[27] Meshram, S.G., Sharma, S., 2017. Prioritization of watershed through morphometric parameters: a PCA-based approach. Applied Water Science, 7, 1505–1519.

[28] Central Water Commission, 2014. Integrated Hydrological Data Book (non-classified river basins). New Delhi, India: Central Water Commission.

[29] INLAND WATERWAYS AUTHORITY OF INDIA, 2017. Final Feasibility Report on Detailed Hydrographic Survey in Chambal River. I.W.A.O. INDIA. Available from: https://iwai.nic.in/sites/default/files/NW-24%20FINAL%20FR%20CHAMBAL%20RIVER.pdf

[30] Kumar, R., Kasana, P., Devrani, R., et al., 2024. The Chambal badlands of Ganga River Basin, India: a fading geoheritage odyssey. Geoheritage, 16(4), 93.

[31] Horton, R.E., 1932. Drainage-basin characteristics. Transactions of the American Geophysical Union, 13(1), 350–361.

[32] Schumm, S.A., 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geological Society of America Bulletin, 67(5), 597–646.

[33] Potter, P.E., 1957. A Quantitative Geomorphic Study of Drainage Basin Characteristics in the Clinch Mountain Area, Virginia and Tennessee. Journal of Geology, 65(1), 112–113.

[34] Beven, K.J., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology/Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. Hydrological Sciences Journal, 24(1), 43–69.

[35] Whipple, K.X., Tucker, G.E., 1999. Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs. Journal of Geophysical Research: Solid Earth, 104(B8), 17661–17674.

[36] Moore, I., Burch, G., 1986. Modelling erosion and deposition: topographic effects. Transactions of the ASAE, 29(6), 1624–1630.

[37] Arnold, J.G., Srinivasan, R., Muttiah, R.S., et al., 1998. Large area hydrologic modeling and assessment part I: model development 1. JAWRA Journal of the American Water Resources Association, 34(1), 73–89.

[38] Rahmati, O., Samadi, M., Shahabi, H., et al., 2019. SWPT: An automated GIS-based tool for prioritization of sub-watersheds based on morphometric and topo-hydrological factors. Geoscience Frontiers, 10(6), 2167–2175.

[39] Abdulkareem, J.H., Pradhan, B., Sulaiman, W.N.A., et al., 2018. Quantification of runoff as influenced by morphometric characteristics in a rural complex catchment. Earth Systems and Environment, 2, 145–162.

[40] Abdulkareem, J.H., Sulaiman, W.N.A., Pradhan, B., et al., 2018. Long-term hydrologic impact assessment of non-point source pollution measured through land use/land cover (LULC) changes in a tropical complex catchment. Earth Systems and Environment, 2, 67–84.