

Measurement And Spatial Analysis Of Sediment Production Rate In The Swat River Basin Sub-Watersheds

Mr. Abdullah¹, Muhammad Ali², Abid Ali³, Taqweem ul haq Ali⁴, Zeeshan Ali⁵, Syed Mamoon Siyar⁶

¹Ph.D Scholar National Centre of Excellence in Geology (NCEG), University of Peshawar-25130, Peshawar, Pakistan abdullahdawar99@gmail.com

²Assistant Professor, National Centre of Excellence in Geology (NCEG), University of Peshawar-25130, Peshawar, Pakistan aliumarzai@uop.edu.pk

³Department of civil and environmental engineering, Lamar University, Beaumont, TX 77710, USA. SGS North America Inc 400 Broadacres Drive, Suite 200, Bloomfield, NJ 07003, USA abidyousfzee@gmail.com

⁴Department of Geology Bacha khan University charsadda taqweem@bkuc.edu.pk

⁵Depart of Civil & Environmental Engineering, Lamar University, Beaumont, TX 77710, USA Occidental Petroleum, Houston, TX, 77046, USA Zeeshanali040@gmail.com

⁶Department of Geology, University of Malakand, Chakdara 18800, Pakistan Email mamoon@uom.edu.pk

Abstract

The present study effort is on the measurement and spatial analysis of sediment production rates in Swat River sub basins watershed using morphometric parameters and GIS based spatial analytical tools. The study assesses the effect of basin form factor, circulatory ratio and compactness coefficient on sediment generation and erosion hazard of nineteen sub-basins of Swat River basin. The spatial variance of sediment yield among sub watersheds was examined using an empirical sediment yield equation. The results indicate a large variation in rates of sediment generation due to changes in basin shape, drainage features, topography and geomorphological variables. SB-3 and SB-17 were found to be particularly sensitive locations with very high sediment production rates, whereas SB-1 and SB-4 had very little sediment production. Results indicated that the steep and long drainage pattern and poor compactness are more prone to enhanced soil erosion and sediment transport mechanisms within the watersheds. GIS and remote sensing techniques are employed to enhance the spatial understanding of erosion prone areas and to prioritize watersheds for conservation planning. The data also show the importance of climate variability and human activities such as deforestation, agricultural expansion, road construction and infrastructure development in increasing the sediment production in the watershed. The study recommends the adoption of integrated watershed management strategies such afforestation, slope stabilization, terracing and check dams to prevent environmental deterioration and increase the basin sustainability. This work provides critical scientific knowledge on sediment dynamics and a very solid platform for future watershed management and geomorphological research in mountainous settings.

Introduction

Sediment production rate refers to the rate at which sediment, such as sand, silt, and clay particles, are eroded and transported by natural processes like wind, water, and ice. This rate can vary significantly depending on factors such as the type of terrain, climate, vegetation cover, and human activities in the basin/watershed (Syvitski et al., 2022). Methods for measuring sediment production rates include sediment traps, sediment yield measurements, and erosion modeling techniques. These measurements are important for understanding soil erosion, sediment transport, and their impacts on ecosystems, water quality, and infrastructure. Sediment production rates are often expressed in units such as tons per hectare per year etc. (Verstraeten & Poesen 2000; Walling, 2017).

Sediment Production Rate (SPR) in basin morphometry refers to the relationship between the physical characteristics (morphometric parameters) of the basin and the rate at which sediment is produced within a

basin (Meshram et al., 2020). Morphometry in this context typically includes parameters such as form factor, circulatory ratio, and compactness coefficient of the basin. Understanding the morphometry of a basin can provide valuable insights into sediment production rates. For example, watersheds with steep slopes and high relief are generally more prone to erosion and sediment production compared to flatter, lower-relief watersheds. Similarly, the size and shape of the watershed can influence factors such as drainage patterns, sediment transport pathways, and erosion processes (Kadam et al., 2019).

By analyzing the morphometry of a watershed utilizing a sediment production rate equation, the geomorphologist and researchers can identify basins that are particularly susceptible to erosion and sediment production. This information can then be used to develop targeted management strategies aimed at reducing sediment production and mitigating its impacts on water quality, ecosystems, and infrastructure within the basin (Rautela et al., 2021).

By controlling the origin and rate of sediment generation, soil and water conservation seeks to reduce soil loss and the resulting sedimentation (Misra et al., 1984). The (form factor (Rf)) , (Circulatory Ratio (Rc)) and (Compactness Coefficient (Cc)) among other geo- morphometric variables, control the rate and intensity of sediment generation (Fenta et al., 2017). Kulimushi et al., (2021) expressed the sediment Production Rate (SPR) empirically as follows in equation 3.1:

$$(SPR) = 4919.80 + 48.64 \log (100 + Rf) - 1337.77 \log (100 + Rc) - 1163.63 \log (100 + Cc) \quad Eq 3.1$$

Where $\log SPR$ is the Sediment Production Rate, (ha

– m/100km²/year, F_f = Form Factor, R_c = Circulatory ratio
and C_c = Compactness Coefficient

Table 3.1 depicts the sub-basin form factor, circulatory ratio, and compactness coefficient of the Swat River basin. Figure 3.1 depicts the sub-basin form factor, circulatory ratio, and compactness coefficient graphically. Figures 3.1, 3.2, and 3.3 illustrate the spatial distribution of sub-basins form factor, circulatory ratio, and compactness coefficient of the Swat river basin. The analysis of Table 3.1 and Figures 3.1 and 3.1 reveals that SB-4 has the lowest (0.23) form factor value and SB-18 has the highest (0.34) form factor value. The average form factor value is 0.289.

Similarly, the sub-basin circulatory ratio is depicted in Table 3.1 and Figure 3.2 depicts the spatial distribution of the sub-basin circulatory ratio. The analysis reveals that the lowest circulatory ratio was computed for SB-4 (0.303) and the highest for SB-9 (0.644). The average ratio computed for the Swat River basin is 0.5107.

The sub-basin compactness coefficient (C_c) is depicted in Table 3.1 and Figure 3.3 depicts the spatial distribution of the sub-basin compactness coefficient. The analysis reveals that the lowest was compactness coefficient computed for SB-9 (1.24) and the highest for SB-1 (1.63). The average ratio computed for the Swat River basin is 1.416.

Table 3.1: The sub-basins form factor, circulatory ratio, and compactness coefficient of the Swat river basin.

Sub-basins	Form Factor $F_f = A/Lb^2$	Circulatory Ratio $R_c = 4\pi A/P^2$	Compactness Coefficient $(C_c) = (P^2/(\pi A)0.5)$
SB-1	0.25	0.37	1.63
SB-2	0.27	0.48	1.44
SB-3	0.28	0.41	1.56
SB-4	0.23	0.31	1.81
SB-5	0.28	0.55	1.33
SB-6	0.28	0.61	1.28
SB-7	0.27	0.51	1.39
SB-8	0.32	0.6	1.28

SB-9	0.29	0.64	1.24
SB-10	0.29	0.53	1.36
SB-11	0.33	0.58	1.3
SB-12	0.25	0.45	1.47
SB-13	0.31	0.47	1.44
SB-14	0.27	0.53	1.36
SB-15	0.28	0.51	1.39
SB-16	0.32	0.53	1.37
SB-17	0.28	0.44	1.49
SB-18	0.34	0.51	1.41
SB-19	0.29	0.61	1.27
Total Sum	5.43	9.64	26.82
Average	0.285789474	0.507368421	1.411578947

Source: Analysis in Arc Map 10.8

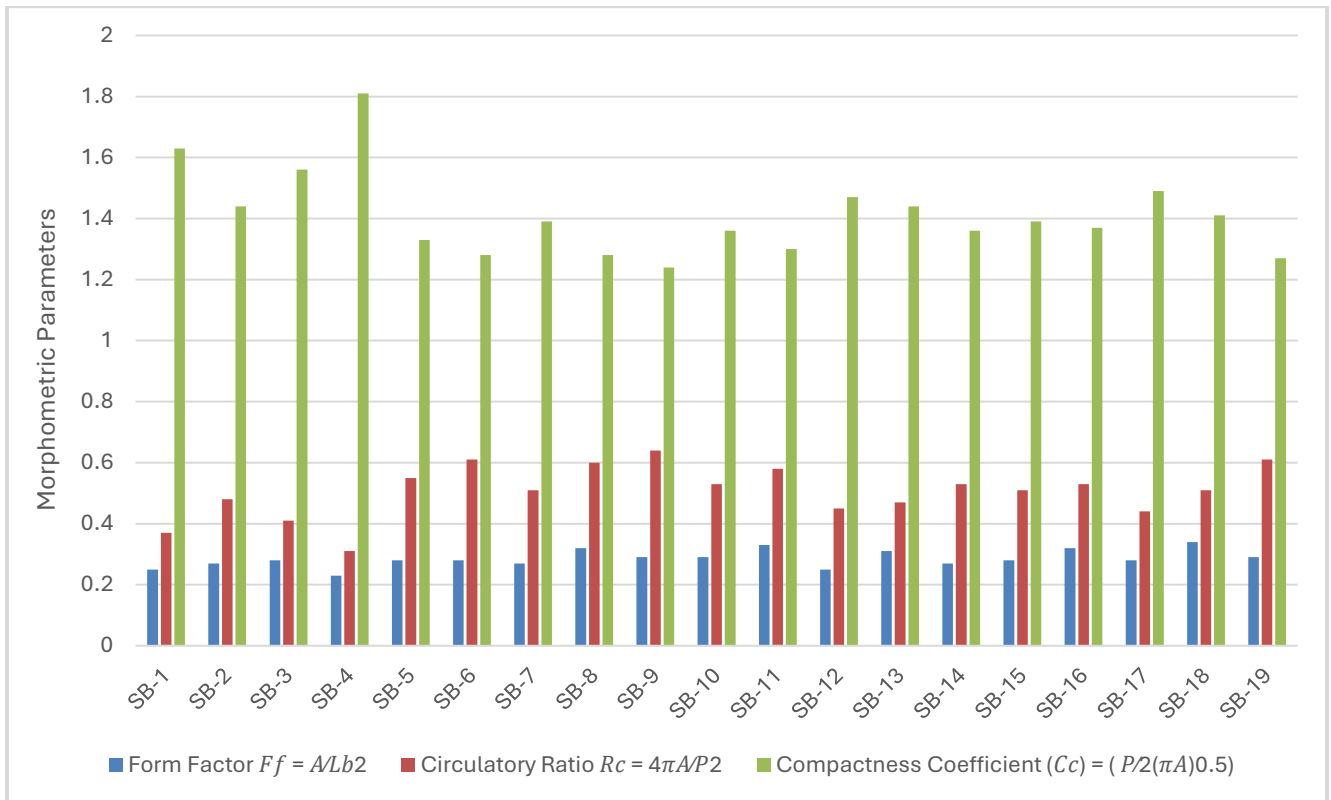


Figure 3.1: Showing sub-basins form factor, circulatory ratio and compactness coefficient of Swat River Basin

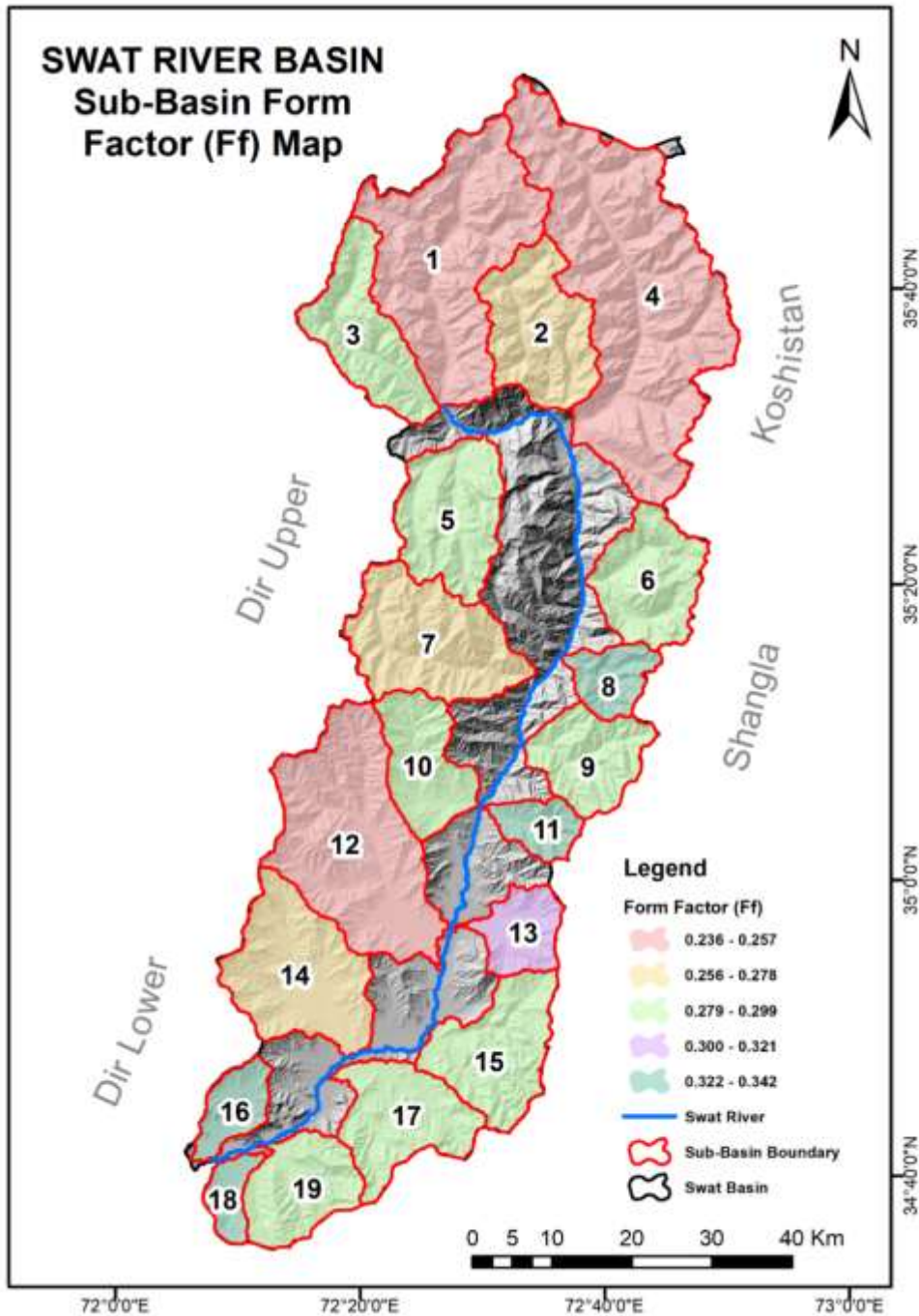


Figure 3.1: Map Showing illustrating the sub-basins farm factor (F_f) of Swat river basin

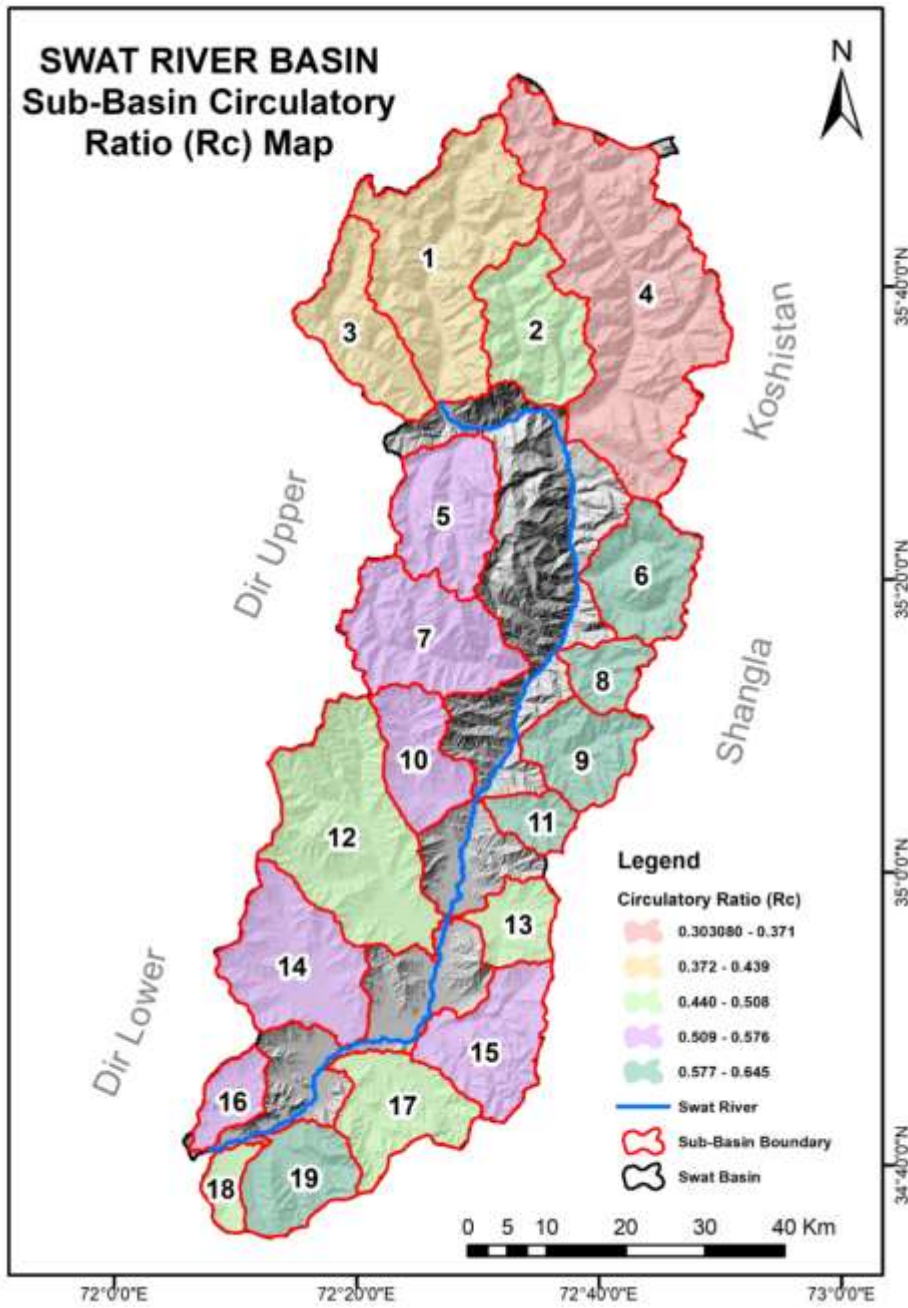


Figure 3.2: Map illustrating the sub-basins Circulatory Ratio (Rc) of Swat river basin.

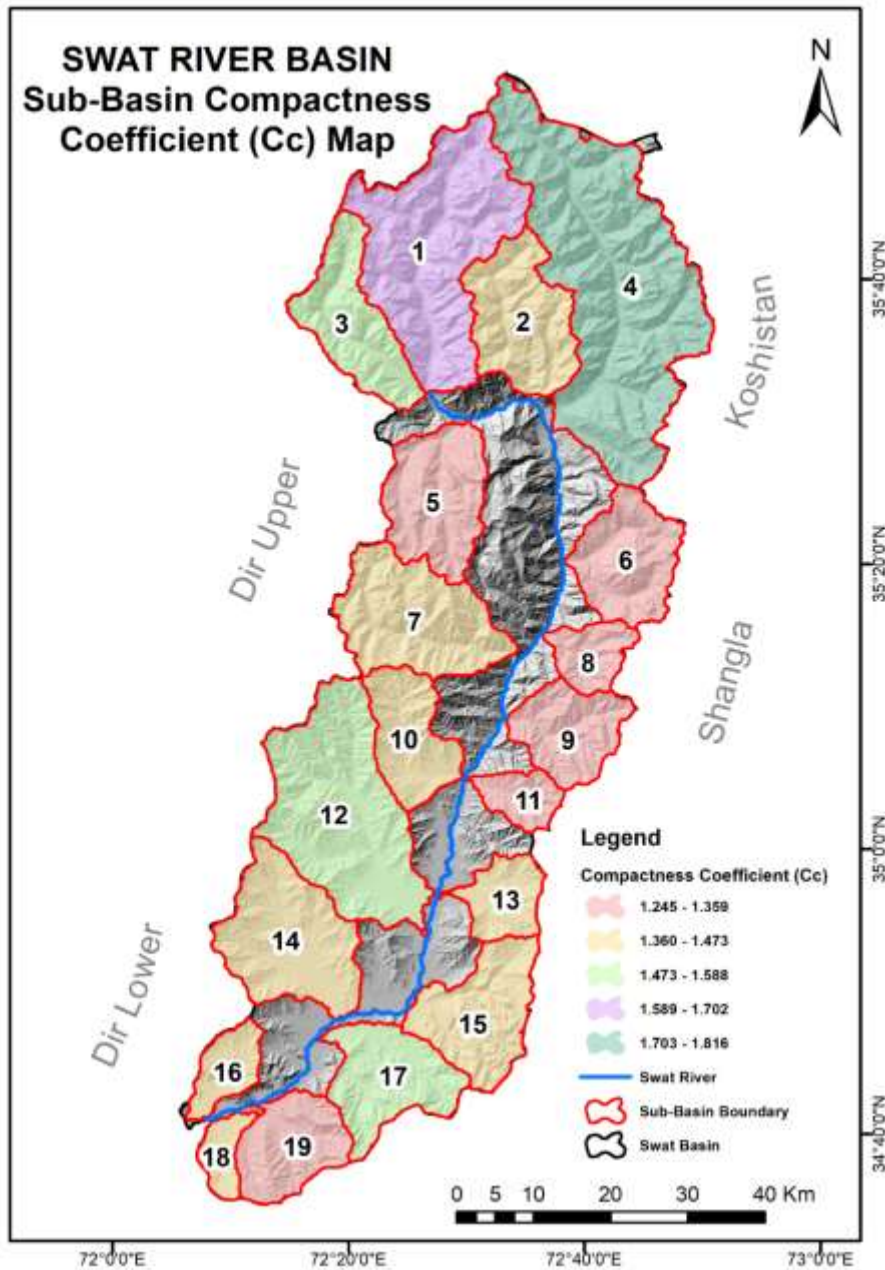


Figure 3.3: Map illustrating the sub-basins Compactness Coefficient (C_c) of Swat river basin

Table 3.2A: Sub-basin Form Factor values and Sediment Production Rate (SPR)

$$4919.80 + 48.64 \log (100 + R_f)$$

SB	Constant	SB Form Factor	100+R _f	Log of 100+R _f	Constant	48.64×D (Log of 100+R _f)	A(4919.8)+ F
	(A)	(B)	(C)	(D)	(E)	(F)	(G)
SB-1	4919.8	0.25	100.25	2.001	48.64	97.32864	5017.12864
SB-2	4919.8	0.27	100.27	2.001	48.64	97.32864	5017.12864
SB-3	4919.8	0.28	100.28	2.001	48.64	97.32864	5017.12864

SB-4	4919.8	0.23	100.23	2.0009	48.64	97.323776	5017.123776
SB-5	4919.8	0.28	100.28	2.001	48.64	97.32864	5017.12864
SB-6	4919.8	0.28	100.28	2.001	48.64	97.32864	5017.12864
SB-7	4919.8	0.27	100.27	2.001	48.64	97.32864	5017.12864
SB-8	4919.8	0.32	100.32	2.0009	48.64	97.323776	5017.123776
SB-9	4919.8	0.29	100.29	2.001	48.64	97.32864	5017.12864
SB-10	4919.8	0.29	100.29	2.001	48.64	97.32864	5017.12864
SB-11	4919.8	0.33	100.33	2.001	48.64	97.32864	5017.12864
SB-12	4919.8	0.25	100.25	2.001	48.64	97.32864	5017.12864
SB-13	4919.8	0.31	100.31	2.001	48.64	97.32864	5017.12864
SB-14	4919.8	0.27	100.27	2.001	48.64	97.32864	5017.12864
SB-15	4919.8	0.28	100.28	2.001	48.64	97.32864	5017.12864
SB-16	4919.8	0.32	100.32	2.001	48.64	97.32864	5017.12864
SB-17	4919.8	0.28	100.28	2.001	48.64	97.32864	5017.12864
SB-18	4919.8	0.34	100.34	2.001	48.64	97.32864	5017.12864
SB-19	4919.8	0.29	100.29	2.001	48.64	97.32864	5017.12864

Source: Arc Map and MS Excel analysis

Table 3.2B Sub-basin Circulatory Ratio values and Sediment Production Rate (SPR)
 $1337.77 \log (100 + R_c)$

SB	SB Circulatory Ratio (A)	100+A (CR) (B)	Log of B (100+Cr) (C)	Constant (D)	C×D (1337.77)
SB-1	0.37	100.37	2.001	1337.77	2676.87777
SB-2	0.48	100.48	2.002	1337.77	2678.21554
SB-3	0.41	100.41	2.001	1337.77	2676.87777
SB-4	0.31	100.31	2.001	1337.77	2676.87777
SB-5	0.55	100.55	2.002	1337.77	2678.21554
SB-6	0.61	100.61	2.002	1337.77	2678.21554
SB-7	0.51	100.51	2.002	1337.77	2678.21554
SB-8	0.6	100.6	2.002	1337.77	2678.21554
SB-9	0.64	100.64	2.002	1337.77	2678.21554
SB-10	0.53	100.53	2.002	1337.77	2678.21554
SB-11	0.58	100.58	2.002	1337.77	2678.21554
SB-12	0.45	100.45	2.002	1337.77	2678.21554
SB-13	0.47	100.47	2.002	1337.77	2678.21554
SB-14	0.53	100.53	2.002	1337.77	2678.21554
SB-15	0.51	100.51	2.002	1337.77	2678.21554
SB-16	0.53	100.53	2.002	1337.77	2678.21554
SB-17	0.44	100.44	2.001	1337.77	2676.87777

SB-18	0.51	100.51	2.002	1337.77	2678.21554
SB-19	0.61	100.61	2.002	1337.77	2678.21554

Source: Arc Map and MS Excel analysis

Table 3.2C Sub-basin Compactness Coefficient values and Sediment Production Rate (SPR)
 $1163.63 \log (100 + Cc)$

SB	Compactness coefficient (Cc)	100+Cc	log of B (100+Cc)	Constant	C × D (1165.65)
	(A)	(B)	(C)	(D)	(E)
SB-1	1.63	101.63	2.007	1165.65	2339.45955
SB-2	1.44	101.44	2.006	1165.65	2338.2939
SB-3	1.56	101.56	2.006	1165.65	2338.2939
SB-4	1.81	101.81	2.007	1165.65	2339.45955
SB-5	1.33	101.33	2.005	1165.65	2337.12825
SB-6	1.28	101.28	2.005	1165.65	2337.12825
SB-7	1.39	101.39	2.005	1165.65	2337.12825
SB-8	1.28	101.28	2.005	1165.65	2337.12825
SB-9	1.24	101.24	2.005	1165.65	2337.12825
SB-10	1.36	101.36	2.005	1165.65	2337.12825
SB-11	1.3	101.3	2.005	1165.65	2337.12825
SB-12	1.47	101.47	2.006	1165.65	2338.2939
SB-13	1.44	101.44	2.006	1165.65	2338.2939
SB-14	1.36	101.36	2.005	1165.65	2337.12825
SB-15	1.39	101.39	2.005	1165.65	2337.12825
SB-16	1.37	101.37	2.005	1165.65	2337.12825
SB-17	1.49	101.49	2.006	1165.65	2338.2939
SB-18	1.41	101.41	2.006	1165.65	2338.2939
SB-19	1.27	101.27	2.005	1165.65	2337.12825

Source: Arc Map and MS Excel analysis

Table 3.3 Sub-basin Sediment Production Rate (SPR)

$$(\text{SPR}) = 4919.80 + 48.64 \log (100 + Rf) - 1337.77 \log (100 + Rc) - 1163.63 \log (100 + Cc)$$

SB	48.64 × Log of 100+Rf × 4919.8	Log of Rc × 1337.77	Log Cc × 1165.65	SPR (A-B- C)	Log D
	(A)	(B)	(C)	(D)	(SPR)
SB-1	5017.12864	2676.87777	2339.45955	0.79132	0.1016
SB-2	5017.12864	2678.21554	2338.2939	0.6192	0.2081
SB-3	5017.12864	2676.87777	2338.2939	1.95697	0.2915
SB-4	5017.123776	2676.87777	2339.45955	0.786456	0.1043
SB-5	5017.12864	2678.21554	2337.12825	1.78485	0.2516
SB-6	5017.12864	2678.21554	2337.12825	1.78485	0.2516
SB-7	5017.12864	2678.21554	2337.12825	1.78485	0.2516
SB-8	5017.123776	2678.21554	2337.12825	1.779986	0.2504
SB-9	5017.12864	2678.21554	2337.12825	1.78485	0.2516
SB-10	5017.12864	2678.21554	2337.12825	1.78485	0.2516
SB-11	5017.12864	2678.21554	2337.12825	1.78485	0.2516

SB-12	5017.12864	2678.21554	2338.2939	0.6192	0.2081
SB-13	5017.12864	2678.21554	2338.2939	0.6192	0.2081
SB-14	5017.12864	2678.21554	2337.12825	1.78485	0.2516
SB-15	5017.12864	2678.21554	2337.12825	1.78485	0.2516
SB-16	5017.12864	2678.21554	2337.12825	1.78485	0.2516
SB-17	5017.12864	2676.87777	2338.2939	1.95697	0.2915
SB-18	5017.12864	2678.21554	2338.2939	0.6192	0.2081
SB-19	5017.12864	2678.21554	2337.12825	1.78485	0.2516
Total					4.3877
Average					0.230931579

Source: Arc Map and MS Excel analysis

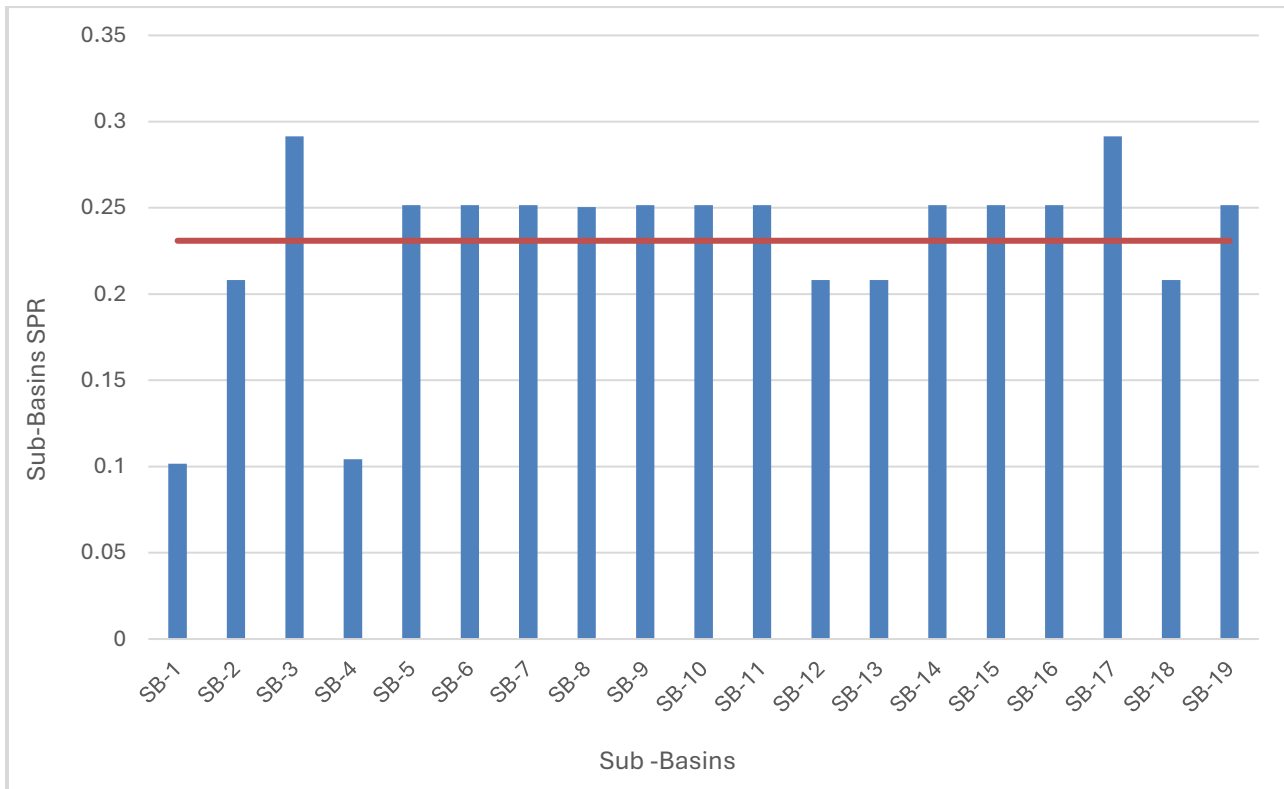


Figure 3.2: Showing sub-basins Sediment Production Rate (SPR) of Swat river basin

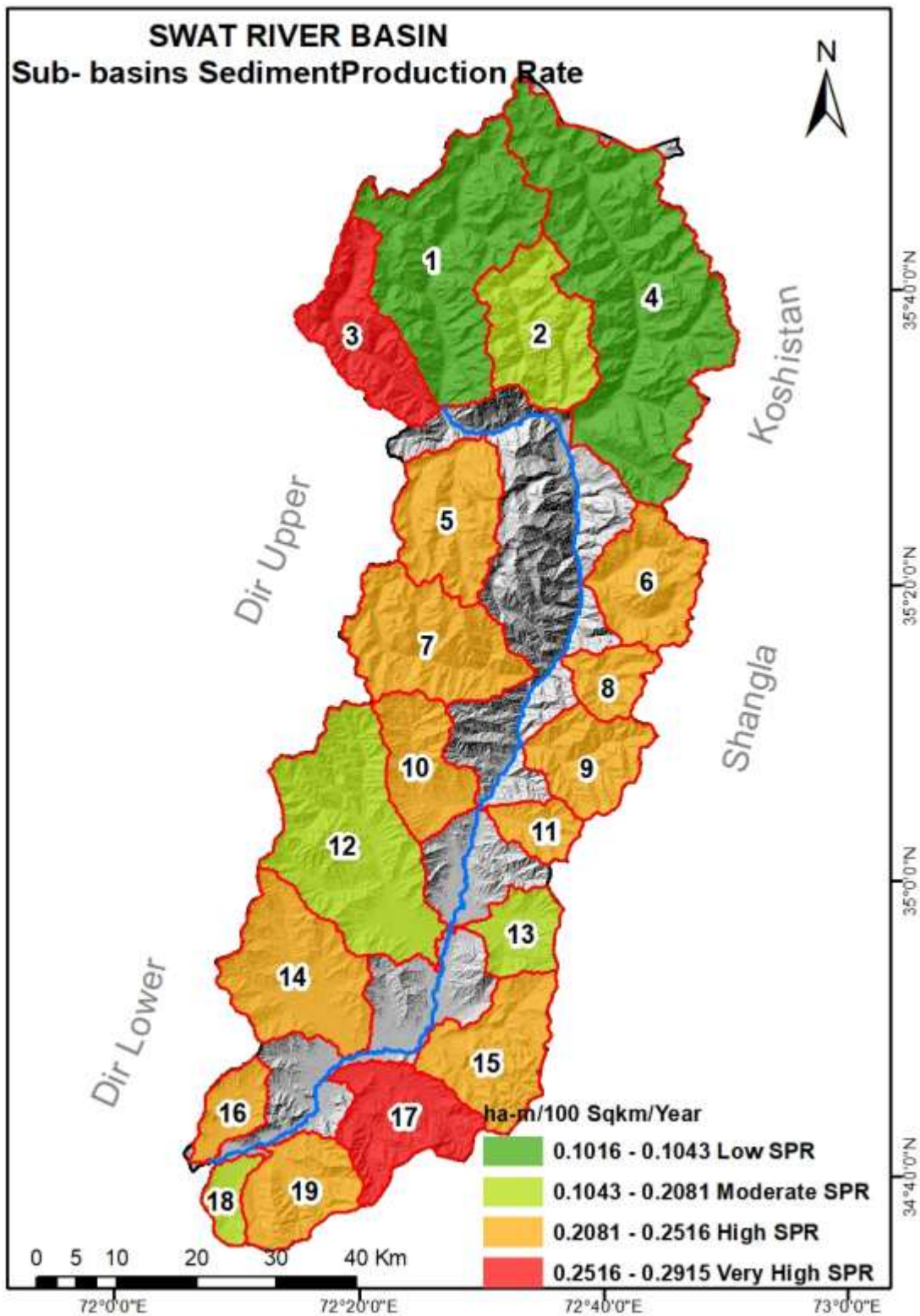


Figure 3.4: illustrating the sub-basins Sediment Production Rate (SPR) of Swat river basin.

3.2 Discussion

- The sediment production from Swat river basin ranges from 0.1016 to 0.2915 ha-m/100 km²/year.

- The analysis suggests that there is a very high sediment production rate in Two sub-basins i.e. SB-3 and SB-17 make up 11 % of Swat river basins. Likewise, Eleven sub-basins (representing 57 % of the Swat river sub-basins) namely SB-5, SB-6, SB-7, SB-8, SB-9, SB-10, SB-11, SB-14, SB-15, SB-16 and SB-19 have reported high levels of sediment production. Of the entire Swat River sub-basins, Four sub-basins SB-2, SB-12, SB-13, and SB-18, have a moderate sediment production rate (21% of the sub-basins, the other Two, SB-1 and SB-4 account for 11 % of the sub-basins have a low sediment production rate.

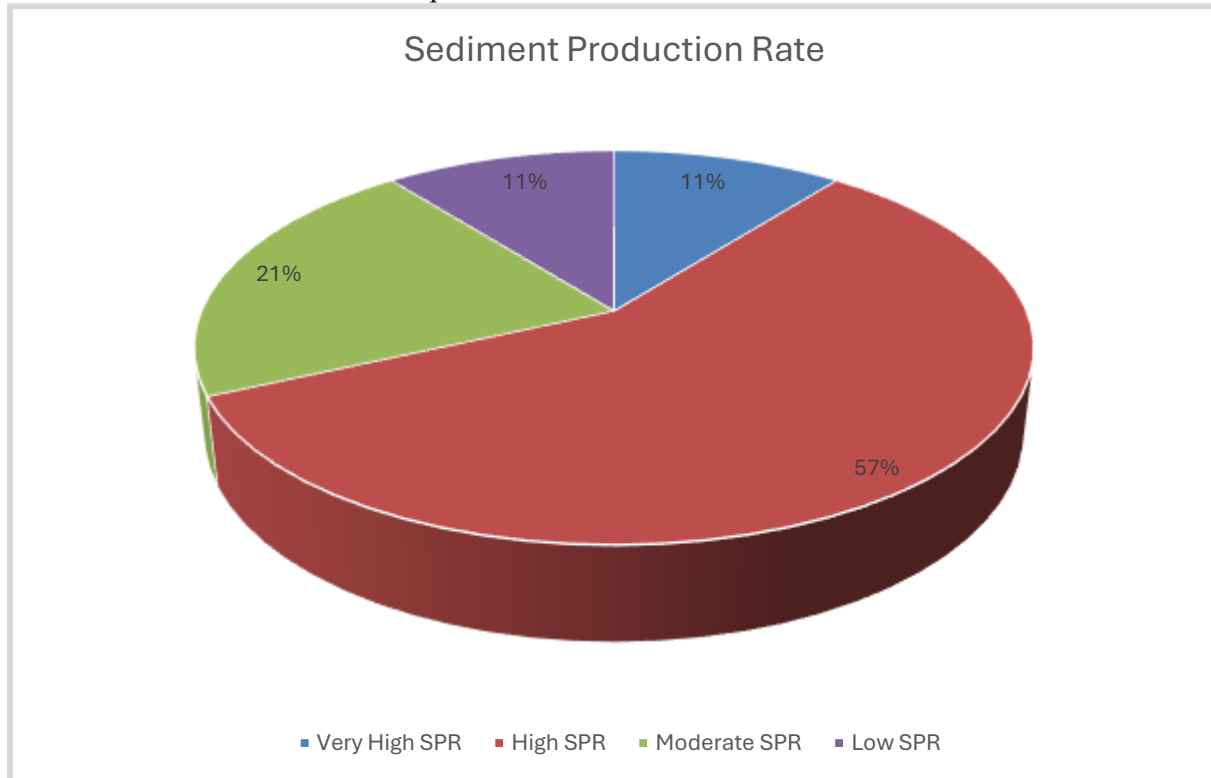


Figure 3.3: Showing Percentage wise SPR of Swat river sub-basins

Enhanced Interpretation and Scientific Analysis

The morphometric analysis of the sub basins of the Swat River highlights the role of basin form in the processes of sediment creation and transit. The extended drainage pattern, steep slopes and high relief energy of the sub-basins promote faster concentration of run-off and consequently the erosion power and pace of sediment formation. SB-3 and SB-17 have geomorphological features which give rise to extremely unstable surface conditions and enhanced susceptibility to soil erosion. The differences in sediment delivery methods in the basin are also controlled by changes in drainage density, relief ratio and stream frequency. The spatial variability in sediment production further indicates that geomorphic processes are not consistent over the whole watershed.

The climate variability and anthropogenic disturbances also influence the process of sediment generation substantially in Swat river basin. Overland flow and stream discharge is enhanced during high rainfall episodes of monsoon season causing quick separation and transportation of tiny soil particles. Furthermore, the natural stability of slopes is violated and the vegetation cover is diminished due to deforestation, increase of agricultural activities, construction of roads and unregulated mining operations in higher catchment areas. Such disruptions increase the surface runoff and lower the infiltration capacity and so increase the silt accumulation inside the watershed. The rate of sediment discharge from the basin is therefore controlled by natural and manmade processes.

The use of GIS and remote sensing techniques has increased significantly the accuracy and spatial precision of the research of sediment generation. The ArcGIS based spatial interpolation was employed for the effective prioritization of the watershed and identification of the sedimentation prone zones. Morphometric indices along with geospatial datasets helped in quantitative assessment of erosion vulnerability and effective comparison across sub-basins was achieved. Spatial research found that sub-basins in harsh hilly terrain generated significantly more sediment than those in low-relief locations. It demonstrates the employment of contemporary GIS technologies in watershed management research and environmental monitoring.

The findings of this study have important implications for sustainable watershed management and environmental conservation in the Swat River basin. High sediment production causes reservoir sedimentation, channel instability, degradation of water quality and increased downstream flooding. Sediment deposition in the river channels can also degrade the hydraulic efficiency and have serious impacts on the irrigation infrastructure and hydropower generation. Hence, integrated watershed management methods such as afforestation, terracing, check dams, slope stabilization and restricted grazing should be taken up in highly vulnerable sub-basins. These approaches can play a good role in preventing soil erosion and improving the ecological resilience of the basin.

Moreover, the empirical model of sediment generation developed in this study provides a helpful scientific basis for predicting erosion risk in mountain watersheds. The link between morphometric factors and sediment output indicates the importance of basin structure and drainage organization in determining the hydrological response. The equation was sufficient to predict the relative variability of sediment production among sub-basins. However, other environmental factors such as land use, lithology, rainfall intensity, soil texture and vegetation density should be included in later research for better prediction of sediment formation. Future papers can explore more detailed sediment dynamics modeling using more advanced machine learning methods and multi-temporal satellite images.

The comparison of sediment production classes shows that large part of the sub-basins of Swat River falls within the class of high sediment production. This indicates the geomorphological vulnerability of the watershed and the need of conservation planning urgently. In contrast, the moderate and low sediment-producing sub-basins display relatively stable geomorphic landscapes with low intensity of erosion. The relatively stable areas could serve as reference sites for measuring the success of watershed management in heavily degraded areas. The classification of sediment production classes thus provides important information to environmental planners and policy makers in the prioritizing of erosion control measures.

In general, the morphometric and geographical evaluation of sediment yield rates in the Swat River basin shows that there is a substantial relationship between variables of the basin and erosion potential. The work gives a nice example of combining morphometric analysis, GIS tools and empirical modelling approaches for sediment evaluation under hilly settings. The spatial information generated can help in the decision-making processes for flood management, watershed rehab, agricultural sustainability and infrastructure protection. The study in general provides substantial scientific knowledge about sediment dynamics of Swat River basin and provides a base for future geomorphological and hydrological studies.

Conclusion

The present study has been thoroughly carried out to investigate the sediment generation rate of Swat River sub-basins using morphometric parameters and spatial analytical techniques. The results indicate that the sub-basins with high topography, low compactness and big basin geometry are more susceptible to rapid sediment accumulation. GIS based mapping and quantitative analysis was adopted for efficient identification of erosion prone zones in the watershed. The study also suggests that sediment production is regulated by natural geomorphic features as well as climate cycles and anthropogenic activities. The results provide a vital insight for priority of watershed, soil conservation strategy and sustainable management of environment. The conservation measures and constant spatial monitoring are essential to avoid environmental damage due to silt and to improve watershed sustainability in Swat River basin.

Implications for Watershed Planning and Future Research

Watershed management in mountain environments needs to be understood in terms of the multidisciplinary of geomorphology, hydrology, climatology and planning for the environment. The Swat River watershed is defined by steep topography and extremely dynamic hydrological conditions which increase the threat of erosion and sediment movement under large rainfall events. Morphometric analysis helps to identify the sediment prone areas which gives a chance to planners to perform preventive efforts before the environmental degradation gets urgent. Sedimentation is a major environmental problem in many developing regions, and has a direct impact on agricultural production, river ecology and the sustainability of water resources.

Sedimentation in downstream reservoirs and irrigation canals leads to loss of water storage capacity and decreases irrigation effectiveness. Especially for the sectors that rely on agriculture and hydropower generating. Excessive sediment transport can also modify the morphology of the river through increasing channel aggradation and decreasing channel depth. Such geomorphic alterations may enhance the flood threat during high discharges. Therefore, the sediment production analysis of the current work can be beneficial for long term river basin management programs and to enhance the sustainability of hydraulic infrastructures in Swat River watershed.

The morphometric factors studied in this research demonstrate significant correlations between the shape of the watershed and its hydrological response. The form factor is an index of the basin shape and concentration of runoff, while the circulatory ratio is a measure of the degree of circularity of the basin and effectiveness of drainage. The compactness coefficient, which describes the variation of the basin form from a perfect circle, also indirectly indicates the vulnerability of the basin to erosion. Runoff occurs more swiftly in sub-basins with less compaction and better drainage. This increases the power of the stream and its capacity to move silt. The results obtained in this paper confirm that morphometric analysis is an effective method for monitoring watershed activity and erosion risk.

Geospatial technologies have transformed environmental research in watershed analysis by enabling the handling of enormous geographical datasets in a short time. Remote sensing photography can be used to produce a continuous record of the land surface and to observe change in vegetation cover, land use and erosion trends over time. Researchers can utilize GIS to overlay variables such as topography, hydrology and geomorphology to provide exact estimations of sediment dynamics. The spatial mapping of sediment source areas reported here provides a scientifically plausible basis for the identification of priority locations for rapid conservation intervention.

Future climate change may also increase silt accumulation in Swat River basin. Higher temperatures, changes in precipitation patterns and greater intensity of heavy falls of precipitation may increase the processes that cause erosion in alpine zones that are vulnerable to erosion. Heavy rains can destabilize mountains, cause landslides and increase the amount of material entering river courses. Therefore, climate adaption techniques should be mainstreamed in the watershed management approaches to avert environmental concerns in the future. Adaptive strategies including reforestation, slope stabilization, sustainable land-use planning and integrated flood management can improve watershed resilience to changing climate conditions.

The socio-economic repercussions of sediment production are also important. Sedimentation can have major effects on local populations by damaging agricultural land, degrading water quality and increasing maintenance expenses of hydraulic structures. The increased erosion and flooding is particularly dangerous for people who depend on river resources to provide for their livelihoods. Hence, the watershed management should involve community engagement and public awareness initiatives. Local stakeholders have a significant role in the conservation of soil through the adoption of sustainable agriculture methods, implementation of managed grazing systems and afforestation activities in erosion prone areas.

The study also revealed that empirical modeling is an effective technique to estimate sediment generation under the condition of data shortage. Many mountain locations lack long-term sediment monitoring data, and direct measurement is difficult and expensive. In such cases, morphometric analysis and empirical equations can be used as an alternative method for calculating the pattern of relative sediment yield. Because empirical models are not free of uncertainties, they might be useful for watersheds comparison

and preliminary environmental planning. These conclusions can be tested by further field sediment sampling and hydrological monitoring research.

This classification of sediment production into low, moderate, high and very high classes provides a useful paradigm for prioritizing watershed management actions. Soil conservation measures and slope stabilization should be attended immediately in the sub-basins with very high sediment output. Controlled land use practices and frequent environmental monitoring are needed for moderate risk locations, while low sediment production zones can be managed using sustainable management measures. This objective increases the efficiency of resource allocation and promotes the implementation of scientifically sound watershed management strategies for policy makers.

This adds to the general scientific knowledge on fluvial geomorphology and sediment transport processes in alpine river systems. Sediment yield is highly related to the form of channel, stream power and evolution of basin. Changes in sediment supply affect channel shape, aquatic habitat quality, and the stability of river ecosystems. These geomorphic interactions are important to river health and protection of biodiversity in the watershed. Therefore, the Swat River basin is an important case study to research the linkage between the geomorphological features and environmental sustainability in the high relief sites.

In short, the findings of the accumulating research suggest that the morphometric analysis integrated with GIS based spatial techniques can effectively support watershed planning, environmental management and sustainable resource exploitation. The study gives a complete scientific base for mapping erosion prone areas, measurement of variability in sediment production and design of conservation measures. The sediment assessment integrates both natural and anthropogenic components, providing a more comprehensive view of the watershed dynamics. These insights may be valuable for future policy creation, environmental monitoring and integrated watershed development programs in Pakistan and other Himalayan regions confronting comparable environmental concerns.

References

1. Abebe, N., et al. (2023). Potential and challenges of the RUSLE-IC-SDR approach for sediment dynamics. *CATENA*, 233, 107480.
2. Ajibade, F. O., et al. (2020). Application of RUSLE integrated with GIS and remote sensing techniques for soil erosion assessment. *Journal of Water and Climate Change*, 11(S1), 407–422.
3. Akgoz, R., Deviren Saygin, S., Erpul, G., & Tel, S. (2022). Monitoring variability of cover management factors affecting erosion. *Environmental Monitoring and Assessment*, 194(6), 395.
4. Akhtar, Z., Nasir, M. J., Ali, Z., et al. (2024). Sediment yield estimation using GIS-based sediment production rate approach: Kunhar River Basin, Pakistan. *Migration Letters*, 21(S11), 111–134.
5. Alebachew, E. D., Abiye, W., Dengiz, O., & Turan, İ. D. (2025). Soil erosion estimation and risk assessment using RUSLE and Google Earth Engine. *Annals of GIS*, 31(1), 123–141.
6. Ali, M. G., et al. (2021). Estimation of potential soil erosion and sediment yield in the Chenab River catchment. *Water*, 13(24), 3647.
7. Arabkhedri, M., Heidary, K., & Parsamehr, M. R. (2021). Relationship of sediment yield to connectivity index in watersheds. *Journal of Soils and Sediments*, 21(7), 2699–2708.
8. Atalla, M. A., et al. (2024). Geospatial techniques and environmental assessment using GIS and Earth Engine. *Scientific Reports*, 14, 29938.
9. Babur, M., Shrestha, S., Bhatta, B., Datta, A., & Ullah, H. (2020). Climate and land-use change impacts on sediment yield in a transboundary watershed. *Journal of Mountain Science*, 17(3), 624–640.
10. Denekewu, G. A., et al. (2025). Morphometric analysis and watershed prioritization for soil erosion management. *Scientific Reports*, 15, 32595.
11. Fenta, A. A., Yasuda, H., Shimizu, K., Haregeweyn, N., & Woldearegay, K. (2017). Quantitative analysis and implications of drainage morphometry of the Agula watershed in the semi-arid northern Ethiopia. *Applied Water Science*, 7(7), 3825–3840.
12. Fenta, A. A., Yasuda, H., Shimizu, K., Haregeweyn, N., & Woldearegay, K. (2017). Quantitative analysis of drainage morphometry and watershed characteristics. *Applied Water Science*, 7(7), 3825–3840.

13. Ijaz, M. A., et al. (2022). Prediction of sediment yield in a data-scarce river catchment. *Water*, 14(9), 1480.
14. Jojju, B., & Subedi, R. (2023). Comparative study of sediment loading in sub-watersheds of Phewa Lake, Nepal. *Journal of Geography and Cartography*, 6(1).
15. Kadam, A. K., Jaweed, T. H., Kale, S. S., Umrikar, B. N., & Sankhua, R. N. (2019). Identification of erosion-prone areas using modified morphometric prioritization method and sediment production rate: A remote sensing and GIS approach. *Geomatics, Natural Hazards and Risk*, 10(1), 986–1006.
16. Kadam, A. K., Jaweed, T. H., Kale, S. S., Umrikar, B. N., & Sankhua, R. N. (2019). Identification of erosion-prone areas using morphometric prioritization and sediment production rate. *Geomatics, Natural Hazards and Risk*, 10(1), 986–1006.
17. Kulimushi, L. C., Choudhari, P., Anornu, G., & Akpa, L. Y. (2021). Morphometric analysis and sediment production rate assessment for watershed prioritization using GIS and remote sensing techniques. *Environmental Challenges*, 5, 100347.
18. Kumar, R., Naqvi, H. R., Devrani, R., Deshmukh, B., & Huang, J. C. (2022). Sediment yield assessment and prioritization using SYI model. *Journal of the Geological Society of India*, 98(11), 1585–1594.
19. Machine learning-based sediment connectivity surrogates for RUSLE and MUSLE in ungauged watersheds. (2025). *Environmental Earth Sciences*.
20. Meraj, G., Romshoo, S. A., Ayoub, S., & Altaf, S. (2017). Geoinformatics-based approach for estimating sediment yield in mountainous watersheds. *Geocarto International*, 33(10), 1–38.
21. Meshram, S. G., Meshram, C., Hasan, M. A., Khan, M. A., & Islam, S. (2022). Morphometric deterministic model for prediction of sediment yield index for selected watersheds in Upper Narmada Basin. *Applied Water Science*, 12(5), Article 106.
22. Meshram, S. G., Meshram, C., Hasan, M. A., Khan, M. A., & Islam, S. (2022). Morphometric deterministic model for prediction of sediment yield index. *Applied Water Science*, 12(5), 106.
23. Misra, V. K., Narayana, D. V. V., & Babu, R. (1984). Estimation of sediment production rate and prioritization of watersheds based on geomorphological and land-use characteristics. *Journal of the Indian Society of Remote Sensing*, 12(2–3), 49–57.
24. Mokarram, M., Pourghasemi, H. R., & Tiefenbacher, J. P. (2023). Using machine learning to predict watershed morphometric features and erosion processes. *Scientific Reports*, 13, 8498.
25. Preetha, P., & Al-Hamdan, A. (2022). Dynamic hydrological modeling and remotely sensed data for sediment yield assessment. *Remote Sensing*, 14(2), 400.
26. Rautela, K. S., Kumar, M., Khajuria, V., & Alam, M. M. (2022). Comparative geomorphometric approach for erosion-prone watershed identification. *Discover Water*, 2(1), 1–18.
27. Rautela, K. S., Sofi, M. S., Abhishek, Khajuria, V., & Verma, S. (2021). Morphometry governs the dynamics of runoff and sediment production rate: A case study of Upper-Kosi micro-watershed, Almora, Uttarakhand. *Journal of Himalayan Ecology and Sustainable Development*, 16, 1–15.
28. Syvitski, J. P. M., Restrepo Ángel, J., Saito, Y., Overeem, I., Vörösmarty, C. J., Wang, H., & Olago, D. (2022). Earth's sediment cycle during the Anthropocene. *Nature Reviews Earth & Environment*, 3(3), 179–196.
29. Syvitski, J., Restrepo Ángel, J., Saito, Y., Overeem, I., Vörösmarty, C. J., Wang, H., & Olago, D. (2022). Earth's sediment cycle during the Anthropocene. *Nature Reviews Earth & Environment*, 3(3), 179–196.
30. Verstraeten, G., & Poesen, J. (2000). Estimating trap efficiency of small reservoirs and ponds: Methods and implications for the assessment of sediment yield. *Progress in Physical Geography*, 24(2), 219–251.
31. Walling, D. E. (2017). Measuring sediment yield from river basins. In *Soil and Water Conservation Society (Ed.), Soil erosion research methods* (pp. 39–82). Routledge.
32. Waseem, M., et al. (2023). Spatial assessment of soil erosion risk using RUSLE embedded in GIS environment. *Applied Sciences*, 13(6), 3775.