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SEDIMENT YIELD QUANTIFICATION IN UNGAUGED FLUVIAL WATERSHEDS USING MODIFIED UNIVERSAL SOIL LOSS EQUATION (MUSLE): A CASE STUDY OF WINDER RIVER BASIN, PAKISTAN

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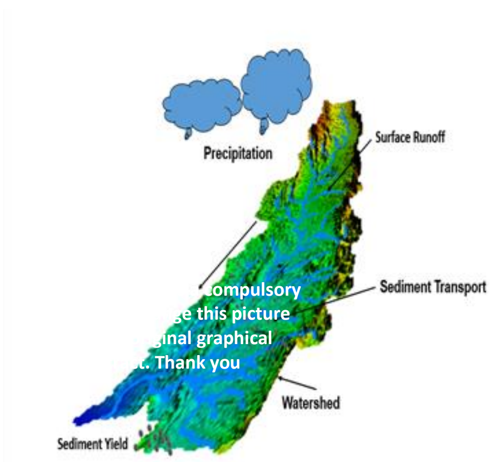

Abstract

The non-availability of observed hydrologic data of watersheds poses a significant hindrance to monitor the runoff and sedimentation regime and to take appropriate watershed management measures, particularly in the less developed quarters of the world. This necessitates the search of a reliable alternative approach for ungauged watersheds to quantify the sediment yield. Based on the literature review, the Modified Universal Soil Loss Equation (MUSLE) has been found as a reliable approach for sediment yield computation. Therefore, this research was intended to determine the mean monthly and yearly sediment yield of Winder River Basin using MUSLE. The daily runoff and discharge of river was estimated using NRCS CN Method. Based on the analysis, the sediment yield of study area was found to be closely following the rainfall and runoff regime, where the highest mean monthly sediment yield was found in July (6.12 million tons), while lowest in October and November. Annually, the mean sediment yield of Winder River Basin was found to be 10.08 million tons. Conclusively, the study comprehensively explained the use of MUSLE to determine sediment yield in ungauged watersheds, where the outcomes can be employed to formulate effective watershed management and soil conservation practices.

Keywords: Watershed management, soil conservation, sediment yield, NRCS CN method, MUSLE

1.0 INTRODUCTION

Erosion and sedimentation are acute issues in hydrology due to the adverse impacts on the freshwater resources, water conveyance structures, and reservoirs, which necessitates a continuous monitoring and gauging of sediment transport across the watershed. Sediment transport refers to the movement of sediments (sand, silt, clay, gravel, or boulders) from one place to another due to the combined action of gravity and a dragging force exerted by the eroding agent (wind, water, or ice). In gauged watersheds, the timely monitoring of streamflows and sediment yield facilitates the formulation and implementation of effective watershed conservation and management practices. However, in ungauged watersheds, the non-availability of hydrologic data poses a serious challenge, which calls for the adoption of alternate approach to quantify the streamflows and sediment yield. Theoretically, sediment yield refers to the amount of sediments passing or received at a place of watershed in a given time length, and strongly depends on the weather conditions, streamflows, watershed's physical and topographical characteristics, land use and land cover, soil texture, and conservation practices (Leta et al., 2023). Conceptually, sediment yield differs from erosion, which is a geological action in which the earthen materials are detached, transported, and deposited by wind, water, ice, or tectonic displacements (Ahmed et al., 2024). In simple words, Sediment yield is a fraction of gross erosion that is delivered to the point of focus in a watershed (Bartholic, 2004).

The prominent consequential impacts of sediment erosion and deposition include the reservoir and channel sedimentation, water quality degradation, change in river's morphology, and loss of nutrient-rich soil. Reservoir sedimentation decreases the storage capacity and the service life of reservoir. In agriculture, the uppermost layer of soil is high in nutrients and organic materials. Excessive erosion depletes nitrogen, phosphorous, and other nutrients from the top soil layer that are needed by the crops and plants to grow (Derbyshire & Owen, 2018, Qureshi et al., 2024).

In fluvial sediment transport, sediments in water generally move in three layers as wash load, suspended load, and bed load as shown in Figure 1(Roushangar et al., 2022). Bed load refers to the large-sized sediments (typically larger than 0.062 mm) that are too heavy to remain suspended by the flow turbulence and are transported along the streambed via rolling, sliding, and saltation. The movement of bed load in a stream channel strongly relies on the flow velocity and the shear stress (also known as the drag force or tractive force) applied by the flowing water along the streambed. The direction of this drag force is same as the flow direction, with greater the drag force and flow velocity, more will be the bed load transportation. The importance of bedload lies in that its composition is that of the streambed, and the material in transport can therefore be actively interchanged with the bed. For this reason, bed load holds a significant control on the river morphology. The major factors governing the bed load movement include the stream channel geometry, streamflow, and sediment properties (sediment size, gradation and specific gravity). Bed load is measured by different samplers, such as box type sampler, slot type sampler, etc., or is estimated by assuming it to be between 3−25 percent of suspended load, depending on the bed material. Conventionally, a value of 10 % is mostly adopted (Turowski et al., 2010).

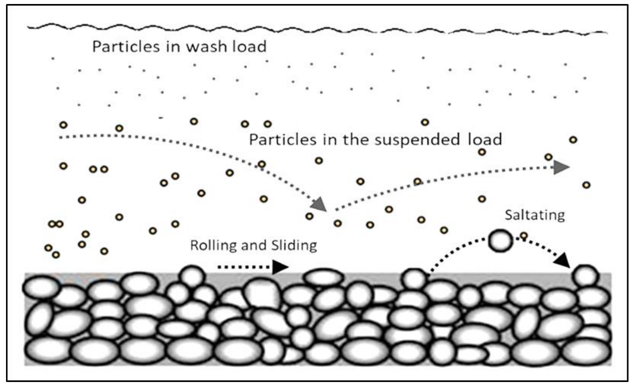

Figure 1 Typical sediment transport in water. Source: Roushangar et al. (2022).

Suspended load refers to the sediments that remain in suspension by the turbulence of flow, and mainly consists of small-sized soil particles (clay, silt, and fine sand), transported within the middle to lower layers of flow at a large fraction of the mean flow velocity of stream (Zaharova & Belyaev, 2023). In actuality, suspended sediments travel with the same speed as the flowing water (Wang et al., 2022). An empirical equation suggested by the United States Geological Survey (USGS, 1940) for suspended sediment load is shown below (Ellison et al., 2014):

$$Q_s = 0.00864\ C_s\ Q_w \quad (1)$$

Where, Q_s is the daily suspended sediment load (tons), C_s is the mean concentration of suspended sediments in flow (mg/L), and Q_w is the mean daily discharge (m^3/sec). Wash load is the upper most layer in fluvial sediment transport and consists of very fine suspended soil particles (typically less than 0.002 mm) and dissolved chemical substances (Krajewski et al., 2024). The drainage basin's sediment yield or the stream's overall sediment load is comprised of these three types of sediment.

In order to find sediment yield, the commonly used methods include stream gauging, use of sediment-discharge rating curves, hydrologic and hydraulic computer models, and empirical equations. In gauged watersheds, stream gauging or sediment rating curves can be employed to determine sediment yield, whereas in ungauged watersheds, computer models or empirical equations can be used. Nevertheless, the computer models (e.g. SWAT, MIKESHE, HSPF, HEC-RAS, etc.) also require observed hydrologic data for model calibration. Therefore, the empirical equations developed after comprehensive research and field-based studies serve as an ideal alternative. The Universal Soil Loss Equation (USLE) is a commonly used technique for calculating soil erosion. Wischmeier & Smith developed USLE in the United States in 1965 based on the soil erosion data collected by the US Department of Agriculture (USDA) Natural Resource Conservation Services (NRCS) to estimate the long-term mean yearly loss of soil. The equation has been widely used across the world and yield satisfactory results. The method incorporates the precipitation characteristics, soil erodibility, topography of watershed, crop and land use features, and conservation practice. The mathematical expression of USLE is shown in Equation 2 as under (Vemu & Pinnamaneni, 2012):

$$A=RKLSCP \quad (2)$$

Where, A is the mean annual gross erosion (tons/ha), R is the rainfall erosivity factor (MJ.mm/ha.hr. year), K is the soil erodibility factor (tons.hr/ MJ.mm), LS is the topographic factor, C is the cover and management factor, and P is the soil conservation or support practice factor (Vemu & Pinnamaneni, 2012). The rainfall erosivity factor depends on the rainfall characteristics and undergoes significant spatial variation. To determine R, different methods have been suggested in the past studies as shown in Table 1 below (Kodimela et al., 2023):

Table 1 Different methods for R computation.

Method	Equation
Wischmeier & Smith (1978)	$R = \sum_{12}^{1} 1.735X10^{\left(1.5Log_{10}\left(\frac{P_i}{P}\right)-0.8188\right)}$ Where, P_i is the monthly rainfall and P is the mean annual rainfall.
Morgan & Davidson (1991)	R= 0.5P
Singh et al. (1981)	R = 79+0.363P
Babu et al. (2004)	R = 81.5 +0.38 P
Zhang & Fu (2003)	$R= 0.3598 \sum_{1}^{12} \frac{P_i}{P}^2$

Source: Kodimela et al. (2023)

Hydrologically, the value of USLE cover and management factor (C) depends on the land or vegetative cover. For example, as a dense canopy of plants lowers the energy of an erosive agent, it reduces erosion. The typical values of C for various land use are shown in Table 2 (Chuenchum et al., 2019).

Table 2 USLE C factor for various land use.

Land Use	C
Metropolitan region	0.10
Barren terrain	0.35
Dense woods	0.001
Bare forest	0.01
Cropland and mixed forest	0.10
Agricultural land	0.50
Flooded vegetation	0.10
Water	0.01
Ice and snow	0.001

Source: Chuenchum et al. (2019)

For soil and runoff conservation, straight rows cropping, contour tillage, strip cropping, and terracing are the widely used conservation methods, with stabilized waterways for the runoff disposal are essential in each conservation practice (Neitsch et al., 2011). Hydrologically, vegetation increases infiltration and reduces runoff, thereby limiting the sediment erosion by anchoring the soil particles. Straight row cropping is generally employed in less steep areas. Naturally, water moves from a high elevation contour to low elevation contour under gravity. Therefore, to conserve runoff and erosion, tillage is done on the contours, offering considerable resistance to soil erosion from light to moderate rainfall but is less effective for intense storms. Strip cropping is a mixed cropping system where the alternating strips of erosion-resistant crop (closely grown crops) and erosion-susceptible crop (row crops) are planted on the contours to reduce runoff and erosion. The crops on these strips are changed annually as a part of crop rotation to increase soil health and its pest resistance. This approach is most effective on the slope of 2 to 10 % (Neitsch et al., 2011).

Terraces are a sequence of horizontal ridges created on a hillside that resemble stair steps and are typically recommended for hilly and mountainous areas. The terrace length, which determines the terrace interval, splits the hill's slope into segments that are equal to the horizontal terrace interval. By lowering the slope length and flow energy, this conservation practice lessens the erosion (Neitsch et al., 2011). The USLE conservation practice factor (P) was determined using Equation 3 as given below (Schwab et al., 1982):

$$P = P_c \times P_s \times P_t \quad (3)$$

Where, P_c is the contouring factor (Table 3), P_s is the strip cropping factor that relies on the watershed slope and crop rotation practice (Table 4), and P_t is the terrace sedimentation factor (1.0 for no terrace, 0.20 for terraces having graded channel sod outlets, and 0.10 for terraces having underground outlets) (Schwab et al., 1982).

Table 3 P_c values for different land slopes.

Land Slope (%)	P_c
1 to 2	0.60
3 to 5	0.50
6 to 8	0.50
9 to 12	0.60
13 to 16	0.70
17 to 20	0.80
21 to 25	0.90

Source: Schwab et al. (1982).

Table 4 P_s values for different crop rotation practices.

Land Slope (%)	P_s		
	A	B	C
1 to 2	0.30	0.45	0.60
3 to 5	0.25	0.38	0.50
6 to 8	0.25	0.38	0.50
9 to 12	0.30	0.45	0.60
13 to 16	0.35	0.52	0.70
17 to 20	0.40	0.60	0.80
21 to 25	0.45	0.68	0.90

Source: Schwab et al. (1982)

Where, A refers to 4-year rotation of row crop, small grain with meadow seeding, and 2 years of meadow, B refers to 4-year rotation of 2 years row crop, winter grain with meadow seeding, and 1-year meadow, and C refers to alternate strips of row crop and winter grain (Schwab et al., 1982).

As mentioned earlier, USLE estimates the mean yearly gross erosion. However, to calculate the daily sediment yield considering the rainfall as well as runoff characteristics, the Modified Universal Soil Loss Equation (MUSLE) was proposed by Williams in 1975. By introducing the runoff energy factor in MUSLE, the equation eliminated the need of SDR for sediment yield computation. In USLE, SDR is needed as the rainfall factor only incorporates the power used in detachment of sediments, whereas in MUSLE, the runoff component incorporates the power used in detachment as well as transporting the sediments. The Modified USLE is shown in Equation 4 as under (Neitsch et al., 2011):

$$SY = 11.8\ (VQ_p)^{0.56}\ KLSCP \quad (4)$$

Where, SY is the daily sediment yield (metric tons), V is runoff volume (m3), Qp is the peak discharge (m3/sec), and K, LS, C, and P are the USLE factors as explained earlier. This equation has been employed in various studies and has shown satisfactory results. For instance, Reda et al. (2024) used MUSLE to determine sediment yield in Agewmariam experimental watershed in northern Ethiopia and found a significant correlation (R^2 = 0.85) between the estimated and observed sediment yield. Shekar & Mathew (2024) also used MUSLE to compute sediment yield in the Peddavagu Watershed (India) and found 82% accuracy of MUSLE with reference to the observed data. Ezenwa et al. (2023) used MUSLE for sediment yield determination in the Kubbani Drainage Basin of Nigeria. This advocates the capability of MUSLE to determine accurate sediment loads. Thus, the equation can be applied with full confidence to determine sediment yield in ungauged watersheds.

Pakistan being a developing country has a limited hydrological gauging network, which poses difficulties to formulate effective watershed management practices. Sedimentation is a serious issue in the major reservoirs of Pakistan, where the service life of Mangla and Tarbela Dams have been significantly declined due to sedimentation. As per the Pakistan's Water and Power Development Authority (WAPDA), the mean annual sedimentation rate of Tarbela Dam is 0.132 billion m^3 (BCM) (Mazhar et al., 2021), where the yearly total sediment yield of reservoir ranges from 100 to 300 million tons (MT). Due to the seasonal streamflow variation, the incoming sediment load varies seasonally in Tarbela throughout the year, with 97% or more is transported during high flows in summer between May and September, with peak in July and August due to snow and glacier melt and precipitation. As per WAPDA, during 1974−2009, the storage capacity of Tarbela Dam has declined by 30% due to sedimentation (Mazhar et al., 2021). Similarly, in Mangla Dam, the capacity has declined by 22% since 1967. Similar conditions prevail in other reservoirs across the country with lack of sediment data inventory to formulate effective conservation measures (Raza et al., 2015).

This stresses that the non-availability of observed hydrologic data is a serious concern for effective watershed management. Therefore, this study was conducted to determine the mean monthly and annual sediment yield using MUSLE, with Winder River Basin in Baluchistan taken as the study area. To compute daily runoff and discharge of Winder River, the NRCS Curve Number (CN) Method was used. The period 1982−2020 was taken as the study period. The research outcomes may help to understand determining the runoff and sediment yield in ungauged watersheds and to devise watershed best management practices.

2.0 METHODOLOGY

2.1 Study Area

With an area of 347,190 km^2, Balochistan is the largest province of Pakistan. The province is situated in Pakistan's southwest and shares borders with the provinces of Sindh in the southeast, Khyber Pakhtunkhwa in the northeast, and Punjab in the east. The province has a large, mountainous plateau with basins separated by peaks that are rugged and high enough. Over 47% of Balochistan's economy is derived from agriculture and animals (Khan et al., 2021).

Climatologically, the upper highlands in Balochistan have very cold winters and hot summers. Winters in the lower highlands range from bitterly cold in the northern areas (where it can be as low as -20°C) to gentler conditions near the coast of Makran. The plains experience moderate winters, with temperatures that never drop below freezing. Summers are hot and dry, particularly in the province's arid regions. In the summer, the plains get up to 50 °C, which is extremely hot. Balochistan has a low population density because of its rugged terrain and water scarcity. The province's notable river basins are Hub, Mula, Nari, Bolan, Dasht, Basol, Porali, and Hingol, which are nourished by precipitation, hill torrents, and groundwater flow. Groundwater serves as the primary supply of water for both home and agricultural purposes in Balochistan because of the fluctuating streamflows (Khan et al., 2021).

Winder River is a seasonal river fed by precipitation, having a drainage area of 920 km2 as shown in Figure 2, where most of the watershed has a hilly terrain devoid of vegetation. Morphologically, the river basin is dominated by fluvial sediment transport and alluvial formations. Climatologically, based on the analysis, the yearly precipitation across the watershed ranges from 125 to 200 mm, with the mean annual precipitation as 131 mm. Due to its geographical location, the study area receives the major amount of its yearly precipitation from summer monsoon, followed by winter rainfall from western disturbances. During extreme monsoon scenarios, the watershed often experiences significant flooding. The length of Winder River is about 54 km, with the average basin slope as 17.31%. Based on the Sentinel-2 land use classification, 0.02% of watershed comprises of waterbodies, 0.04% as dense vegetation, 0.005% as crop fields, 0.005% as built area, 0.46% as bare ground, and 99.45% as rangeland as shown the Figure 3. Based on the Food and Agriculture (FAO) soil classification, I-Rc-Yk-c having silty clay texture was found to be the dominant soil in the watershed. Geologically, the Winder River Basin mainly consists of Cretaceous and Paleogene sedimentary rock formations as shown in the Figure 3.

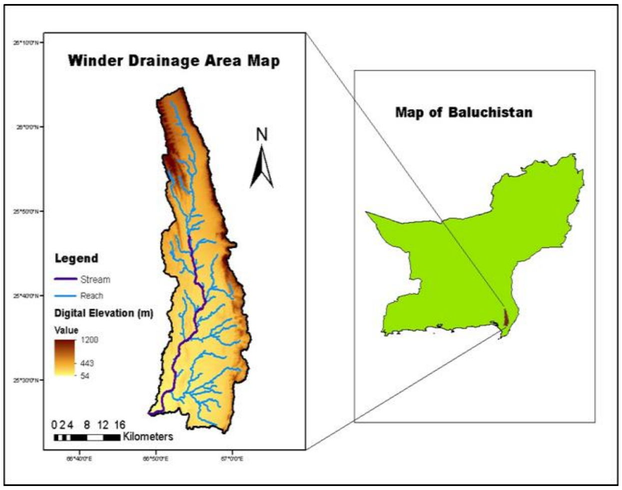

Figure 2. Description of study area.

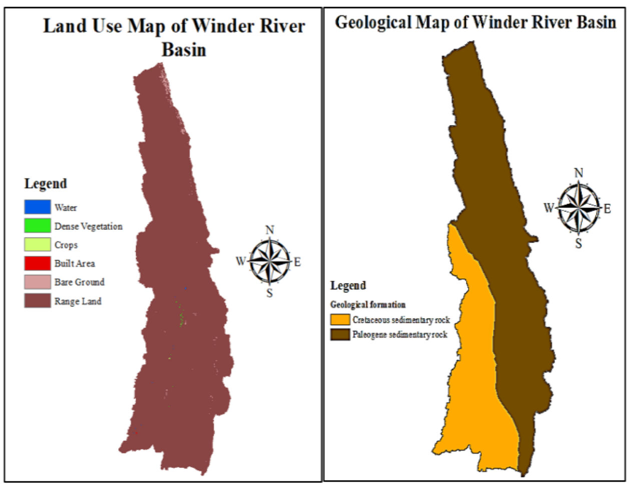

Figure 3 Land use and geological map of Winder River Basin.

2.2 Global Precipitation Climatology Center (GPCC)

Global land surface gridded precipitation data sets for the GPCC are gauge-based and offered at 1.0° latitude by longitude spatial resolution. The center is Germany's contribution to the Global Climate Observing System (GCOS) and the World Climate Research Programme (WCRP) (Schamm et al., 2014). Due to the non-availability of rainfall data, the GPCC daily gridded rainfall dataset was employed in this study.

2.3 NRCS Curve Number Method (1972)

To compute daily runoff, the NRCS Curve Number (CN) Method was used. This approach was formulated by USDA and NRCS in 1972 to synthetically compute direct runoff from a single precipitation event on a daily scale. The NRCS CN Equation is shown in Equation 5 as under (Kobus, 2024):

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \quad (5)$$

Where, Q is the direct runoff depth (mm), P is the gross precipitation (mm), and S is the maximum potential retention (mm), which is the highest difference between rainfall and runoff, measured from the instant the precipitation commences. As per NRCS, prior to surface runoff, rainfall must exceed interception, depression storage, and infiltration, collectively known as initial abstraction (Ia). NRCS relates S to CN (Equation 6), which is an empirical watershed parameter that accounts the influence of antecedent moisture condition (AMC), land use, soil texture, hydrologic condition, and conservation practice on runoff (Moglen et al., 2022).

$$S=\frac{25{,}400}{CN}-254 \quad (6)$$

and,

$$I_a=0.2S \quad (7)$$

2.3.1 Curve Number (CN)

Due to the consideration of initial soil moisture before the given precipitation event, CN is estimated individually for every precipitation event. CN generally varies from 30 to 100, where a high CN shows greater runoff prospective (Chin, 2023).

Antecedent Moisture Condition (AMC) is a soil moisture level prior to the given rainfall and significantly impacts the watershed's response to rainfall. For instance, a wet soil generates higher runoff than dry soil from the same rainfall amount. Based on the soil water content prior to the given rainfall, NRCS defined three initial moisture conditions as AMC-I, which indicates dry soil before rainfall. AMC-II shows fair moisture condition, while AMC-III shows high soil moisture prior to the given rainfall. In addition, high water table or waterlogging also create AMC-III. CN significantly varies with AMC, with higher CN for wet soil and lower CN for dry soil. To select the true representative AMC, NRCS considers cumulative rainfall of preceding five days before the given storm) as described in Table 5 below (Schwab et al., 1982):

Table 5. Description of NRCS AMCs.

AMC	Total Rainfall + Irrigation during Preceding Five Days (mm)	
	Dormant Season	Growing Season
I	Less than 13	Less than 36
II	13 to 28	36 to 53
III	Above 28	Above 53

Source: Schwab et al. (1982)

The Hydrologic Soil Group in NRCS refers to the infiltration and runoff ability of a soil texture, with the soil having high infiltration rate will produce lower runoff. NRCS defines four hydrologic soil groups as described in Table 6 below:

Table 6. Description of NRCS Hydrologic Soil Groups. **Source:** Schwab et al. (1982)

Hydrologic Soil Group	Soil Texture	Rate of Infiltration (mm/hr)
A	**Low Runoff**: Coarse sand and sandy loam.	8.0–12.0
B	**Moderately Low Runoff**: Loam or silt loam.	4.0–8.0
C	**Moderately High Runoff**: Sandy clay loam.	1.0–4.0
D	**High Runoff**: Silty clay, clay loam, silty clay, sandy clay, silty clay loam, or clay.	0.0–1.0

The watershed's hydrologic condition also impacts runoff, infiltration, and erosion. As per NRCS, hydrologic condition accounts the factors that govern infiltration and runoff in a watershed including its vegetation cover, percent of bare land, degree of surface roughness, etc. Hydrologic condition is classed as "good", "fair", or "poor". A well-established root system, large surface covered areas, long stand of vegetation, large quantities of organic matter, humus and peat soil, presence of wetlands, swamps, small ponds, etc. refers to good hydrologic condition that reduces runoff and erosion. On the contrary, a poor hydrologic condition results in higher runoff and erosion. For example, lack of vegetative cover, soil compaction, and urbanization results in poor condition. As per NRCS, a good hydrologic condition refers to more than 75% ground cover, whereas fair hydrologic condition refers to 50 to 75% of ground cover, and a poor hydrologic condition refers to less than 50% ground cover. The CN values suggested by NRCS (1972) were adopted in this study (Schwab et al., 1982).

2.4 Sediment Yield Estimation

To compute daily sediment yield, MUSLE was used in this study as described in Equation 4.

2.4.1 Peak Discharge (Q_{peak})

Peak discharge refers to the maximum runoff rate from a precipitation or flood event. To compute Q_{peak}, the NRCS Dimensionless Unit Hydrograph (DUH) theory was used in this study. L.K Sherman proposed the UH concept in 1932. UH is a hydrograph which shows the temporal distribution of surface runoff in response to a unit excess precipitation (Alia et al. 2023). Unit hydrograph is generally of two types as natural and synthetic. A natural UH is prepared by separating the baseflow from total runoff. However, in ungauged watersheds, synthetic unit hydrographs are prepared based on the watershed's physical characteristics (i.e. drainage area, slope, CN, and flow length) to determine peak discharge from excess precipitation (You-qin et al., 2024).

The NRCS DUH theory was proposed by Victor Mockus by deriving many natural unit hydrographs in Texas from watersheds of wide range of physical characteristics. The resulting hydrograph was then made dimensionless so as to make it globally applicable by taking the discharge ratios (Q/Q_p) as ordinate and time ratios (T/T_p) as abscissa. The theory assumes the base time (T_b) of hydrograph as five times of time to peak (T_p). The NRCS peak discharge equation is shown in Equation 8 as under (Verma et al., 2017):

$$Q_{peak}=\frac{KAQ}{T_p} \quad (8)$$

Where, K is the peak rate factor (484 standard), A is the drainage area (sq. mile), Q is the direct runoff or excess precipitation (inch), and Tp is time to peak (hr) (Verma, Verma et al. 2017). T_p is the time duration from the rainfall commencement to the maximum runoff rate and is calculated by the following expression (Babiker & Mohamed, 2019):

$$T_p=\frac{0.133\,T_c}{2}+T_{lag} \quad (9)$$

Where, T_c is the time of concentration (i.e. length of time it takes for runoff to travel from the watershed's hydraulically farthest point to its outlet, hr), and T_{lag} is the lag time (i.e. the time duration between the peak excess rainfall and maximum runoff rate, hr). As per NRCS,

$$T_{lag}=\frac{L^{0.8}(S+1)^{0.7}}{1900\,Y^{0.5}} \quad (10)$$

Where, T_{lag} is in hr, L is the length of main channel (ft), S is the maximum potential retention (inch), and Y is the average watershed slope (%) (Babiker & Mohamed, 2019). As per NRCS,

$$T_c=\frac{T_{lag}}{0.60} \quad (11)$$

2.4.2 Soil Erodibility Factor (K)

Sediment yield strongly relies on the soil texture and its structural composition. A well compacted fine-grained soil due to higher cohesion is more resistant to detachment than coarse soil. Theoretically, K refers to the soil loss rate per erosion index unit for a specified soil as measured on a unit plot of 22.1 m length, with a uniform length-wise slope of 9%, in continuous fallow and tilled up and down the slope (Neitsch et al., 2011). The equation proposed by Wischmeier et al. (1971) for K was used as shown in Equation 12 below (Neitsch et al., 2011):

$$K = 2.8 \times 10^{-7}\, M^{1.14}\, (12-a) + 4.3\times10^{-3}\, (b-2) + 3.3 \times 10^{-3}\, (c-3) \quad (12)$$

And,

$$M = (\%\ silt + \%\ very\ fine\ sand)\,(100 - \%\ clay) \quad (13)$$

Where, M is the particle size diameter, a is the percent organic matter, b is soil structure code (1 for very fine granular soil, 2 for fine granular soil, 3 for medium or coarse granular soil; and 4 for massive, prismatic, blocky, or platy soil), and c is soil profile permeability class (1 for rapid, 2 for moderate to rapid, 3 for moderate, 4 for slow to moderate, 5 for slow, and 6 for very slow). On the basis of saturated hydraulic conductivity, the soil permeability classes as described in the Soil and Water Assessment Tool (SWAT) theoretical manual (2009) are shown in Table 7 below (Neitsch et al., 2011):

Table 7. Description of soil profile permeability classes. **Source:** Neitsch et al. (2011)

Soil Permeability Class	Hydraulic Conductivity (mm/hr)
Rapid	Above 150
Moderate to rapid	50 to 150
Moderate	15 to 50
Slow to moderate	5 to 15
Slow	1 to 5
Very slow	Below 1

The percent organic matter (a) was computed using the following expression (Neitsch et al., 2011):

$$a = 1.72\ (\%\ \text{organic carbon}) \qquad (14)$$

The arrangement of particles inside a soil mass is referred to as soil structure. A single natural soil aggregate is referred to as a ped. The size, differentiation, and durability of peds, as well as their shape and arrangement, are all included in a broad field description of soil structure. Based on these three characteristics, the USDA classifies soil structures into three categories: type (defined by the arrangement and shape of ped), class (ped size), and grade (degree of distinctness) (Neitsch et al., 2011).

The type and class of soil structure that is present in the layer defines the soil structure codes. The four basic types of soil structure are blocklike (particles arranged around a point and bounded by flat or rounded surfaces which are casts of the molds formed by the faces of surrounding peds); prismlike (particles arranged around a vertical line and bounded by relatively flat vertical surfaces); and platy (particles arranged around a plane). Spheroidal (particles arranged around a point and bounded by carved or very irregular surfaces that are not accommodated to the adjoining aggregates). There are two other classifications into which the prismlike, blocklike, and spheroidal soil structures are further divided as prismatic (particles with rounded upper ends) and columnar (particles with rounded caps). Similar to this, the blocklike soil structure found in a watershed can be classified as subangular blocky (containing a mixture of rounded and plane faces with rounded vertices) or angular blocky (particles surrounded by planes intersecting at relatively sharp angles). Granular spheroidal structures are comparatively non-porous, while crumb spheroidal structures are significantly porous. To select the correct soil structure code, the following criteria (Table 8) proposed in the SWAT theoretical manual (2009) was followed (Neitsch et al., 2011):

Table 8. Soil structure size (mm) classifications. **Source:** Neitsch et al. (2011)

Size Class	Platy	Prismatic and Columnar	Blocky	Granular
Very fine	< 1	< 10	< 5	< 1
Fine	1 to 2	10 to 20	5 to 10	1 to 2
Medium	2 to 5	20 to 50	10 to 20	2 to 5
Coarse	5 to 10	50 to 100	20 to 50	5 to 10
Very coarse	Above 10	Above 100	Above 50	Above 10

2.4.3 Topographic Factor (LS)

Apart from soil, sediment yield also relies on the watershed's topography, with steep topography results in high runoff rate and higher sediment transport. Theoretically, LS is the expected ratio of soil loss per unit area from a field slope to that from a 22.1 m length of uniform 9% slope under otherwise identical conditions (Neitsch et al., 2011). In this research, LS was computed using the Moore & Burch Equation (1986) as shown in Equation 15 below (Moore & Burch, 1986):

$$LS = 1.4\left(\frac{\text{Slope length}}{22.13}\right)^{0.4}\left(\frac{0.01745\ \text{Sin}\emptyset}{0.0896}\right)^{1.4} \qquad (15)$$

Where, Ø is the slope angle in degrees (Moore & Burch, 1986).

2.4.4 Cover and Management Factor (C)

Conceptually, C is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled continuous fallow. The value of C typically varies from 0 to 1, with greater sensitivity to erosion and less vegetation are indicated by higher C values (Neitsch et al., 2011). In this study, the equation proposed by European Soil Bureau was used to compute C as shown in Equation 16 below (Vemu & Pinnamaneni, 2012):

$$C = e^{-\alpha(NDVI/(\beta - NDVI)} \qquad (16)$$

Where, NDVI stands for Normalized Difference Vegetation Index and the parameters that depict the NDVI-C curve's form are α and β, taken as 2 and 1 respectively following the past studies (Vemu & Pinnamaneni, 2012). NDVI is a widely used parameter for quantifying the health and density of vegetation over an area, and varies from 0 to 1. Higher values of NDVI shows dense vegetation, while lower values of NDVI indicates barren land or sparse to no vegetation. In this study, the Landsat band 4 and 3 satellite images obtained from United States Geological Survey (USGS) Earth Explorer were processed in ArcMap 10.5 to compute NDVI for the watershed using the expression below (Vemu & Pinnamaneni, 2012):

$$NDVI = \frac{\text{Band 4} - \text{Band 3}}{\text{Band 4} + \text{Band 3}} \qquad (18)$$

2.4.5 Conservation Practice Factor (P)

As per USLE, P is the ratio of soil loss with a specific conservation practice to the corresponding loss with up- and-down slope practice (Vemu & Pinnamaneni, 2012). In this study, the value of P was taken as 1.0 due to no conservation practice.

3.0 RESULTS AND DISCUSSION

3.1 Runoff Estimation

Following the NRCS CN method, the daily runoff and discharge was estimated for the Winder River Basin. The estimated discharge showed good correlation (R^2= 0.77) compared to the available monthly observed data (1997−2004) as shown in Figure 4 below:

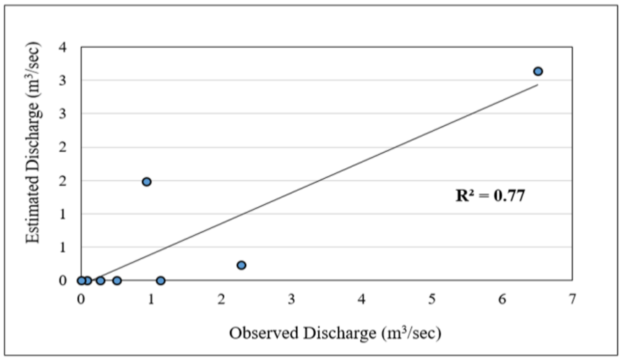

Figure 4 Goodness of fit between the estimated and observed monthly discharge of Winder River Basin.

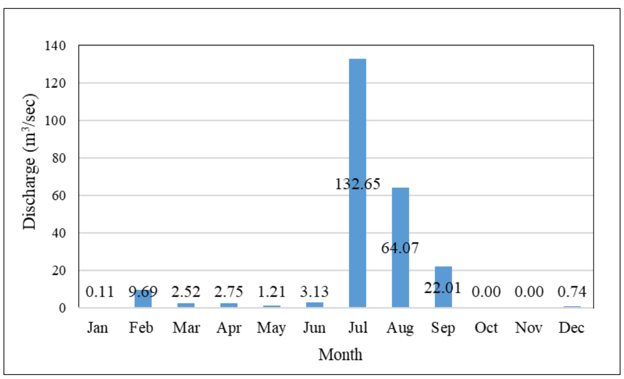

Figure 5 Estimated mean monthly discharge of Winder River Basin.

As shown in Figure 5, being a seasonal rainfed river, the streamflows of Winder River closely follows the precipitation trend of the study area, where the major share of its annual total runoff is received during monsoon season. According to the analysis, the average yearly discharge of Winder River was found to be 20 m^3/sec. Seasonally, the mean summer seasonal discharge (July−September) was found to be 72.91 m^3/sec, whereas in winter (December−March), the average discharge was found to be 3.5 m^3/sec.

3.2 Sediment Yield

3.2.1 Soil Erodability Factor (K)

Using Equation 14, the soil erodibility factor was found to be 0.34 for the Winder River Basin.

3.2.2 Topographic Factor (LS)

Using the Moore & Burch Equation (1986), the topographic factor of the study area was found to be 0.98.

3.2.3 Cover and Management Factor (C)

Based on the GIS analysis, the mean NDVI of study area was found to be 0.09. Using Equation 18, the value of C for the study area was found to be 0.82.

3.2.4 Estimated Sediment Yield

The estimated average monthly sediment yield of Winder River Basin for the period 1982−2020 is shown in Figure 6 below:

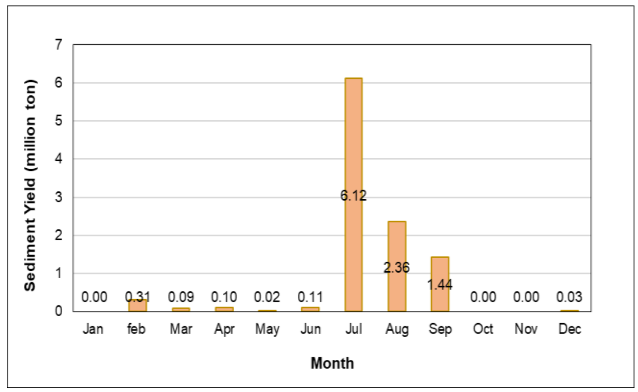

Figure 6 Estimated mean monthly sediment yield of Winder River Basin (1982−2020).

The above Figure 6 shows a profound interrelationship between the streamflow patterns and sediment yield, where the highest mean monthly sediment yield was found in July (6.12 million tons) due to high monthly rainfall and discharge, while lowest mean sediment yield was found in October and November due to low rainfall and runoff. The estimated annual sediment yield of Winder River Basin for the period 1982−2020 is shown in Figure 7 below:

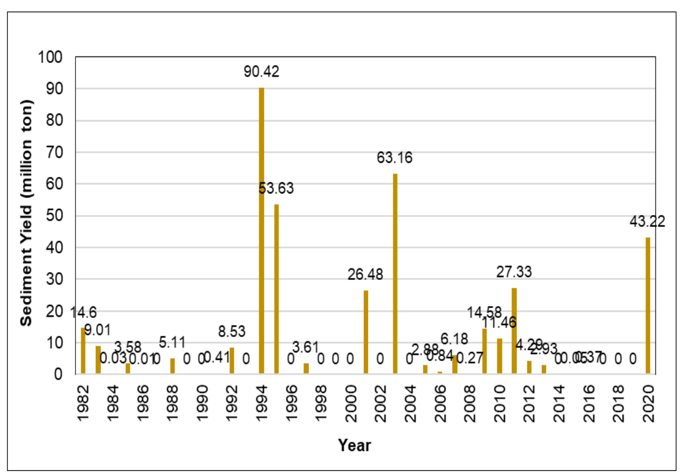

Figure 7 Estimated annual sediment yield of Winder River Basin (1982-2020).

As per the analysis, the average yearly sediment yield of Winder River Basin was computed to be 10.08 Million Tons.

3.3 Sediment Discharge Rating Curve

As discussed earlier, sediment yield strongly depends on the streamflow patterns, with larger discharge results in high erosion and sediment yield. In this study, based on the estimated daily discharge and the corresponding sediment yield, a sediment-discharge rating curve was developed for Winder River Basin as shown in Figure 8 below:

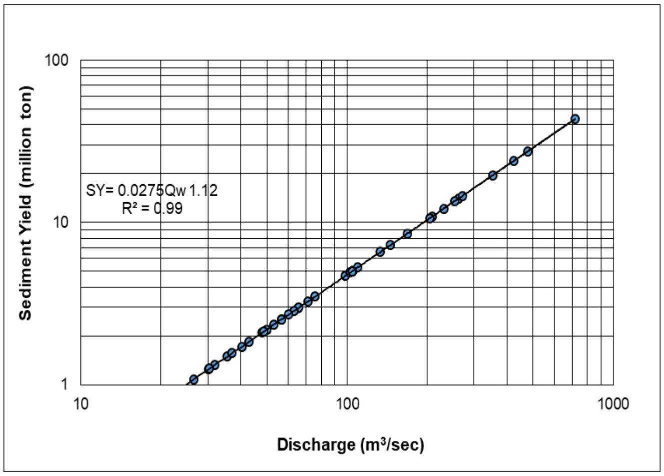

Figure 8 Sediment-discharge rating curve of Winder River Basin.

Based on the statistical analysis, the power function was found to be the best-fitted relationship between the two hydrologic parameters. The best-fitted equation of sediment-discharge relation for Winder River Basin is shown in Equation 18 below:

$$SY = 0.0275\ Q_w^{1.12} \tag{18}$$

Where, SY is the daily sediment yield (MT) and Q_w is mean daily discharge (m^3/s) of river. This relationship can be used with full confidence by the natural resource managers and hydrologists to compute the daily sediment yield of the study area to plan effective soil conservation and watershed management practices.

4.0 CONCLUSIONS AND RECOMMENDATIONS

This research was carried out to compute the flow and sediment yield in ungauged Winder River Basin in Balochistan. As per the research outcomes, the following conclusions are established:

- The NRCS CN method well estimated the daily discharge of the ungauged Winder River Basin. Based on the statistical analysis, a good correlation (R^2 = 0.77) was found between the monthly observed and estimated discharge.
- Following the NRCS CN method, the computed average yearly discharge of Winder River Basin was found to be 20 m^3/s (712.6 cfs). The runoff patterns were found to be closely following the precipitation trends, where the highest seasonal discharge in the river was found during summer (72.91 m^3/s).
- The sediment-discharge rating curve developed from the estimated daily discharge and sediment yield showed a strong correlation (R^2 =0.99). The annual sediment yield of Winder River Basin was found to be 10.08 MT.
- Based on the literature review and research outcomes, MUSLE was found to be a reliable approach to compute sediment yield.
- In view of the author's opinion, based on the numerical results of study, a suitable conservation practice (contouring, terracing, or strip cropping) is recommended for the river basin that will aid to conserve the soil and runoff movement and to facilitate an effective watershed management.
- In addition, for capturing a more detailed and localized sediment and runoff regime of the study area, sediment and streamflow gauging stations can be installed to timely monitor the runoff patterns and sediment erosion.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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