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Integrating RUSLE and SDR in GIS framework for assessment of soil erosion and sediment yield in Kandi region of Punjab

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ABSTRACT

Soil erosion continues to be one of the serious environmental problems that hinder the sustainable agriculture. The *Kandi* region is identified as one of the most degraded ecosystem of India and is severely affected by soil erosion. Therefore, it is necessary to estimate the soil erosion in this region for successful implementation of appropriate soil and water conservation measures for sustainable agriculture. The present study was conducted to estimate the soil erosion and sediment yield for a small earthen dam using Revised Universal Soil Loss Equation (RUSLE) integrated with the sediment delivery ratio (SDR) model in the GIS environment. The various input factors for RUSLE model (R factor, K factor, LS factor, C factor and P factor) were prepared as raster layers in ArcGIS to estimate the average annual soil loss. The various empirical formulae were used to obtain the SDR for the dam catchment. The results showed that the average annual soil loss varied from 0 to 8.94 t $ha^{-1}yr^{-1}$ which accounted to total soil loss of about 361319.45 tonnes. The average SDR was found to be 0.581 which indicates that about 58.1% of total generated sediments (209926.6 tonnes) have deposited the dam. The implementation of various soil conservation structures in the catchment would reduce the soil loss and sediment yield which may increase the life of the earthen dam. The results of the present study may provide an insight for policy makers to design and execute the watershed management practices to reduce erosion hazard and sediment accumulation in the small reservoirs.

1. INTRODUCTION

Soil erosion is identified as one of the serious environmental concerns because it not only results in the degradation of land and nutrient deprivation of soil but also causes environmental problems such as siltation, flooding and pollution (Ahmad *et al*., 2020). Soil erosion is the major limitation to attain the sustainable food production and maintain the water quality in rivers, lakes and streams. Soil erosion is the main cause of the soil degradation across the world, which has catastrophic impacts on soil health, thus posing a great threat to global food security. Soil degradation results in decreased crop production resulting in huge economic losses thereby risking the livelihood of the farming community (Bhattacharya *et al.,* 2015). Sediment yield (SY) is the amount of eroded soil that reaches the watershed outlet or the outlet of the terrace diversion channels (Yousuf *et al.,* 2022). The sediment transport depends upon the various factors including topography, landuse, soil type and sources of sediments. The measurement of the SY is important for design of various soil and water conservation structures including check dams, earthen dams, trenches, etc. The sediment deposition reduces the capacity of the reservoirs like dams which ultimately affects the hydro-power generation and decreases the availability of water both for domestic and industrial purposes. The siltation decreases the reservoir capacity by 2% annually (Aga *et al.,* 2018). Non-point pollutants like heavy metals, nutrients contaminants and chemicals are also transported with the sediments to already susceptible aquatic ecosystems leading to water eutrophication and destruction of water ecosystems. SY estimates are essential for many reasons such as planning appropriate soil and water conservation measures, river morphological studies and estimation of chemical concentrations absorbed to sediment particles. The measurement of SY is difficult at the watershed scale due to lack of monitoring stations, technical staff and funds (Yousuf and Bhardwaj, 2022). Many hydrological models including universal soil loss equation (USLE), revised universal soil loss equation (RUSLE), watershed erosion prediction project (WEPP), soil and water assessment tool (SWAT), agricultural non-point source model (AGNPS) and EROSION-3D model have been developed and applied to estimate the soil erosion at various scales, *viz.,* river basin, catchment and watershed scales. However, RUSLE is one of the most extensively used empirical soil erosion model for assessment of soil erosion. The model has found great applicability in soil loss assessment owing to its simplicity and low data requirement. The RUSLE model has been integrated with remote sensing (RS) and geographic information system (GIS) for estimation of soil loss from the watersheds. RUSLE coupled with RS and GIS have been used for soil erosion in *Kandi* region of Punjab and also Bino watershed of Himalaya (Sudhishri *et al.,* 2014). Although RUSLE has successfully estimated soil loss all over the globe, its main limitation is that it cannot predict the SY. In order to overcome this limitation, the RUSLE model has been coupled with the sediment delivery ratio (SDR) concept/model. The RUSLE-SDR coupled model has been widely used for estimation of soil erosion and SY by incorporating the catchment transport efficiency (Magesh and Chandrasekar, 2016). Thomas *et al.* (2018a) applied the RUSLE based SDR model to estimate gross soil erosion and SY in Muthirapuzha river basin in western ghats, India and revealed that gross soil loss was about 14.36 t $ha^{-1}yr^{-1}$ while as SY was only 3.65 t $ha^{-1}yr^{-1}$. Thomas *et al.* (2018b) integrated RUSLE and SDR in GIS environment to estimate soil erosion and SY in Pambar river basin, India and revealed that the average annual soil loss was about 11.70 t $ha^{-1}yr^{-1}$ and SY was 2.92 t $ha^{-1}yr^{-1}$. Bhattacharya *et al.* (2020) estimated the SY using RUSLE and SDR in Kangsabati basin, India and evaluated that the soil erosion and SY was about 74-226 t $ha^{-1}yr^{-1}$ 13.2-32.0 t $ha^{-1}yr^{-1}$, respectively. Kushwaha *et al.,* (2022) applied the GIS based RUSLE model for soil erosion assessment and watershed prioritization in Takarla-Ballowal watershed located in Kandi area. Yousuf *et al.* (2022) applied RUSLE model coupled with SDR to estimate the sediments accumulated in the check dam located in *Kandi* area. RUSLE-SDR has found its application all over the world (Gelagay 2016; Ebrahimzadeh *et al.,* 2018; Kidane *et al.,* 2019). A recent study by Borelli *et al.* (2021) revealed that RUSLE-type models have been extensively used and remain the most employed modelling tool today. In addition to this, many studies have reported that efficiency of RUSLE is more or at par with USLE (Tiwari *et al.,* 2000; Kinnel *et al.,* 2017), SWAT (Boufala *et al.,* 2020) and WEPP (Tiwari *et al.,* 2000; Kinnel *et al.,* 2017). Keeping this in view, this study was planned to estimate the soil erosion and sediment yield in a small water harvesting structure located in *Kandi* area of Punjab by coupling the RUSLE with SDR in GIS framework.

2. MATERIALS AND METHODS

Study Area

The study area (Golu Majra dam) is located between 31°3'57" to 31°4'44"N latitudes 76°25'46" to 76°26'20"E longitudes, covering an area of 76.06 ha. The weather is sub-humid with hot and dry summer and extremely cold winter. The maximum temperature is about 44°C and minimum temperature is about 5°C, experienced in May and January, respectively. The average annual rainfall is about 1050 mm, 80% of which is received in monsoon months (July to September) (Kaur *et al.,* 2021). The soil of the study watershed is sandy loam in texture. The watershed is primarily inhabited by forest and shrub lands.

Data Used

Rainfall data (2010-2020) of the study area was obtained from Punjab Agricultural University-Regional Research Station (PAU-RRS), Ballowal Saunkhri. The soil sampling of the watershed was carried out to determine the

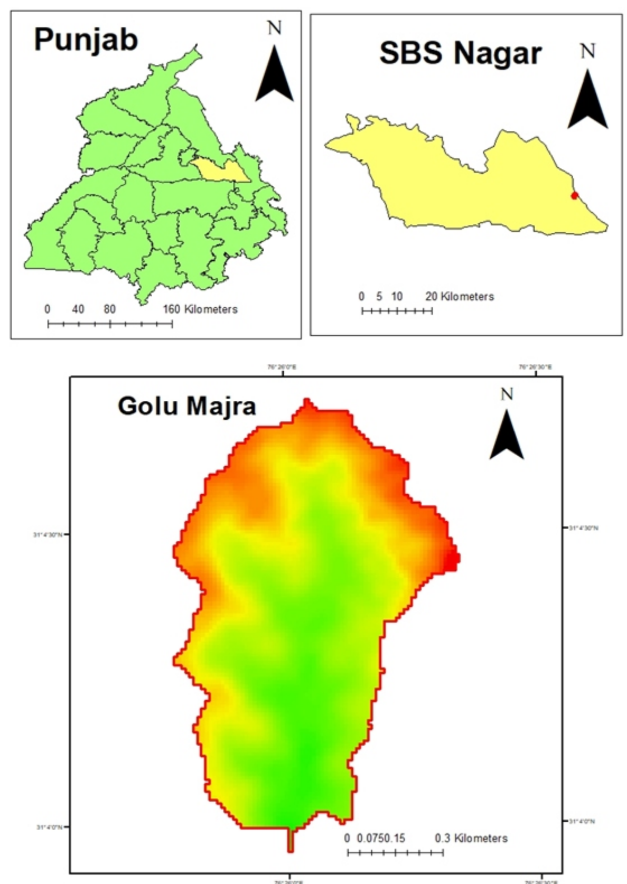

Fig.1. Location map of the study area

soil texture and organic matter. ALOS PALSAR DEM having the spatial resolution of 10 m was used to generate the topographical parameters like flow direction, flow accumulation, drainage network, slope and slope aspect (Fig. 2).

RUSLE Model Parameters

The RUSLE model mainly incorporates five important soil erosion controlling factors to compute the annual soil loss rate. The input factors and the general formula of the RUSLE can be expressed as:

$$A = R \times K \times LS \times C \times P$$

Where, A denotes the average annual soil loss (M t ha^{-1} yr^{-1}), R is the rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}), K is the soil erodibility factor (in M t ha MJ^{-1} mm^{-1}), LS is a slope length and steepness factor (which is dimensionless), C is the cover management factor (dimensionless), and P is the support and conservation practice (dimensionless).

Rainfall Erosivity (R) Factor

Rainfall is one of major factors that is responsible for soil erosion. The rainfall erosivity factor (R) takes in account the impact of rainfall characteristics on the erosion. The R factor is strongly influenced by rainfall intensity (I_{30}) and kinetic energy (E) data obtained over a 30 min period (Wischmeier and Smith, 1978). In the current study area, however, the required (I_{30} and E) data were not available; therefore, kriging interpolation techniques were used in the

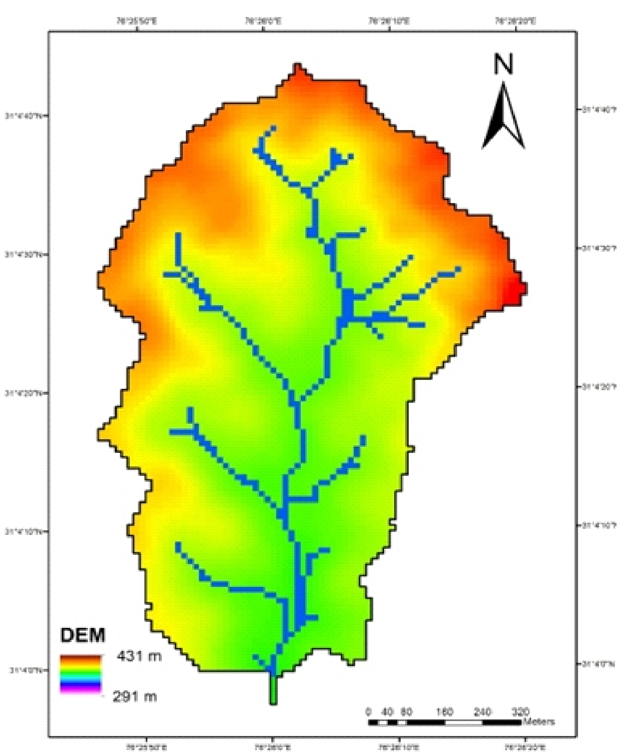

Fig.2. Digital elevation model and drainage channels of study area

GIS platform to generate the annual R factor map of the watershed using annual rainfall data from meteorological station RRS, Ballowal Saunkhri. The equation given below was used in the computation of R factor:-

$$R = 79 + 0.363 \times P$$

Where, R = Rainfall erosivity factor (MJ mm ha^{-1}h^{-1}yr^{-1}), P = Annual rainfall (mm).

Soil Erodibility (K) Factor

A soil's K factor determines its susceptibility to erosion based on its physical and chemical characteristics. Wischmeier and Smith (1978) developed a regression equation to calculate the K factor. By integrating soil texture, permeability, OM content, and soil structure, K values are obtained. Therefore, in the current study, soil erodibility map was created based on the clay, silt, sand, and organic carbon content.

$$K_e = \left\{0.2 + 0.3exp\left[-0.0256S_d\left(1 - \frac{S_i}{100}\right)\right]\right\}\left(\frac{S_i}{C_i + S_i}\right)^{0.3}$$
$$\left[1 - \frac{0.25C}{C + \exp(3.72 - 2.95C)}\right]$$
$$\left[1 - \frac{0.07(1 - S_d)}{1 - S_d + \exp(-5.51 + 22.9(1 - S_d))}\right]$$

Where, Ke = soil erodibility (Mg m^2 h m^{-1}Mg^{-1}cm^{-1}), and S_d, S_i, C_i and C represents the percentage of sand, silt, clay and organic carbon, respectively.

Topographic (LS) Factor

According to Wischmeier and Smith (1978), topography significantly influences runoff and sediment yield. A topographic (LS) factor is used by the RUSLE to estimate soil erosion based on surface topography. Soil erosion is affected by slope length (L) and slope steepness (S), both of which are considered in the LS factor. Based on the erosion rate at a standard topography site and the erosion rate at an existing topography site, this factor determines the erosion rate at the existing topography site (Ganasri and Ramesh, 2016). LS factors influence accumulated runoff and, therefore, soil erosion by water due to slope length and slope steepness (Amsalu and Mengaw, 2014). A slope and flow accumulation layer are computed directly from the digital elevation model in the Arc-Hydro extension of the Arc-GIS environment, which can be used to calculate the LS layer. As a final step, LS factor was computed using DEM and slope using the following equation:-

$$\text{LS} = \left(\text{Flow accumulation} * \frac{\text{Cell size}}{22.13}\right)^{0.2} * (0.065 + 0.045 * slope + 0.0065 * (slope)^2)$$

Where, $Facc$ represents the flow accumulation matrix, M is the Cell size (12.5 × 12.5 m), S is the cell slope (%).

Cover and Management (C) Factor

An index of the soil loss on land with specific cover and management against bare fallow land is called the cover and management factor (Xue *et al.,* 2018). As a result, it provides a means to minimize the volume and impact of raindrops and surface runoff by improving the soil's ability to infiltrate (Chuenchum *et al.,* 2020). An indicator of poor surface/vegetation cover is a C factor value close to 1, while an indicator of premium ground cover is a *C*-factor value close to 0 (Tamene *et al.,* 2017). *C*-factors had previously been assigned directly to land use land cover maps based on literature (Koirala *et al.,* 2019). The value of *C*-factor was taken as forest landuse was 0.003 for the forest landuse (Sharma *et al.,* 2023).

Conservation Practices Factor (P)

Due to their ability to reduce runoff effects, supporting and conservation practices such as contouring, strip cropping, and terracing can significantly reduce erosion risk. In RUSLE, the conservation practice (P) factor is included as a consideration for the effect of support and conservation practices on soil erosion (Renard *et al.,* 1997). An ideal conservation practice is selected if it prevents soil erosion completely, whereas an insufficient conservation practice is selected if it does not prevent soil erosion at all. The P factor varies between 0 and 1 (Ganasri and Ramesh, 2016). Because conservation practices were not practiced throughout the entire study area, the P value for the study area was taken as 1.0 in the present study.

Sediment Yield

As part of the assessment and design of soil erosion protection structures, sediment yield (SY) has a pivotal role. While without accounting for sediment yield, the RUSLE model assesses the average annual soil erosion. The amount of eroded soil (*i.e.,* gross erosion) that reach the watershed while being transported through the watershed is known as sediment yield (*i.e.,* net erosion). Although sediment yield cannot be calculated directly using RUSLE modelling, sediment yield can be estimated by combining RUSLE with the SDR (Kamuju, 2016). The SDR is the ratio of the sediment yield and gross erosion and can be expressed as follows:

$$SDR = \frac{SY}{E}$$

SDR = sediment delivery ratio, SY = sediment yield (*i.e.,* net erosion), and E = average water erosion).

RUSLE can be used to determine the total watershed's gross erosion (E). The SDR must first be computed in order to evaluate the sediment yield. The SDR value demonstrates how well the drainage area's topography allows for the movement and sedimentation of eroded soil. Slope length, sediment particle size, runoff-rainfall, land use, and land cover management all have an impact on how much sediment is stored in the drainage basin (Tamene *et al.,* 2017). Seven distinct empirical equations established by Vanoni (1975), Renfro (1975), USDA SCS (1979), USDA (1972), Renfro (1975), Maner (1962), and USDA (2002) from field experimental data were used to calculate the average SDR (Table 1). The methodology adopted for estimation of sediment yield using RUSLE model is given in Fig. 2.

The overall methodology for the simulation of the above all five factors in the GIS and remote sensing environment are shown in Fig. 3.

Sensitivity Analysis of RUSLE Parameters

Sensitivity analysis is an important step to determine the most sensitive input parameters among a set of given parameters (Yousuf *et al.,* 2017). In the present study, RUSLE model parameters were evaluated to study their impact on the model by changing the estimated/calculated value by ±20% (Kleijnen 2005; Kanito *et al.,* 2023). The equation given by McCuen and Snyder, 1983 was used to determine the sensitivity ratio for each parameter:

$$S_r = \frac{(P_2 - P_1)/P_{12}}{(I_2 - I_1)/I_{12}}$$

3. RESULTS AND DISCUSSION

RUSLE Parameters

The average annual rainfall of the region is about 1050 mm and the rainfall erosivity is about 460.51 MJ mm ha^{-1}h^{-1} yr^{-1} (Fig. 4). Due to the small size of the study area, there was

Table: 1
Methods used to estimate the sediment delivery ratio

Method	Formulae	Description
Vanoni (1975)	$SDR = 0.472A^{-0.125}$	A: Area (km^2)
Renfro (1975)	$\log(SDR) = 1.8768 - 0.14191 \log(2.59A)$	A: Area (mi^2)
USDA SCS (1979)	$SDR = 0.51A^{-0.11}$	A: Area (mi^2)
USDA (1972)	$SDR = 0.5656A^{-0.11}$	A: Area (km^2)
Renfro (1975)	$\log(SDR) = 1.7935 - 0.14191 \log(A)$	A: Area (km^2)
Maner (1962)	$\log(SDR) = 1.8768 - 0.14191 \log(10A)$	A: Area (mi^2)
USDA (2002)	$SDR = 0.51A^{-0.11}$	A: Area (km^2)

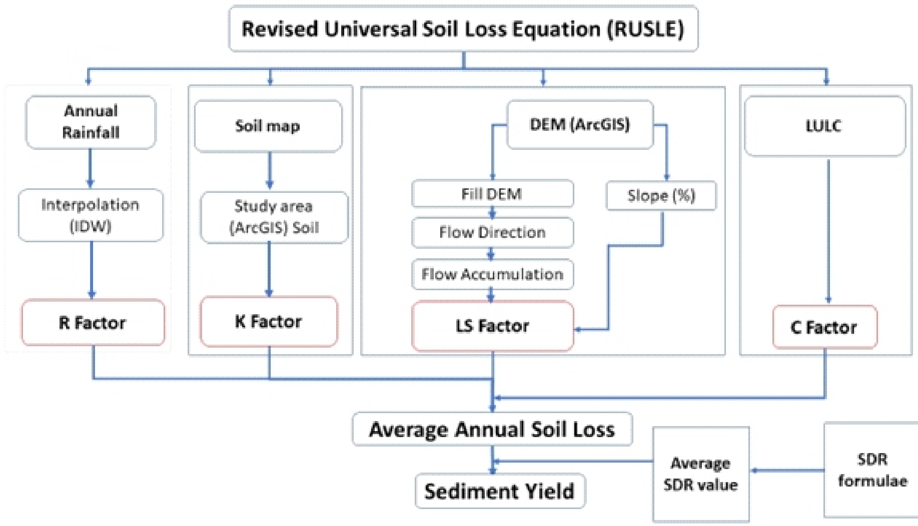

Fig.3. Methodology adopted for estimation of sediment yield

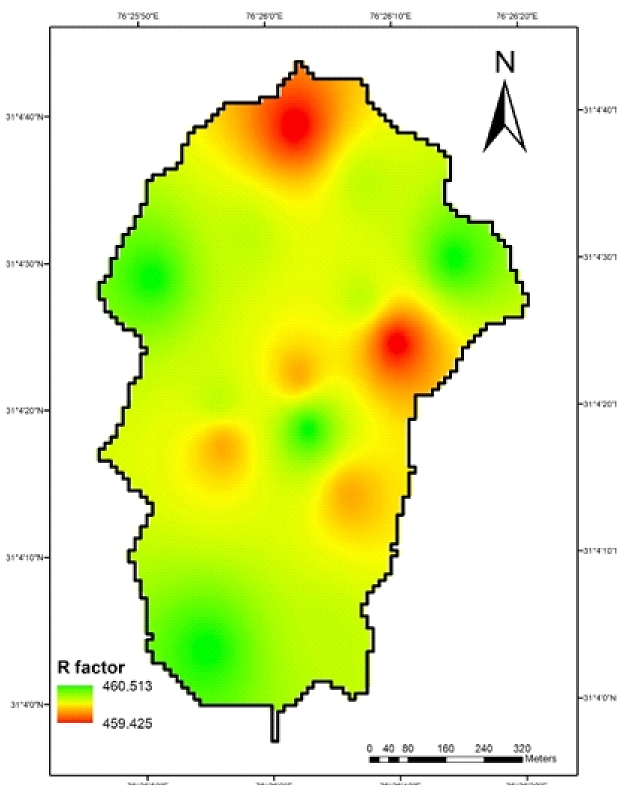

Fig.4. Rainfall erosivity map of the study area

not much variation in the *R*-factor. According to Mahapatra *et al.* (2018), the range of Uttarakhand's rainfall erosivity factor (R) in terms of its spatial distribution is between 400 and 700 MJ mm ha^{-1} h^{-1}. Similarly, Kumar and Kushwaha (2013) obtained a value of 383 MJ mm $ha^{-1}h^{-1}$ in a study conducted in the *Shivalik* Himalayan region. Similary, Kalambukattu and Kumar (2017) projected that mid-Himalaya has *R*-factor value of 606 MJ mm $ha^{-1}h^{-1}$. There has been evidence of a relationship between *R*-factor and SE across the globe (Ferro *et al.,* 1991; Renard and Freimund, 1994). The higher value of *R*-factor means higher erosion. The *K*-factor, which is based on the soil's physical and chemical properties, indicates how susceptible the soil is to erosion (Sharma *et al.,* 2011). The *K*-factor map was obtained by using the kriging technique and varied from 0.18 to 0.21 (Fig. 5). The higher values of *K*-factor may be due to higher percentage of sand content and low organic carbon. The LS factor varied from 0.1 to 46.14 (Fig. 6). The highest value of LS factor was found in the pixels having the highest slope. Similar LS values were calculated in *Shivalik* hills and a hilly sub-watershed in the middle of the Himalayas (Kalambukattu and Kumar, 2017; Kumar and Kushwaha, 2013). High LS values are correlated with higher surface runoff water velocities on the land surface, which leads to higher SE rates (Haan, 1994). According to the topography, SE rates increases as LS values increase (Renard and Freimund, 1994). The value of the *C*-factor was taken as 0.003 as the study area is mostly occupied by the forests and grasses. Similar *C*-factor values were employed in a various other studies (Gupta and Kumar, 2017; Kalambukattu and Kumar, 2017; Jena *et al.,* 2018). The different types of forest cover in the watershed are less prone to SE than barren or fallow land, which is particularly prone to erosion. The value of *P*-factor was taken as one because the study area was devoid of any soil conservation measures. Liu *et al.,* (2020) also suggested considering P factor value as one where no effective soil and water conservation measures are implemented.

Sensitivity Analysis of RUSLE Parameters

The results of sensitivity analysis of each RUSLE parameter are shown in Table 3. Among R, K, LS and C factors, the *C*-factor was found to be most sensitive parameter

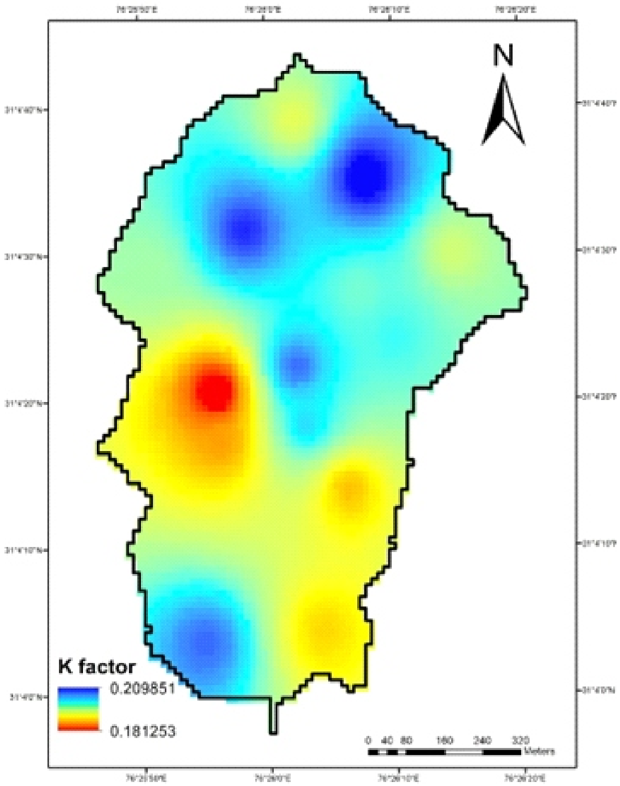

Fig.5. Soil erodibility map of the study area

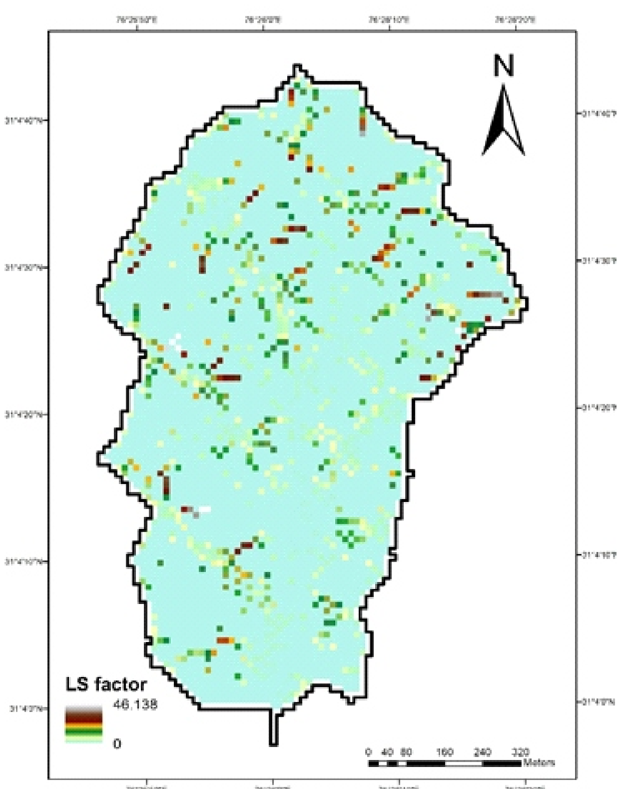

Fig. 6. Slope length and steepness factor map of the study area

with sensitivity ratio of 0.415, followed by LS factor with sensitivity ratio of 0.381. This indicates that minor changes in *C* and LS factor have pronouncing effect of soil erosion estimates of RUSLE. The sensitivity ratio for *R*-factor was found to be 0.342. The RUSLE model was least sensitive to *K*-factor having sensitivity ratio of 0.287. Bobe (2004) also reported that RUSLE model is most sensitive to *C* and LS factors. Similarly, Kanito *et al.,* 2023 revealed similar results with sensitivity ratio of 0.405 and 0.403 for L factor and *C*-factor, respectively.

RUSLE factor	Average value of parameter	Range of values		Sensitivity ratio
		-20%	+20%	
R-factor	460.5	368.4	552.6	0.342
K-factor	0.19	0.152	0.228	0.287
LS factor	23.05	18.4	27.6	0.381
C-factor	0.003	0.0024	0.0036	0.412

Sediment Delivery Ratio (SDR)

The SDR values obtained from different methods are given in Table 3. The highest value of SDR (0.650) was obtained using the Renfro (1978) and Maner (1962) methods while as the lowest value (0.491) was obtained using the Vanoni (1975). The average SDR value was 0.586. The higher value of SDR may be due to the small watershed area and steep slopes. The watershed area plays an important in determining the sediment yield. Large sized watersheds often have lower SDR values as the sediments detached and transported have more space and time to get deposited in the watershed area. Ebrahimzadeh *et al.,* (2018) also obtained SDR value by averaging the seven empirical methods was 0.27 for the Nozhian watershed, Iran. Similarly, Kidane *et al.,* (2019) reported SDR value range from 0- 0.26 for Ethiopia watershed. Singh *et al.,* (2019) also reported SDR value of the sub-watershed in Indian Himalayan region from 0.32 to 0.71.

Soil Erosion and Sediment Yield

The individual layers of RUSLE were multiplied in the raster calculator to obtain the soil erosion map for the study watershed (Fig. 7). RUSLE estimated the total average

Table: 3
Sediment delivery ratio using different formulae

Method	SDR
Vanoni (1975)	0.491
Renfro (1975)	0.569
USDA SCS (1979)	0.587
USDA (1972)	0.586
Renfro (1978)	0.652
Maner (1962)	0.652
USDA (2002)	0.529
Slope of main drainage line	0.623
Average	0.586

annual soil loss is about 0-8.94 t ha^{-1}yr^{-1} which has resulted in the total soil erosion of about 361319.5 tonnes (Table 4). The huge quantity of sediments indicates the serious soil erosion in the watershed. The average sediment delivery ratio of the watershed was about 0.581 indicating that 58.1% of the total eroded soil reaches to the outlet. Using the spatially distributed soil erosion map and SDR, the spatial distribution of SY was calculated; this varies from 0 to 6.54 t ha^{-1}yr^{-1}, with a mean yield of 5.33 t ha^{-1}yr^{-1}. Similar to the spatial distribution of soil erosion, SY is also relatively high in the steeply sloping topography. This shows that the LS factor has direct relation with the soil erosion and SY. The findings of the previous studies must be weighed against the reasonable and realistic findings of this study. SDR values were therefore estimated using the average of seven methods in the present research and were shown to be more realistic. For the computation of SY from the watershed, it is advised to utilise SDR derived from techniques for smaller watersheds. Based on SY, this method is simpler to use and more trustworthy for soil and water conservation measures. Gelagay (2016) estimated sediment yield in Koga Watershed, Upper Blue Nile Basin, Ethiopia by integrating sediment

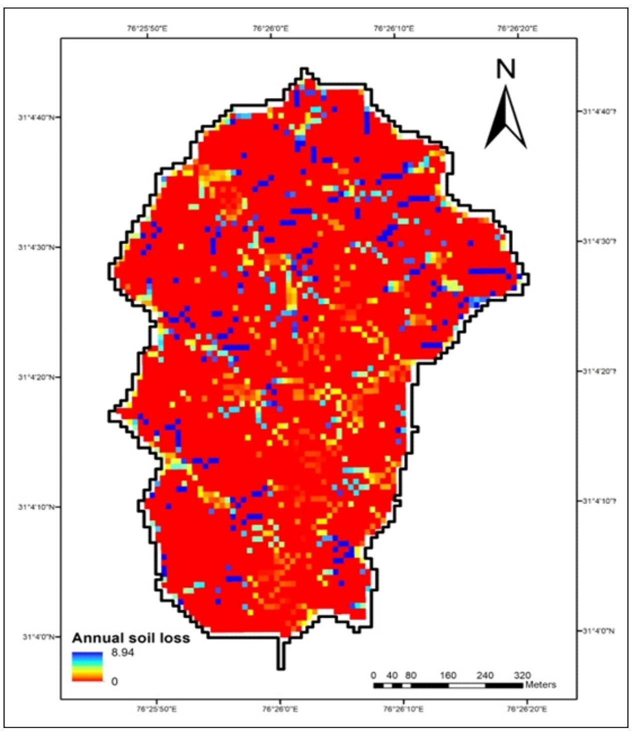

Fig. 7. Average annual soil loss map of the study area

Table: 4
Average annual soil loss and sediments accumulated in the dam

Parameters	Value
Average annual loss (t ha^{-1}yr^{-1})	8.94
Sediment delivery ratio (-)	0.581
Sediment yield (t ha^{-1}yr^{-1})	5.33
Total sediments accumulated in 20 yrs (t)	209926.6

delivery ratio and annual soil loss computed from RUSLE and found that 96% of eroded materials were redeposited in the watershed. According to Ouyang and Bartholic (1997), watersheds with steep slopes, smaller drainage areas, and fields that are close to streams transport sediment at a higher rate than those with flat, wide valleys, big drainage areas, and fields that are far from streams. Similarly, the findings of this study from the above map demonstrated that SDR values in the steeper, fields with close proximity to the stream, and narrower upper catchment of the watershed are higher than those in the middle and lower catchments of the watershed, which are flatter and wider. Therefore, it is important to implement the proper soil and water conservation measures in the steeper slopes and carry out the drainage line treatments for effective soil erosion control (Sudhishri and Dass, 2012).

4. CONCLUSIONS

The present study was conducted to determine the soil erosion and sediment yield of earthen dam located in Kandi region of Punjab. The RUSLE has been integrated with SDR models in GIS to estimate the sediment yield. The results of the study revealed that the average annual soil loss varied from 0-8.94 t ha^{-1}yr^{-1}. The highest soil erosion was found in areas with high LS factor. This suggests that proper soil conservation structures including check dams may be constructed on erosion prone areas which would reduce the soil erosion and sediment yield. Further, it is recommended to carry out the desiltation of earthen dam to increase its capacity. It can be concluded that the application of remote sensing and GIS enables fast and reasonably accurate estimation of soil erosion and sediment yield.

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