



Modeling sedimentation in small water harvesting structures using RUSLE, SDR and GIS in Kandi region of Punjab

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ABSTRACT

Sedimentation is one of the major factors reducing the storage capacity and operational life of small water harvesting structures in the *Kandi* region of Punjab. This study aimed to estimate soil erosion, sediment yield, and reservoir sedimentation in the water harvesting structures located in villages Ballawal and Malewal using the Revised Universal Soil Loss Equation (RUSLE), Sediment Delivery Ratio (SDR), and Geographic Information System (GIS) techniques. The RUSLE model was used to estimate spatial soil loss by integrating rainfall erosivity, soil erodibility, topography, land use/land cover, crop management and conservation practice factors. Sediment yield was computed using empirical SDR methods, and the sediment deposition in the reservoirs was estimated over a 20-year period. The average annual soil loss was estimated to be 12.64 and 14.22 t ha⁻¹ year⁻¹ for the Ballawal and Malewal watersheds, respectively. The average SDR values were 0.634 and 0.569, indicating considerable sediment transport from the catchments to the reservoirs. Based on these estimates, approximately 1.9 lakh tonnes of sediment are expected to accumulate in the Ballawal reservoir and 1.8 lakh tonnes in the Malewal reservoir over 20 years, leading to a substantial reduction in storage capacity. The findings demonstrate that small water harvesting structures play an important role in reducing runoff velocity and trapping sediments; however, periodic desilting and integrated watershed management practices are essential to maintain their efficiency. The RUSLE–SDR–GIS framework developed in this study provides a practical and cost-effective tool for predicting sedimentation and prioritizing soil and water conservation measures in erosion-prone watersheds.

Keywords: Check dams, Earthen dams, RUSLE, GIS, SDR, Kandi

INTRODUCTION

Soil erosion is a relentless menace to land, inland waters, and marine ecosystems around the world (Sharma *et al.*, 2022). Soil erosion poses a big challenge for the management of natural resources as it directly affects the water quality, capacity of water reservoirs (rivers, dams, etc.) and other human

activities (Eniyew *et al.*, 2021). With the increasing population, soil erosion endangers the global food security with about 80% of agricultural land facing threat of moderate to severe erosion and reduction in global crop production by 0.4% (FAO, 2019). Climate forecasts show a trend towards a more intense hydrological cycle, which could amplify

magnitude of water erosion worldwide for all global dynamic scenarios (Borrelli *et al.*, 2020). Soil erosion has resulted in annual financial loss of about US \$400 billion due to loss of 75 billion tonnes of fertile soil from the cultivated lands across the world (GSP, 2017). About one billion people worldwide are affected by soil erosion, out of which almost 50% of the susceptible population dwell in African continent (Blanco-Canqui and Lal, 2008). The situation is no good in Asian countries including India, as slight increase in eroded area (roughly 1%) is expected in Asia, due to a considerable augmentation in soil erosion in countries such as China (2%) and India (0.45%). In India, about 120.7 million ha area (about 36.6% of total geographical area) is affected by land degradation, out of which 68.4% is affected by the water erosion. As a result, the average annual rate of soil erosion in India is 1559 Mg km⁻² year⁻¹ (Sharda and Ojasvi, 2016). About 7.2 million tonnes of the main crops are lost due to the soil erosion annually which accounts to 1 to 1.7% loss in annual Gross Domestic Production (GDP). In addition to this, soil erosion results in the loss of about 74 million tonnes of major nutrients in soil annually (Reddy, 2003). The *Shivalik* foot-hills, located in north-west India, is regarded as one of the most degraded ecosystems of the country. The region is characterized by extreme rainfall events, steep and undulating, lack of vegetation cover which makes the region highly vulnerable to the soil erosion (Yousuf *et al.*, 2022). About 30% of the rainfall received in *Shivalik* foot-hills is lost as surface runoff taking away large quantities of top nutrient-rich soil. Therefore, various forms of land and water management strategies are needed in the region to reduce the soil erosion hazard. The appraisal of soil erosion and its spatial distribution is important for proper implementation of soil and water conservation measures. Various hydrological models, including USLE, RUSLE, MUSLE, WEPP, SWAT, ANSWERS, etc. have been devised to predict the soil erosion. These hydrological models have varying degrees of complexities, and data requirement for their application. Among many available models, Revised Universal Soil Loss Equation (RUSLE) is one of the most extensively used empirical models to assess the soil loss from the watersheds. The model estimates the average annual soil loss by taking into account the climatic and various watershed characteristics (Yousuf *et al.*, 2025). RUSLE estimates soil loss by considering the effect of various factors, including climate,

topography, soil and land use and management practices on soil erosion (Renard *et al.*, 1991).

The Remote Sensing (RS) and Geographic Information system GIS has found an enormous application in the soil erosion estimation and identification of the erosion prone areas (Ganasri and Ramesh, 2016). Hydrological models in conjunction with RS and GIS, not only helps to estimate soil loss but also identifies the erosion hotspots by giving the spatial distribution of soil erosion (Chen *et al.*, 2019). The application of RS and GIS has made it possible to conduct the erosion studies over the large areas. The Digital Elevation Models (DEMs) have been used to extract the topographic characteristics including flow direction and accumulation, slope, aspect and drainage networks of the watersheds for assessment of soil erosion. The use of geospatial technique and RUSLE model is an advantageous combination and widely used method owing to its simpleness and applicability over large-scale areas with better reliability and cost-effectiveness. The capabilities of empirical models such as RUSLE increase manifold when integrated with RS and GIS. The RUSLE integrated with GIS predicts the soil erosion on a cell-by-cell basis, which helps in identifying and prioritizing the erosion hotspots within the large watersheds (Thapa, 2020). RUSLE and GIS have been applied worldwide in different scales including plots, watershed and large catchments (Renard *et al.*, 1991; Prasannakumar *et al.*, 2012; Ranzi *et al.*, 2012; Wijesundara *et al.*, 2018; Das *et al.*, 2021). RUSLE estimates the average annual soil loss rather than the sediment yield; therefore, sediment delivery ratio was coupled with RUSLE to estimate the sediment yield. Many researchers have used such approach for sediment yield estimation (Gelagay, 2016; Ebrahimzadeh *et al.*, 2018; Singh *et al.*, 2019; Yousuf *et al.*, 2022 and Yousuf *et al.*, 2023). Keeping in view the applicability and efficiency of RUSLE and GIS for assessment of soil erosion across the world, the present study was conducted to assess the soil loss from two water harvesting structures located in *Kandi* region of Punjab.

MATERIALS AND METHODS

Study area

The present study was undertaken on two small water harvesting structures located in villages Ballowal Saunkhri and Malewal of District Shaheed

Bhagat Singh Nagar of Punjab in *Kandi* region of Punjab (Fig. 1). The weather in the region is subhumid with cold winters and hot summers. The average annual rainfall of the region varies between 900-1100 mm, out of which around 80% is received during the monsoon season (Kaur *et al.*, 2021). The soil texture of the study areas is primarily sandy loam while as forest is the major landuse. The characteristics of the selected water harvesting structures are given in Table 1.

DATA COLLECTION

Rainfall

The erosion process is primarily dependent on the rainfall of the region. In other words, rainfall is the principal cause of the soil erosion. The rainfall data for the present study was obtained from the Punjab Agricultural University-Regional Research Station, Ballawal Saunkhri. The data so obtained

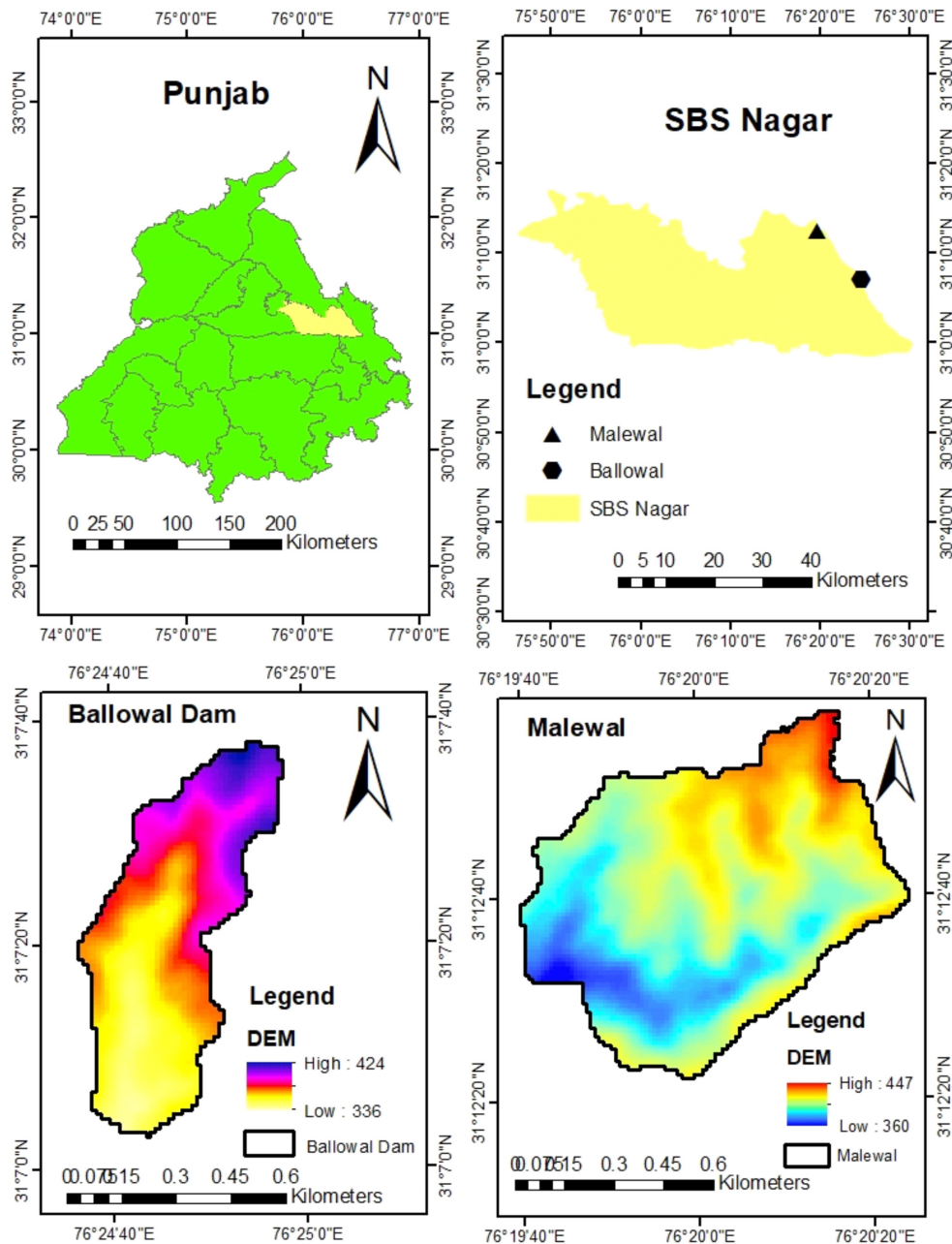


Fig. 1. Map of study area

Table 1. Characteristics of selected dams

Name	Type of WHS	Height of dam (m)	Width of dam (m)	Catchment area (ha)
Ballowal	Check dam	3	10	32.8
Malewal	Earthen dam	6	35	77.3

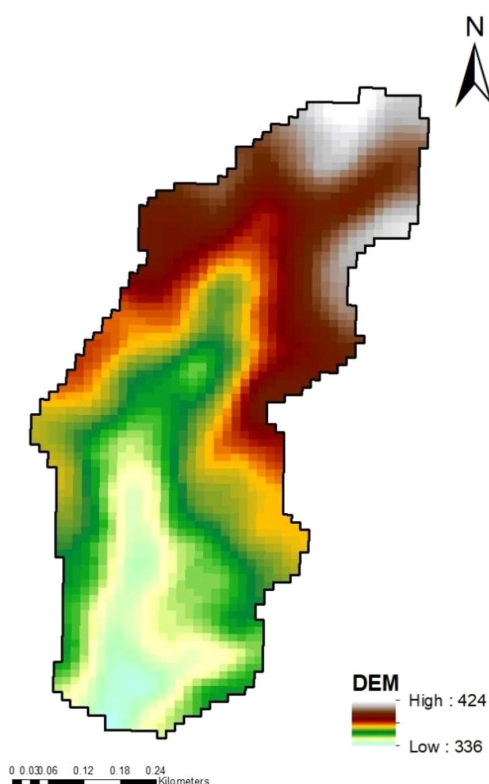
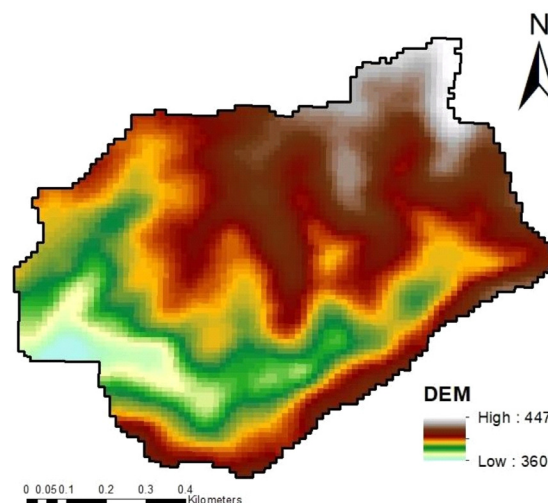
was used to compute the rainfall erosivity, which is required as an input to the RUSLE model.

Land use and landcover

A 10-m high-resolution cloud free Land Use/Land Cover (LULC) map for the year 2022 was downloaded from Earth and Environmental Systems Research Institute (ESRI) portal for the study areas.

Slope

Soil erosion is highly influenced by slope of the watershed as it affects the hydrological response of the watershed. The information on topography is imperative to understand the erosion process in the watershed. The high resolution (12.5 m), freely available, ALOS PALSAR digital elevation model (DEM) was used to generate the slope of the study areas using ArcGIS 10.4 software. The DEM of study watershed is given in Fig. 2 and Fig. 3.

**Fig. 2.** DEM of Ballawal dam**Fig. 3.** DEM of Malewal dam

Soil

Soil sampling of the selected dams was carried out to determine the soil characteristics. Ten samples were taken from each dam catchment from two soil depths (0-15 cm, 15-30 cm). The soil samples were analyzed for various physico-chemical properties in soil laboratory of RRS Ballawal Saunkhri.

Revised Universal Soil Loss Equation (RUSLE) Parameter Estimation

RUSLE is one of the most extensively used empirical soil erosion to estimate the average annual soil erosion rates (Renard *et al.*, 1991). The model uses the data of five parameters including rainfall, soil, topography, LULC and conservation practices. In the present study, RUSLE model has been used to estimate the average annual soil erosion. The RUSLE model is expressed as:

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

A is the average annual soil loss per unit area ($\text{t ha}^{-1} \text{ year}^{-1}$), R is the rainfall-runoff erosivity factor ($\text{MJ mm ha}^{-1} \text{ h}^{-1} \text{ year}^{-1}$), K is the soil erodibility factor ($\text{t ha h MJ}^{-1} \text{ mm}^{-1}$), LS refers to slope length and steepness factor (dimensionless), C is the cover management factor (dimensionless), and P is the support and conservation practices factor (dimensionless).

Rainfall Erosivity Factor (R)

The rainfall erosivity factor (R) symbolizes the kinetic energy or erosive power of the raindrops, and is identified as the main force which is responsible for the soil erosion (Nampak *et al.*, 2018). The numerical value of R enumerates the impact of the raindrop and signifies the quantity and amount of runoff that can be associated to the definite amount of the rainfall (Renard *et al.*, 1991). In the present study, mean annual rainfall data of 10 years (2011-2020) was used to compute the R factor using the equation (Pal *et al.*, 2016):

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

Where,

R is the rainfall erosivity factor (MJ mm ha⁻¹ h⁻¹ year⁻¹), P is the annual rainfall (mm). The tabulated and analysed data (in MS excel) was imported into the ArcGIS as .csv file. The Inverse Distance Weighted (IDW) was used to interpolate the calculated R factor to generate the raster layer of R factor.

Soil erodibility factor

The soil erodibility factor (K) reveals the resistance of soil to detachment and transportation and determines the vulnerability of soil to get eroded (Fenta *et al.*, 2016). The value of K generally varies from 0 to 1 and primarily depends on the soil characteristics, including soil texture, unsaturated hydraulic conductivity and organic matter. The soil sampling was carried out to determine the soil texture and the data obtained was used to calculate soil erodibility factor. The values of soil textural class, structure code (S) and permeability (P) were calculated using USDA soil texture triangle. The erodibility factor was calculated using the following equation:

$$K = (M^{1.14} \times (19 - OM) \times (0.00000028 + 0.0043) \times (S - 1) + 0.0033 \times (P - 3))$$

Where, K is the soil erodibility factor in t ha⁻¹ MJ⁻¹ mm⁻¹, M is particle size parameter and is given by (% silt + % sand) × (100 - % clay), OM is the organic matter (%), S is the soil structure code and P is the soil permeability class.

Slope Length Steepness Factor (LS)

The LS-factor combines the slope length (L) and slope steepness (S) factors and signifies the effect of slope length and steepness length on the soil erosion

(Amsalu and Mengaw, 2014). In the present study, LS factor was estimated using “flow accumulation” raster. The flow accumulation raster contains information on the cumulative number of pixels that contributes flow into a particular cell. The flow accumulation matrix is obtained using the “flow direction matrix”. The “flow direction matrix” determines the natural drainage direction for every cell in a DEM (Yousuf and Bhardwaj, 2022). Based on flow accumulation matrix, pixel size and slope of each pixel, the LS was calculated in ArcGIS using the “raster calculator” by applying the the following equation (Panagos *et al.*, 2015).

$$LS = (\text{Flow accumulation} * \frac{\text{Cell size}^{0.2}}{22.13})$$

$$*(0.065 + 0.045 * \text{slope degree} + 0.0065 * (\text{slope})^2)$$

Where Flow accumulation is the accumulated-up slope contributing area for a given cell, Cell size is the size of grid cell (for this study 12.5×12.5 m) and slope is the cell slope (in degrees).

Crop Management Factor (C)

The cover management factor (C) determines the impact of LULC on the soil erosion by dissipating the kinetic energy of the raindrops and prevents the direct impact of raindrops on the soil surface (Sujatha and Sridhar, 2018). The plant material in contact with the soil surface protects the soil from raindrop/splash erosion and acts a hinderance to the free flow of surface runoff. It depends on type, growth stage and cover extent of landuse and represents the effects of plants, soil biomass and soil disturbing activities on erosion (Chen *et al.*, 2019). The value of C factor varies between 0 and 1, and the value closer to 1 indicates susceptibility of the land for erosion (Ganasri and Ramesh, 2016). In the present study, the value of C was taken as 0.003 for the forest land use type (Wijesundara *et al.*, 2018).

Support and Conservation Practices (P)

The support and conservation practices factor (P) reflects the impact of different conservation practices on the soil erosion. It is an imperative deliberation of the RUSLE model, and is expressed as “the ratio of soil loss with a specific supporting practice to the corresponding loss without any supporting practices.” The values of P factor vary between 0 and 1. The higher values of P factor characterizes the area/watershed where no

conservation practices have been implemented (Renard *et al.*, 1991). In the present study, the value of P factor was assigned as one for forest landuse.

Average Annual Soil Loss (A)

The estimated factors of RUSLE were taken as various layers in map calculator to estimate the average annual soil loss and its distribution in the study area. The raster layers of factors R, K, C and P were in 10 m × 10 m resolution, whereas, the DEM (and hence LS factor) was in 12.5m × 12.5 m resolution. Therefore, the DEM was resampled into 10 m × 10 m using the “bilinear method” to create the LS map for the perfect overlay analysis. The pixel-based information of each individual factor of the RUSLE model was used to compute the average annual soil loss rate for each pixel at 10 m × 10 m resolution.

Sediment yield

Estimation of sediment yield (SY) in different temporal and spatial scales is quite a demanding task since it has a pivotal role for the assessment and designing of soil erosion protection structures (Kaliraj *et al.*, 2025). The RUSLE model is an estimator of soil erosion but not sediment yield. Sediment yield (i.e., net erosion) is the portion of eroded soil (i.e., gross erosion) that is not deposited into the watershed while being transported to the watershed or catchment outlet that reaches the downstream area. The amount of sediment yield can be directly observed and measured in the field and can, therefore, be applied for validation. Although sediment yield cannot be directly derived from RUSLE modeling, the integration of RUSLE and the sediment delivery ratio (SDR) can estimate sediment yield. The SDR, which is the ratio between the sediment yield (i.e., net erosion) and gross erosion, can be expressed as follows:

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

Where, represents the sediment delivery ratio, S_y represents the sediment yield (i.e., net erosion or sediment transportation), and E represents the average gross erosion for the entire watershed (i.e., average water erosion). Therefore, the sediment yield can be obtained via the following equation:

$$S_y = SDR \times E$$

The gross erosion for the entire watershed (E) can be estimated from RUSLE. To estimate the sediment yield, the SDR must be calculated first. The SDR value shows the topographic ability of the drainage area for transporting and sedimentation of eroded soil. The amount of sediment stored within the drainage basin is affected by slope length, sediment particle size, runoff- rainfall and land use and land cover management. The average SDR was computed using seven different empirical equations derived from field experimental data developed by Vanoni, (1975), Renfro, (1975), USDA SCS, (1979), USDA, (1972), Ouyang and Bartholic, (1997) and Maner, (1962) separately (Table 3).

RESULTS AND DISCUSSION

RUSLE parameters

The average annual rainfall of the region is about 1051 mm and the rainfall erosivity varies from 458.33 to 460.51 MJ mm ha⁻¹ h⁻¹ yr⁻¹ (Fig. 5a and Fig. 6a). The R factor was almost constant for both the watersheds due to same amount of rainfall in both the watersheds. Similar, R factor values were found in Kandi region by Yousuf *et al.*, 2022 and Yousuf *et al.* 2023. Similarly, Kumar and Kushwaha, (2013) obtained a value of 383 MJ mm ha⁻¹ h⁻¹ yr⁻¹ in a study conducted in the *Shivalik* Himalayan region. The K factor varied from 0.18 to 0.22 for the study areas (Fig. 5b and Fig. 6b) indicating the vulnerability of soils for erosion. The LS factor varied from 0.1 to 51.2 for Ballowal and 0.1 to 17.42 for Malewal dam (Fig. 5c and Fig. 6c) indicating that the Ballowal watershed is having steeper slopes compared to Malewal. Higher values of LS factor

Table 3. Sediment Delivery ratio formulae

Method	Formulae	Description
Vanoni (1975)	$SDR = 0.472A^{-0.125}$	A: Area (km 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)	$\log \log(SDR) = 1.7935 - 0.14191 \log(A)$	A: Area (km ²)
Maner (1962)	$\log(SDR) = 1.8768 - 0.14191 \log(10A)$	A: Area (mi ²)

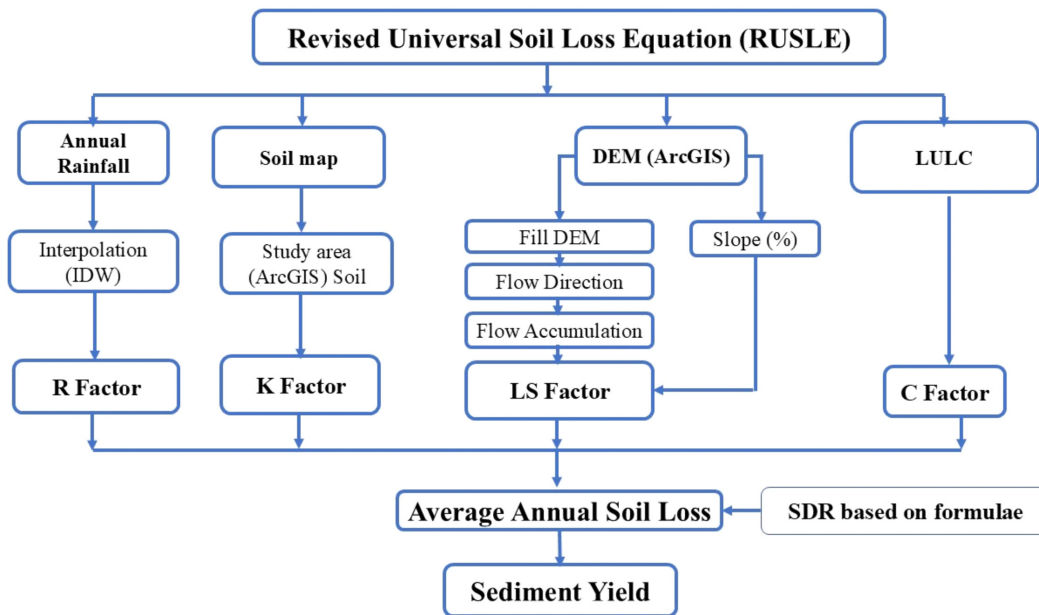


Fig. 4. Methodology adopted for estimation of sediment yield

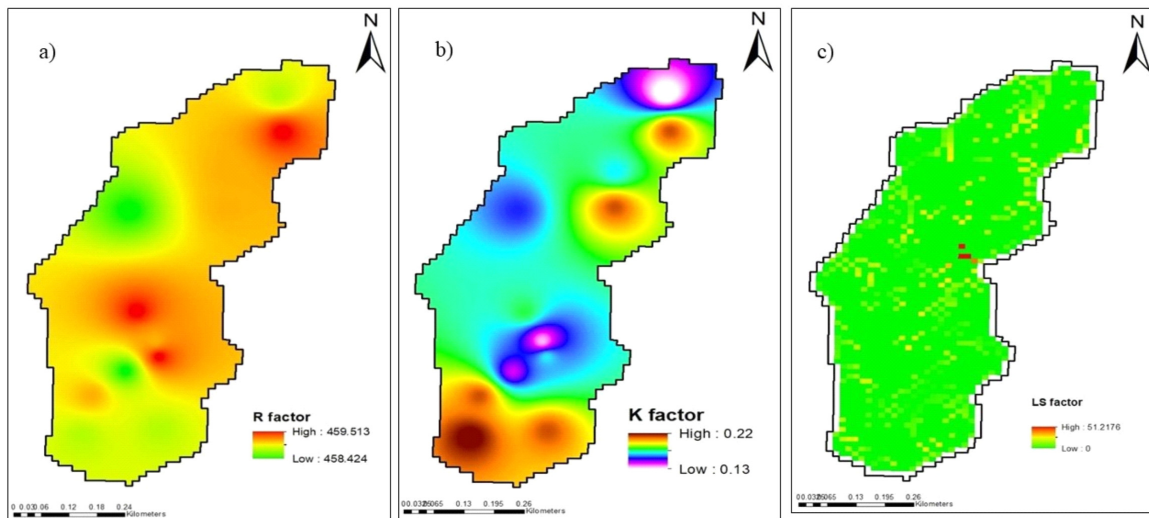


Fig. 5. a) Rainfall erosivity factor b) soil erodibility factor and c) Slope Length and Steepness factor for Ballawal dam catchment

indicate higher slope percentage which makes the area more prone to soil erosion. The C factor, which depends on the LULC of watershed was taken as 0.003 for the forest landuse and P factor was taken as one for both the watersheds.

Soil erosion and sediment yield

RUSLE estimated the total average annual soil loss for both the watersheds. The average annual soil loss varied from 12.64 to 14.22 t ha⁻¹ year⁻¹ for Ballawal and Malewal, respectively (Fig. 7). The sediment delivery ration varied from 0.728 to 0.491

for Ballawal while as the values ranged between 0.645 and 0.441. The average SDR value was found to be 0.634 and 0.569 for Ballawal and Malewal respectively. Among the methods used for SDR calculations, maximum values were given by Renfro, (1965) and Maner, (1962) while as minimum values were given by Vanoni, (1965). The estimate shows that about 1.9 lakh tonnes of sediments will be deposited in Ballawal (check) dam while as in Malewal (earthen) dam, 1.8 lakh tonnes of sediments are expected to accumulate in 20 years. These findings emphasize the need for periodic desiltation

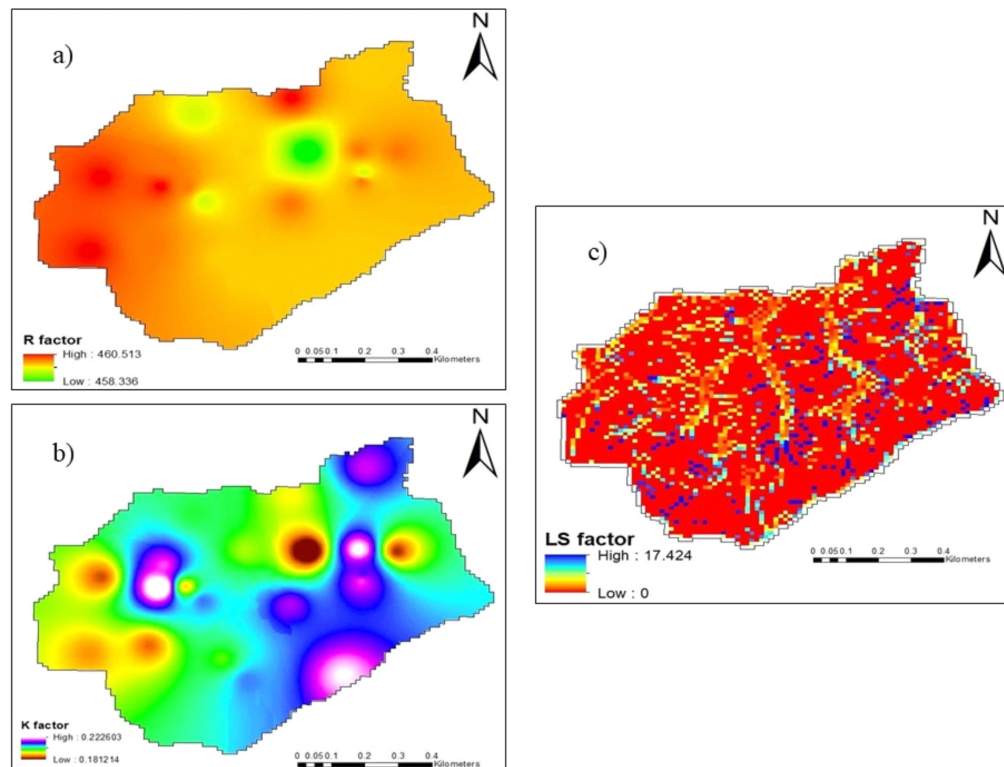


Fig. 6. a) rainfall erosivity factor b) soil erodibility factor and c) Slope Length and Steepness factor for Malewal dam catchment

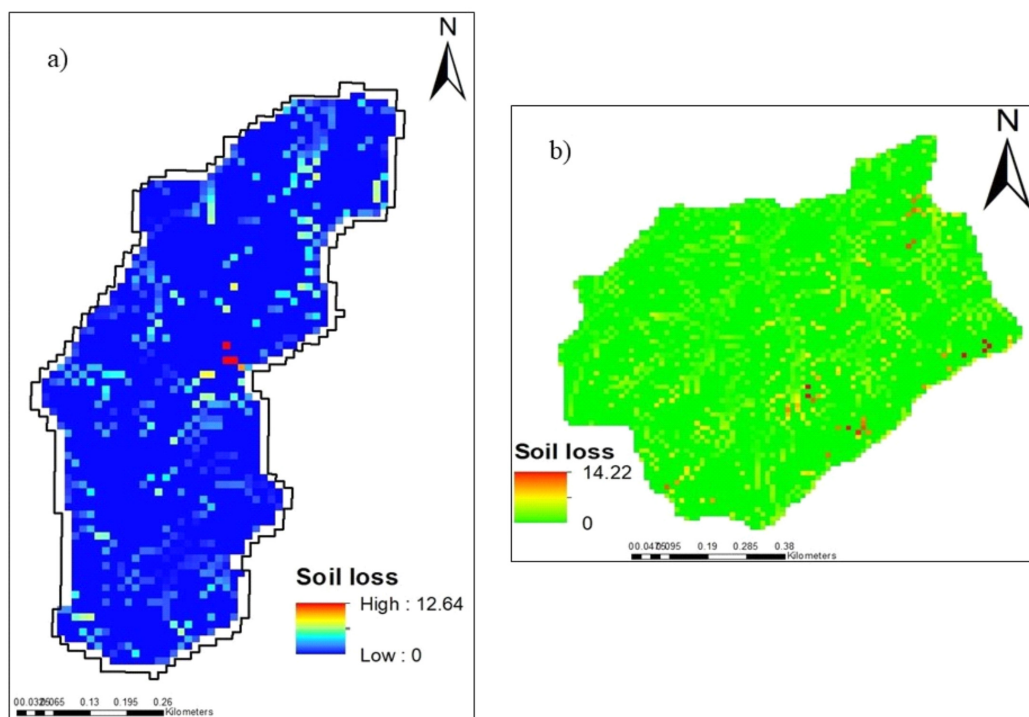


Fig. 7. Average annual soil loss for a) Ballawal dam and b) Malewal dam

Table 4. Sediment delivery ratio for study dams

Methods	Ballawal	Malewal
Vanoni (1975)	0.491	0.441
USDA SCS (1979)	0.640	0.583
USDA 1972	0.639	0.582
Renfro (1975)	0.728	0.645
Maner (1962)	0.728	0.645
Average	0.634	0.569

and the implementation of integrated watershed management practices, including afforestation, vegetative barriers, and gully stabilization, to minimize sediment generation at the source. Furthermore, the presence of check dams within the drainage network contributes to sediment trapping by reducing runoff velocity and flow energy, thereby lowering the sediment transport capacity of the channels. This demonstrates the effectiveness of small hydraulic structures not only in water conservation but also in mitigating downstream sedimentation.

Small water harvesting structures such as earthen dams, check dams and farm ponds play a crucial role in controlling soil erosion and enhancing watershed sustainability in the *Kandi* region. By intercepting surface runoff, these structures reduce peak discharge, decrease flow velocity, and dissipate the erosive energy of runoff before it reaches downstream channels. Consequently, they promote the deposition of suspended sediments within the structures and reduce sediment transport to larger reservoirs and streams. The retained sediments often contain nutrient-rich topsoil, which can be reused for agricultural purposes, thereby improving soil fertility and reducing land degradation. In addition to sediment retention, water harvesting structures facilitate groundwater recharge by increasing the residence time of runoff, improve soil moisture availability, and enhance vegetation growth, which further stabilizes the soil and reduces erosion. When implemented as part of an integrated watershed management strategy alongside biological measures such as afforestation, contour cultivation, grassed

waterways, and vegetative filter strips, these structures substantially reduce sediment yield from the catchment. Therefore, the construction and maintenance of appropriately designed water harvesting structures represent an effective and sustainable approach for mitigating soil erosion, conserving water resources, and extending the operational life of reservoirs in the highly erosion-prone Shiwalik foothills of Punjab.

Based on the estimated rates of soil loss and reservoir sedimentation, a combination of structural and non-structural soil conservation measures is recommended to reduce sediment inflow into water harvesting structures (WHS). Priority should be given to treating erosion hotspots identified through the RUSLE-GIS analysis by implementing contour bunding, graded bunds, vegetative barriers, contour trenching, terracing on steeper slopes, and gully control structures. Afforestation and assisted natural regeneration in degraded upper catchments should be promoted to increase vegetation cover and reduce raindrop impact and surface runoff. Periodic maintenance of existing check dams, silt traps, and diversion channels is essential to sustain their sediment-trapping efficiency. In addition, scheduled desilting of water harvesting structures, particularly before the onset of the monsoon, should be undertaken based on sediment accumulation surveys using bathymetric measurements or remote sensing techniques. The excavated sediment, being rich in organic matter and nutrients, can be beneficially reused as a soil amendment in nearby agricultural fields, thereby reducing disposal costs and improving soil productivity. Establishing a long-term sediment monitoring programme using GIS and remote sensing, coupled with community participation and regular maintenance, will enhance the operational lifespan, storage efficiency, and overall sustainability of water harvesting structures in the *Kandi* region. The integration of RUSLE, GIS, and SDR models provides a practical and cost-effective framework for predicting long-term sediment yield and reservoir sedimentation, supporting informed decision-making for the planning, design, and maintenance

Table 5. Soil erosion and sediment yield

Parameters	Ballawal	Malewal
Average annual soil loss ($\text{t ha}^{-1} \text{ year}^{-1}$)	12.64	14.22
Sediment Delivery ratio (-)	0.634	0.569
Sediment yield Average annual loss ($\text{t ha}^{-1} \text{ year}^{-1}$)	8.01	8.09
Total sediments accumulated/to be in 20 years (t)	190068.1	188481.54

of water harvesting structures in erosion-prone Himalayan foothill watersheds.

CONCLUSIONS

The integration of RUSLE, SDR, and GIS is an effective approach for estimating soil erosion, sediment yield, and reservoir sedimentation in small water harvesting structures of the Kandi region of Punjab. Moderate to high soil erosion, with substantial sediment deposition expected in both reservoirs over their operational life, highlighting the need for timely sediment management. The study also emphasizes the role of water harvesting structures in reducing runoff velocity, trapping sediments, and conserving soil and water resources. Adoption of integrated watershed management practices, along with periodic desilting and maintenance of existing structures, is essential to enhance their storage efficiency and longevity. The developed methodology provides a practical decision-support tool for prioritizing soil and water conservation measures and can be applied to similar erosion-prone watersheds for sustainable watershed management.

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