Arab J Geosci. manuscript No.
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Sediment Yield Assessment and Identification of Check Dam Sites for Rawal Dam Catchment

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Received: date / Accepted: date

Abstract Sediment yield is the amount of erosional debris from drainage basin deposited in reservoirs. The economic life of storage reservoir depends upon the estimation of the time it takes for the reservoir to be filled with the deposition of sediments. This research is based on assessing the sediment yield in Rawal Dam catchment by using Soil and Water Assessment Tool (SWAT) model. Digital Elevation Model (DEM), land use maps, soil maps, and weather data of the study watershed were used as input to SWAT model. Monthly sedimentation data of year 2010 and discharge data from 1998-2005 is being used for model calibration and validation respectively. Whereas simulations are being generated from 1998-2011 for both sedimentation and discharge. Modified Universal Soil Loss Equation (MUSLE) was used for the estimation of sediment yield. The Nash and Sutcliffe coefficient of the model was found to be 0.79 which depicts its effectiveness. After the estimation of the sediment yield and discharge by using SWAT model, double mass curve was used to evaluate the sedimentation rate. The rate of sediment transport can be reduced by the construction of check dams. Various sites have also been proposed for check dams construction to prevent the sediments transported into the Rawal Catchment.

Keywords Sediment yield · SWAT model · watersheds · DEM, Double mass curve · MUSLE · Rawal Dam

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1 Introduction

Soil erosion is one of the most serious environmental problems. It results in soil degradation and increases the natural level of sedimentation in rivers and reservoirs which reduces their storage capacity and life span [3]. Soil erosion is an important item of consideration in the planning of watershed development [1]. About 85% of global land degradation is associated with soil erosion [22,4,5]. Out of total geographical area of 79.61 Mha, the suitable area for agriculture in Pakistan is about 29.37 Mha while 50.24 Mha is uncultivated [10]. Almost 15.9 Mha of total land (20% of total) is affected by soil erosion and out of this 11.2 Mha (70%) is affected by water erosion [21].

Sediment yield refers to the amount of sediment exported at the basin outlet over a period of time. It is also referred as the amount which would enter into a reservoir located at the downstream limit of the basin [19]. To calculate the sedimentation yield total area under the watershed and the mass of area flow out due to runoff are required. It is measured in ton per hectare. All the soil particles eroded from a watershed are not transported to the outlet due to their trapping and deposition in the upstream reaches. Estimates of sediment yield are needed for the studies of reservoir sedimentation, river morphology and planning of soil and water conservation measures [6]. Apart from rainfall and runoff, the erosion rate of an area also depends upon its soil, vegetation and topographic characteristics. These characteristics vary greatly within the various segments of a catchment [14].

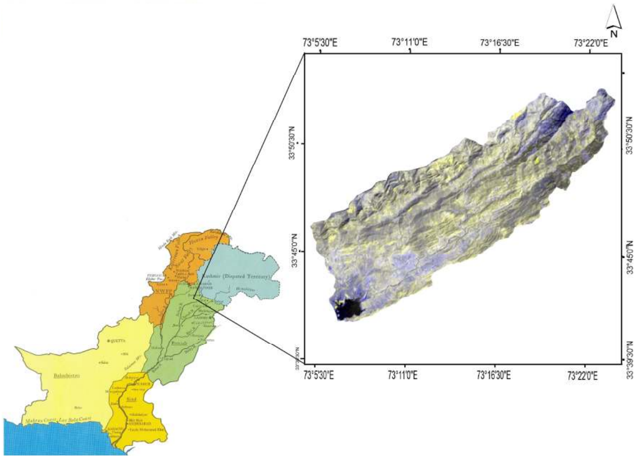


Fig. 1 Study area. Source: `http://www.izhar.com/cms/Maps.aspx`

A number of Models have been developed to measure the soil erosion and sediment yield index. In this research we used SWAT model to measure the sediment yield index in Rawal catchment area (Fig. 1). A SWAT model can be built by using the Arc-map (Arc Hydro) interface which provides suitable means to enter data into the SWAT code. Input data of the SWAT model were prepared using remote sensing (RS), geographical information system (GIS) and image processing softwares. The advent of Remote Sensing images from satellite based platforms has provided opportunities for extraction of up-to-date information on land use and soils of a watershed which can be used to identify critical soil erosion areas within the watershed for prioritization [24]. The recent advancements in satellite imaging with respect to spatial resolution has provided additional advantages of obtaining information at micro level [8]. The remote sensing and GIS techniques are being utilized in various domains of life e.g., [13, 30, 31, 11, 33]. They have also eased the estimation of soil erosion and its spatial distribution, and it can be achieved at a reasonable cost and with high accuracy and in larger areas [18, 34].

2 Description of Study Area

The study was applied on Rawal Dam catchment area shown in Fig. 1. The Rawal watershed is facing risks of rapid urbanization and deforestation, due to which the land use of watershed is changing. This situation is ultimately affecting the climate and the watershed health, i.e., Rawal lake storage-capacity has been reduced by 34% due to sedimentation [23]. Rawal watershed, as shown in Fig. 1, lies within longitudes 73° 03′ - 73° 24′ E and latitudes 33° 41′ - 33° 54′ N in the Pothwar region of Pakistan [27].

Rawal Lake is the main source of water supply for Rawalpindi city. It is situated in the capital territory of Islamabad at 33° 41′ 47.18″ N latitude and 73° 08′ 07.64″ E longitude and at an Elevation of 1,728 ft. above mean sea level. The lake is located on Korang River and has a catchment area of 106 sq. miles, which generates 84,000 cubic feet of water in an average rainfall year. There are four major streams and 43 small streams contributing to its storage. Its total storage capacity is 47,500 acre feet and live storage is 43,000 acre feet [17].

3 Methodology

In order to estimate the sediment yield, RS and GIS data was processed to meet the input data requirements of SWAT model. SWAT is a continuous time, physically based hydrological model developed by the United States Department of Agriculture - Agricultural Research Service (USDA-ARS) [2]. The catchment is divided into several hydrological response units (HRUs) based on soil type, land use and slope classes. The eroded sediments at HRUs level are routed along the channels to the outlet of the catchment. The major model components include: hydrology, weather, soil erosion, nutrients, soil temperature, crop growth, pesticides agricultural management, and stream routing. The model predicts the hydrology at each HRU using the water balance equation which includes daily precipitation, run-off, evapotranspiration, percolation, and return flow components [6]. This study mainly aims at:

- Sediment yield calculation by using MUSLE;
- Estimation of the temporal change in sedimentation yield by using double mass curve;
- Validation of SWAT model results by using Nash-Sutcliffe coefficient, root mean square error (RMSE) and regression analysis;
- Identification of check dam sites for controlling sedimentation in Rawal Lake.

3.1 Sediment Yield Calculation by Using MUSLE

MUSLE is used to estimate the sediment yield of Rawal catchment. It is computed by using the runoff and peak runoff rates measured at the outlet of the study watershed. In general, MUSLE can be expressed as:

$$Y = 11.8 \times (Q \times q_p)^{0.56} \times K \times LS \times C \times P \qquad (1)$$

where Y is sediment yield in tones, Q is volume of runoff in cubic meters, q_p is peak flow rate in cubic meters per second. K is the soil erodibility factor which is the erosion rate per unit of erosion index for specified soil in cultivated continuous fallow having 9% slope and 22.13 m length. LS is the slope length and gradient factor. It is the ratio of soil loss from the field slope length and gradient to that from 22.13 m length on the same soil type with a 9% slope. C is the

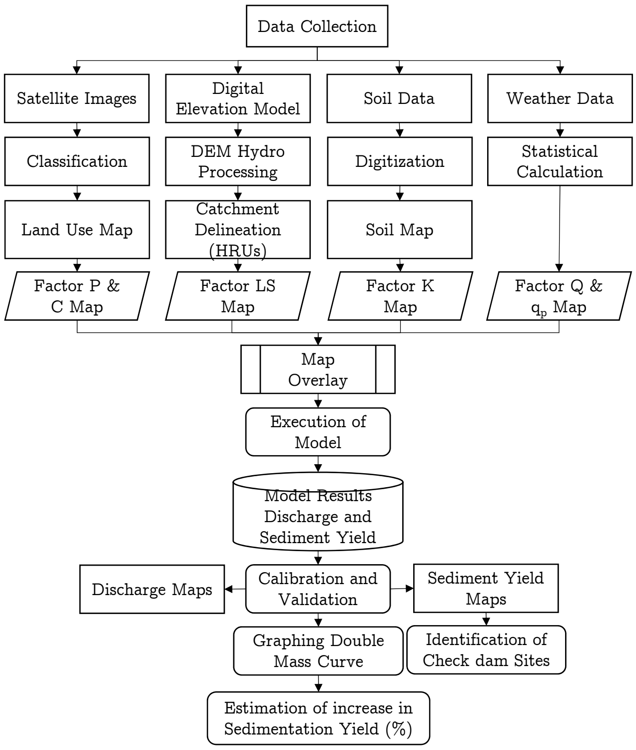
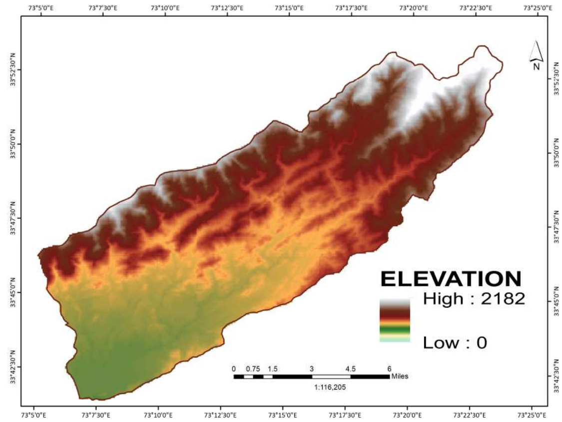


Fig. 2 Methodology

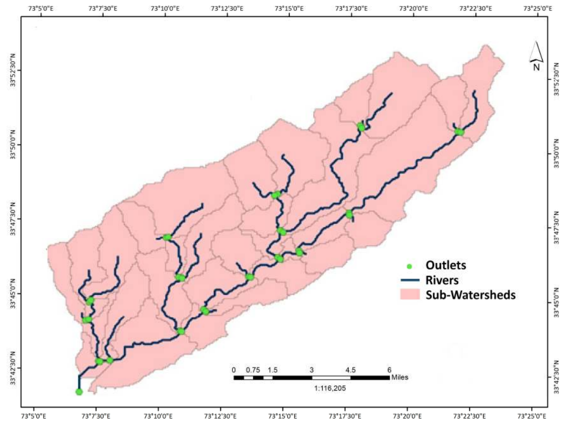
cropping management factor defined as the ratio of soil loss from a field with a specified cropping and management to that from the fallow condition for which the factor *K* is evaluated. *P* is the erosion control practice factor which is the ratio of soil loss with contouring, strip cropping, or terracing to that with straight row farming, up and down slope [1].

To fulfill the data requirements of SWAT model, multiple spatial and non-spatial data were processed (Fig. 2 shows the methodology flowchart). Digital Elevation Model (DEM) was processed by using Arc Hydro. Arc Hydro is a model developed for building hydrologic information systems to synthesize geospatial and temporal water resources data that supports hydrologic modeling and analysis. It is used to extract topologic variables from a DEM model for building geometric networks for hydrologic analysis [9, 15]. The DEM allows the estimation of surface area as well as some topographic attributes (e.g., slope, slope length) or characteristics of channel network including length, width, and mean slope gradient [20]. The watershed boundary is automatically derived from DEM following a series of steps such as sink removal, assigning flow direction, and calculation of flow accumulation [28]. In this study, Shuttle Radar Topographic Mission (SRTM) DEM[1] was used for characterization of watershed.

The first step in DEM processing is removal of errors from DEM which is achieved by using fill sinks method. It removes sudden depressions in the DEM by using 8-neighbor pixels. The next step is DEM hydro processing which involves the estimation of flow accumulation, flow direction, and slope, etc. In the next step, the watershed boundary was delineated from the DEM; the drainage network and catchment tables generated by the DEM hydro processing were linked by using common table ID columns. After the delineation of the watershed boundary, the DEM was masked and superimposed on the stream network and the entire study area was divided into 32 Hydrological Response Units (HRU). Fig. 3a shows the DEM of study area and Fig. 3b shows delineated catchment, the stream network and watershed boundaries.



(a)

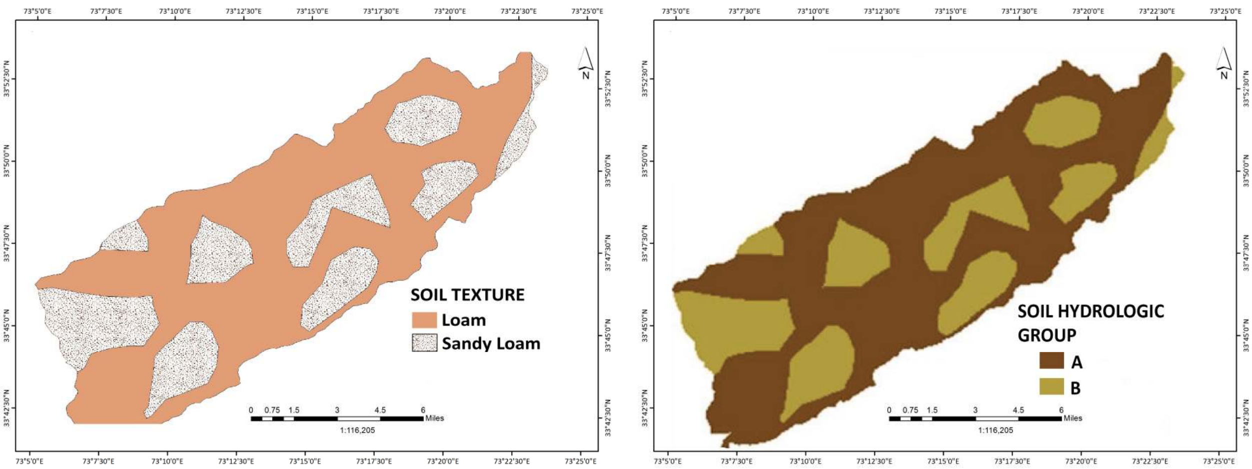


(b)

Fig. 3 (a) DEM of study area, (b) DEM hydro-processing.

There are several soil properties which influence soil erodibility and transportability during run-off, e.g., particle size, organic matter content, structure, soil depth, texture, and mineralogy [25]. The soil erodibility factor (*K*) represents both susceptibility of soil to erosion and the amount and rate of runoff [32]. The value of soil erodibility factor may range from 0.02 to 0.69 [26, 10].

[1] http://srtm.usgs.gov



(a) (b)

Fig. 4 (a) Vector soil map, (b) Soil erodibility factor (K)

In this study, the data source for *K* factor was the soil map prepared by Soil Fertility Research Institute[2]. In Rawal Catchment the dominant soil texture was identified as sandy loam and loam. As the source map was in JPG format it was geo-referenced and digitized in Arc Map and a polygon map was produced consisting of two classes: loam and sandy loam (Fig. 4a). Polygons of these two soil classes were given code numbers. The final vector map was used as an input to Arc SWAT model to obtain *K* factor raster map consisting of soil erodibility factor which is 0.24 inches per hour in loam and 0.15 inch per hour in sandy loam class (see Fig. 4b).

LS factor is the slope length gradient factor. Slope of a terrain generates velocity of the runoff water which affects surface soil detachment. Gentle slope condition may generate less velocity where as steep slope conditions may generate high velocity of the run-off water [25]. The *L* and *S* factors represent the effects of slope length *L* and slope steepness *S* on the erosion of a slope. *LS* factor was calculated by using DEM. Slope length in meters was derived from DEM and it ranges from 9.15 meters to 21.95 meters. As in DEM the elevation value ranges from 507 meters to 2,128 meters, the entire elevation range was classified into 4 classes. First class was of 25% elevation values ranging from 507 to 925 meters, second class was of 25% to 50% of elevation values ranging from 926 to 1,344 meters, third class consisting of 50% to 75% of elevation values ranging from 1,345 to 1,764 meters and the fourth class consisting of greater than 75% elevation values ranging from 1,765 to 2,182 meters. Based upon the slope length and the classified gradient, the *LS* factor was calculated using Arc SWAT and it ranges from 0.48 meters to 21.18 meters as shown in Fig. 5.

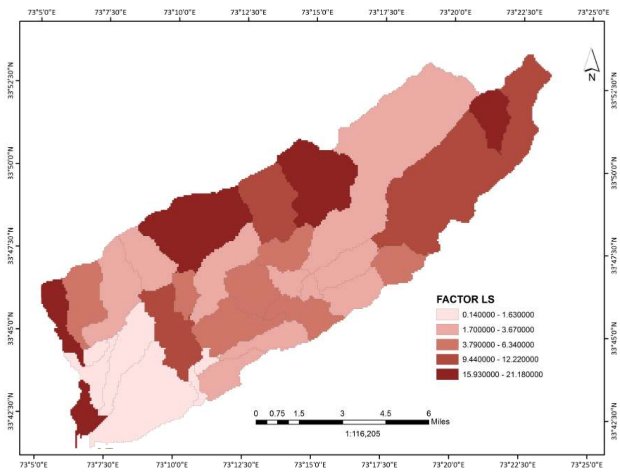


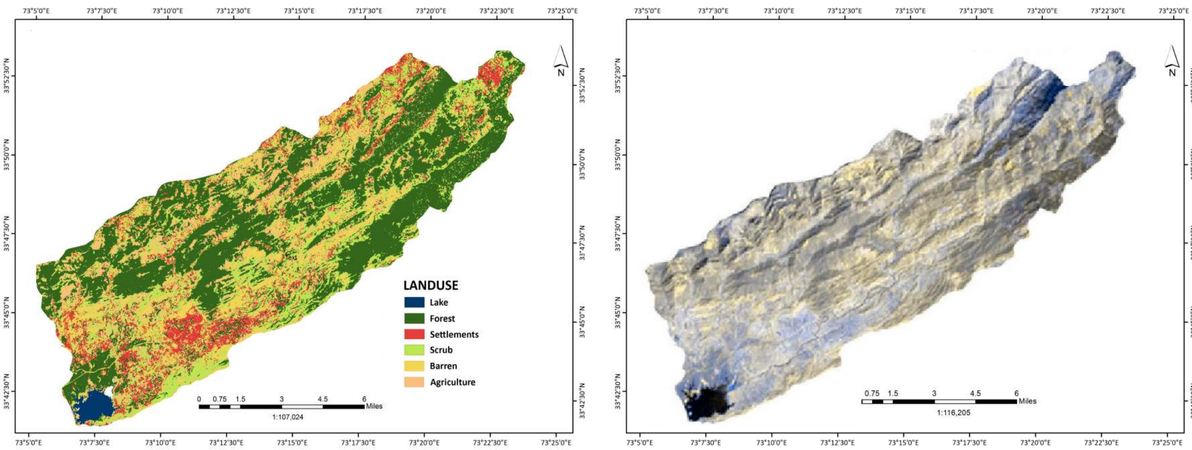
Fig. 5 Slope length and slope steepness factor (*LS*)

C factor is the crop/vegetation and management factor. It is the ratio of soil loss from an area with specified cover and management [32]. The *C* factor is related to the land use and is a reduction factor to soil erosion vulnerability. This is an important factor in MUSLE, since it represents the conditions that can be changed to reduce erosion [1]. In relating to C factor, the most widely used indicator of vegetation growth based on the RS technique is the Normalized Difference Vegetation Index (NDVI), which for Landsat Enhanced TM (ETM) is given by the following equation [16]:

$$NDVI = \frac{NIR - R}{NIR + R} \tag{2}$$

where *NIR* and *R* are near infrared and red bands respectively. *NDVI* values range in [-1, 1] [1]. *C* factor is calculated from land use map. To prepare a land use map of the study area, LANDSAT ETM+ images were used (Fig. 6a). First, NDVI was calculated by using TM3 and TM4 to iden-

[2] http://www.sfripunjab.gov.pk/



(a) (b)

Fig. 6 (a) Satellite image of study area, (b) Land use map of study area

tify vegetation in study area. Then, the classification of the images was performed in Erdas Imagine using supervised method following maximum likelihood rule mostly used to acquire reliable classification results. The classification output was supported with NDVI data that helps in segregating vegetative areas from non-vegetative. As a result six major land use/land cover classes: forest, agriculture, settlement, scrub, barren, and water were identified in study area (Fig. 6b).

Factor P in the MUSLE is the ratio of soil loss with a specific support practice to the corresponding loss with up and down slope culture. Improved tillage practices, sod-based rotations, fertility treatments and greater quantities of crop residues left on the field contribute materially to erosion control and frequently provide the major control in a farmers field [36, 32]. Arc SWAT model by default considers P value as 1 in case the practice factor is unknown. In study area, the cross slope cultivation, contour farming and strip cropping are commonly carried out at agricultural land but because of non-availability of location based practice information P factor was set to 1 for entire study area. The factors Q and q_p define the surface runoff (mm) and the peak runoff rate (m^3/s) respectively. SWAT estimates the surface runoff with the SCS curve number method and the peak runoff rate is calculated with the rational method:

$$q_p = \frac{c \times I \times A_{area}}{3.6} \tag{3}$$

where q_p is the peak runoff rate (m^3/s), A is area (km^2), c is the runoff coefficient, I is the rainfall intensity (mm/hr), and 3.6 is a unit conversion factor [7]. Peak flow was estimated using a modification of the rational method which relates rainfall to peak flow on a proportional basis. The rational equation is:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{4}$$

where Q is runoff (in), P is rainfall (in), S is potential maximum retention after runoff begins, and I_a is the initial abstraction. The Q and q_p factors are computed from geo-database of climatic data and landuse map. Climatic data was acquired from Satra Meel Weather observatory of Climate Change, Alternate energy and Water Recourse Institute (CAEWRI). From the source data a geo-database was prepared having attributes of climate on monthly bases spanning from 1998-2005. Variables of geo-database were monthly minimum and maximum temperature and its standard deviation, monthly maximum precipitation and its standard deviation, skewness of monthly maximum precipitation, monthly days of precipitation, monthly solar radiation and average monthly wind speed.

3.2 Estimation of the temporal change in Sedimentation Yield by using Double Mass Curve

A Double Mass Curve (DMC) is defined as the plot of cumulative value of one variable against the cumulative value of other quantity in the same time period. The continuous slope of the line shows constant proportionality between two the quantities and the break in the slope of the line indicates the change in the proportionality constant between the two quantities. The DMC can give us significant information about the time in which changes occurred in those variables for which DMC is plotted [29, 12]. In this study, the DMC analysis was performed to assess the changes in the sediment yield at Rawal Lake due to changes in land use in catchment. The results showed a significant increase in the annul sediment yield from 1998 to 2010, whereas no large variation in cumulative flow is identified. An average 30% and 38% sediment yield has been increased at Rawal Lake during period extending from 2002 to 2006 and 2007

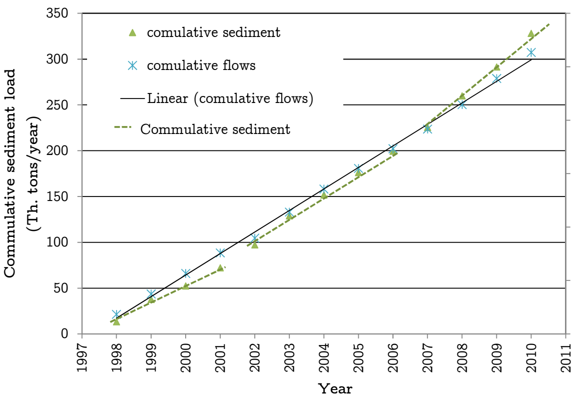


Fig. 7 Double Mass Curve Analysis

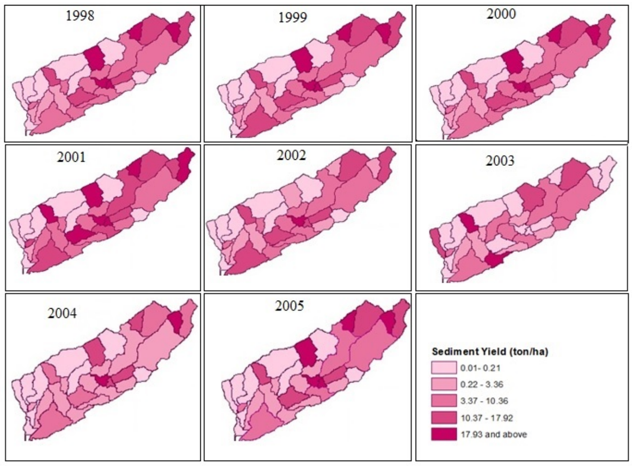


Fig. 8 Temporal sediment yield in subcatchments

to 2010 respectively (see Fig. 7), although the annual runoff has essentially remained stable.

The DMC presented in Fig. 7 shows the plot of cumulative discharge and the cumulative sediment yield against time. There is a break in the sediment yield slope in 2002 and again in 2007. This change is because of construction, urbanization, increase/decrease in vegetation, climate changes, etc. Sedimentation occurs when vegetation is removed for construction purposes (e.g., roads, buildings). The rise in the amount of the sediment in the Rawal catchment could be due to the construction of Murree-Islamabad expressway that was started in the 1999 and it was completed in 2011. This construction did not affect the discharge however, it significantly increased the amount of sediment.

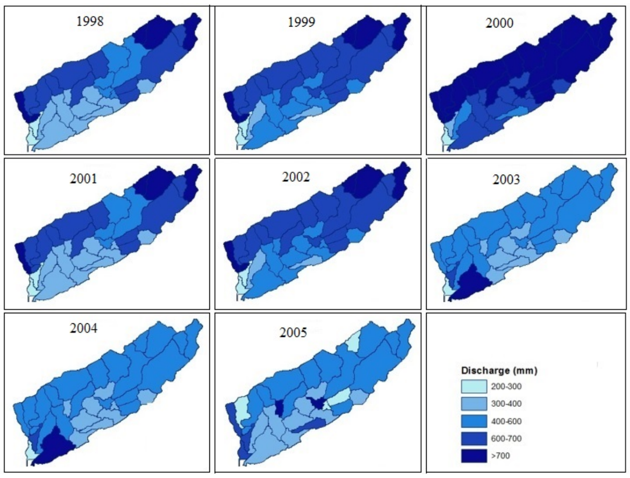


Fig. 9 Temporal variation in discharge at subwatersheds

3.3 Calibration and Validation of Results

The calibration and validation of the model is considered to be a key factor in reducing the uncertainty and increasing user confidence in its predictive abilities which makes the application an effective model [35]. The SWAT model was run for years 1998 to 2005; the first 4 years of the simulated output were discarded in the calibration process as per requirement of the model to stabilize its results. Thus the final calibration period was from January 2003 to December 2005. As a result a geo-database was produced containing the data for all 32 sub-catchments on monthly basis. The aim of this analysis was to analyze the monthly sediment yield, inflow and outflow for each sub-catchment. The geo-database was associated with the shape-file of subcatchments processed from DEM hydro processing, and the classified sediment yield maps from 1998-2005 were processed in Arc Map as shown in Fig. 8. Classified maps for discharge in *mm* were processed from 1998-2005 to identify the temporal variation (Fig. 9).

The calibration accuracy was checked by calculating Nash & Sutcliffe coefficient, Root Mean Square Error (RMSE) and the correlation coefficient (R^2) of the time series. The results are summarized in Tab. 1. The Nash & Sutcliffe coefficient is an estimate of the variation of a time series from another as given by following equation:

Table 1 Calibration of discharge and sediment data.

Variable	Nash & Sutcliffe	RMSE
Discharge	0.787	12.1
Sediment Yield	0.735	14.0

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(q_o - q_s)^2}{\sum_{i=1}^{n}(q_o - \bar{q}_o)^2} \quad (5)$$

The Nash & Sutcliffe coefficient approaching to unity indicates that the estimated and the observed time series are identical. The NSC index reached the value of 0.80, signifying a quite precise calibration. Later the model was validated using the same indexes for the period of January 2003 to December 2005. Root mean square error (RMSE) was

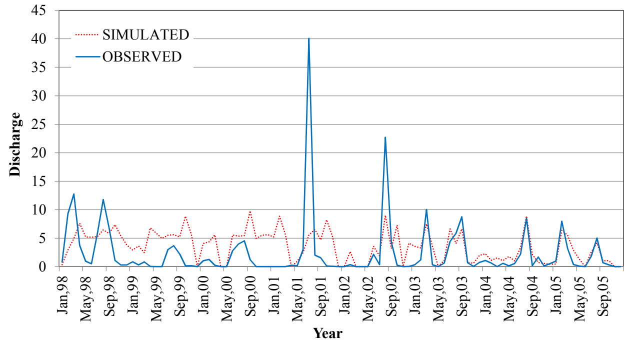


Fig. 10 Simulated vs. observed discharge.

computed to find the difference in simulated discharge and observed discharge and is calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}[Q_{sim}(i) - Q_{obs}(i)]^2}{n}} \tag{6}$$

where, Q_{sim} is simulated time series, Q_{obs} is observed time series, and n is the number of measurements. The results presented in Tab. 1 show RMSE of 12 and 14 for discharge and sediment yield respectively which shows high calibration between the two series.

Fig. 10 shows the observed and the simulated discharge in the Rawal reservoir from 1995 to 2005. First four years were termed as warm-up as these years are very essential part of the simulation process to bring the hydrologic processes to an equilibrium condition. There is a notable difference in the observed discharge and the simulated discharge from June 1998 to February 2000 as these years are included in the warm-up period. A peak in the observed discharge can be noted in May 2001 which might be due to a storm event in that period and the model did not incorporate the storm events in the simulation.

Regression analysis encompasses the identification of the relationship between a dependent variable and one or more independent variables. More specifically, regression analysis aids to understand how the value of the dependent variable varies when any one of the independent variables is changed. For validation of Arc SWAT Model, discharge is taken as the independent variable while the sediment yield is taken as the dependent variable. For regression analysis sediment concentration in Kg/ha was calculated from 1998 2005 at Rawal lake catchment and the results are presented in Fig. 11a. The rise in the amount of sediment is noticed in the 1999, 2000, and 2002 which is due to the construction of Murree-Islamabad expressway. Forests play an important role in reducing the amount of sedimentation. For the construction of Murree-Islamabad expressway, a large area of forest was cleared from Murree, lower Topa to Satrameel. Due to the cutting of the trees, the rate of sedimentation increased. Fig. 11b shows the comparison of the simulated and observed sediment concentration in the catchment. To estimate the accuracy, the model was executed for the year of 2010 because the sediment concentration data was available for 2010. The estimation of the model is significantly high for the month of May because of the flood event in Pakistan in that particular month.

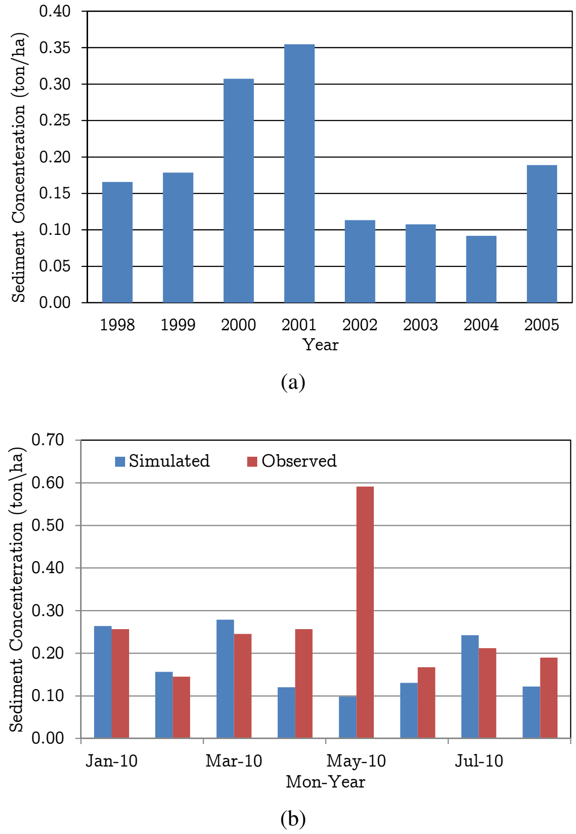


Fig. 11 (a) Sediment concentration data from 1998 to 2005, (b) Simulated and observed sediment concentration.

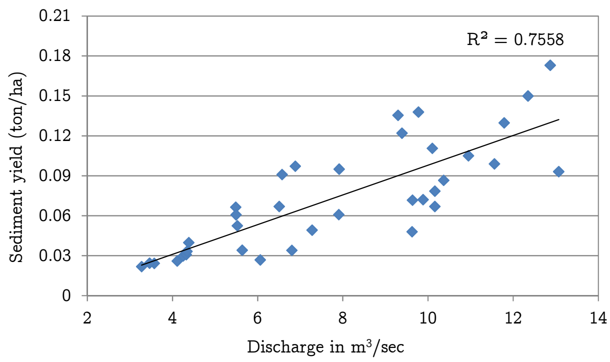


Fig. 12 Relation between sediment yield and discharge.

The results of the regression analysis between sediment yield and discharge are presented Fig. 12. The scatter plot shows a moderately strong positive relationship ($R^2 = 0.76$) between the discharge and the amount of sediment in the catchment, indicating that increase in discharge increases the sediment yield too, but the change in the sediment yield

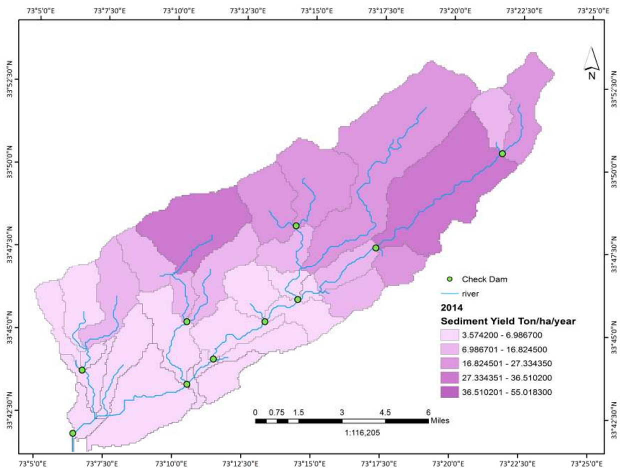


Fig. 13 Potential check dam sites based on the sediment yield of 2014.

is more than the change in discharge. This significant increase in the sediment yield of the catchment is due to the change in the land use of the catchment. This does not affect the discharge but the sediment yield was significantly affected.

3.4 Identification of Check Dam Sites

The high sedimentation in the catchment of the Rawal dam can be reduced by constructing small dams or check dams at various locations in the catchment. Remote Sensing and GIS have been applied considering sediment yield index (SYI) model and morphometric analysis for check dam positioning by prioritization of watersheds [25]. To identify the locations of small dams, few parameters must be considered like the dam should be used only in small open channels that drain on 10 acres or less areas. The maximum height of the check dam should be 2 ft. (0.6 m). The center of the check dam must be at least 6 in (152 mm) lower than the outer edges. Small dams should be constructed where the slope is less than 15%. The land should be barren shrub land or river bed. To fulfill this criteria, the 32 sub-watershed in the Rawal Dam catchment were merged based on elevation, and it was than overlaid on the land use map and DEM to identify the potential sites for check dams. After the overlying analysis 11 sites were identified in the catchment. Fig. 13 shows the classification of the sediment yield in the year 2014 and the potential sites identified for the construction of check dams. A priority index given to each site is presented in Tab. 2.

4 Conclusions

Sediment yield is an important measure of geomorphic activity which represents the amount of sediment exported at the basin outlet over a period of time. This paper presents

Table 2 Construction of check dams with priority index. Sediment Yield is in ton/ha/yr.

Catchment Name	Sediment Yield	Priority
A	43.0813	3
B	36.5102	4
C	47.6537	2
D	30.6785	5
E	55.0183	1
F	27.3343	6
G	16.8245	8
H	22.9597	7
I	6.9897	9
J	4.1986	10
K	3.5742	11

some exploratory steps towards the estimation of the sediment yield at dam sites. The study was carried out for the Rawal Dam Catchment, which is affected by a number of land use changes in the catchment due to the construction of Murree-Islamabad expressway. We particularly focused on estimating the change in the sedimentation yield of the catchment due to construction of this expressway. The SWAT model MUSLE was used to estimate the discharge and sediment conditions in the catchment. LANDSAT imagery, DEM, land use map, soil map, and weather data were used in this analysis. The study area was divided into 32 sub-catchments to obtain accurate results. The model results were also calibrated and validated using Nash and Sutcliffe coefficient, which was found to be 0.79 which shows the accuracy and effectiveness of the proposed research. The results showed an increase of 30-38% in the amount of sedimentation in the study area. This increase was noticed after year 2001 - two years later after the start of the expressway construction (September 1999). A large forest land was cleared for the construction of this expressway, and this deforestation increased the sedimentation from 0.076 ton/hac/year to 31.45 ton/hac/year in 32 catchments.

The Rawal dam is an important water reservoir for the residents of Rawalpindi. Due to the increase in the sedimentation yield in the catchment the capacity of the dam is depleting at an enormous rate. Check dams are cheaper and useful structures to control the amount of sedimentation. They help in preventing the sediments entering into the main reservoirs. Using the sediment maps, we also proposed sites where check dams can be constructed. We identified 11 check dam sites along their priority index to reduce the sedimentation in the catchment.

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