Micro watershed management for erosion control using soil and water conservation structure and SWAT modeling

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Abstract. This study evaluated the effectiveness of soil and water conservation structures for soil erosion control by applying a semidistributed basin-scale Soil and Water Assessment Tool (SWAT) model in various small watersheds of the Chakwal and Attock districts of Pothwar, Pakistan. Analyzing various slope gradients revealed that all selected sites had a maximum slope area of less than 5 %; soil conservation stone structures were installed at these sites to reduce sediment yield. The model was calibrated and validated on a daily basis for a small but representative catchment of the Dharabi watershed without any soil conservation structures. Statistical measures (R^2 and NSE) were used to evaluate model performance; the model performed satisfactorily for both surface runoff and sediment yield estimations, with the R^2 and NSE values both being greater than 0.75, during calibration (2009–2010) and validation (2011). Based on calibrated and validated SWAT model, the average annual runoff at the outlet was predicted to be 80 mm. The model predicts 15.5 t ha−1 as an average annual sediment yield. After, the model was applied to various small watershed sites in the Chakwal and Attock districts having soil conservation stone structures. The stone bund type structures intervention was done in the model through modification of USLE support practice factor (P-factor), the Curve Number and average slope length (SLSUBBSN). The structures had significant effects, and the average sediment yield reduction caused by soil conservation stone structures at these sites varied from 40 to 90 %. The sediment yield and erosion reductions were also compared under conditions involving vegetation cover change. Agricultural land with winter wheat crops had a higher sediment yield level than fallow land with crop residue, which facilitated sediment yield reduction along with the soil conservation structures. The slope classification analysis indicated that 60 % agricultural area of Chakwal and Attock districts lies in a slope range of 0–4 %; where considerable potential exists for implementing soil conservation measures by installing soil conservation stone structures. The overarching findings of this study show that the

SWAT model provides reliable performance, which can be used in rocky mountainous watersheds for erosion control and watershed management. These findings can serve as a reference for policymakers and planners.

Keywords: SWAT Modeling, Soil Erosion, Land Management, Soil Conservation Stone Structures

1 Introduction

Soil erosion is a slow process and have a significant impact on degradation of good quality top fertile soil. It is estimated that approximately 75 billion tons of fertile soil are lost from world agricultural systems each year (Myers, 1993; Eswaran et al., 1999). Erosion rate varies from land to land topography, according to Patric, J.H. 1976, erosion rates range from a low of 0.001 t ha^{-1} $year^{-1}$ on relatively flat land with grass or forest cover, to rates ranging from 1 to 5 t ha^{-1} $year^{-1}$ in mountainous regions with natural vegetation (Patric, 1976). Currently, about 80% of the world's agricultural land suffers moderate to severe erosion, while 10% experiences slight erosion (Lal, 1994; Speth, 1994). Worldwide, soil erosion losses are highest in agro-ecosystems of Asia, Africa, and South America, averaging 30 to 40 t ha^{-1} $year^{-1}$, where it is the lowest in the United States, Europe and Australia, averaging 5-20 t ha^{-1} $year^{-1}$ (Pimentel, 2006; Pimentel et al., 1995; Ananda and Herath, 2003). Agricultural land degradation in rainfed mountainous areas is a major onsite problem that also causes offsite effects such as downstream sediment deposition in fields, floodplains, and water bodies. The costliest off-site damages occur when soil particles enter lake or river systems (KRIS,2002; Ontario Envirothon,2007). The USDA, 1989 reports that 60% of water-eroded soil ends up in streams. Out of 75 billion tons of soil lost, approximately two-thirds become deposited in lakes and rivers (USDA, 1989; Pimentel, 1997). Annual soil loss in the middle Yellow River basin of China amounts to 3,700 t km^{-2}, the largest sediment carrying river in the world. It has been documented that World's 13 large rivers carry 5.8 billion tons of sediments to the reservoirs every year (Nasir et al., 2006). The Indus River in Pakistan ranks third in the world with an annual sediment load of 435 million tons. According to an estimate, the Indus River is adding 500,000 tons of sediment to the Tarbela Reservoir every day, due to which the dam has lost about 35% of its reservoir capacity in 24 years (Ashraf et al., 2000). It is estimated that the Indus river and its tributaries carry about 0.35 MAF (million acre feet) of sediment load annually, almost 60% (0.2 MAF) of which deposits in the reservoirs, canals and irrigation fields (Kahlown et.al., 2002). According to Rafiq (1984), 76 % of Pakistan's area is affected by erosion, of which 36 % is affected by water erosion and 40 % by wind erosion. Water and soil are the most crucial natural resources for agriculture and livestock production. They are playing a key role in the economic growth of any region. However, when anthropogenic activities disturb fertile soil formation, this can lead to soil degradation, soil productivity reduction, and crop production loss; this ultimately instigates problems in agroecological farming systems and environment watershed plans (Panomtaranichagul and Nareuban, 2005). Globally, water resources deterioration caused by soil erosion is a growing concern; an estimated productivity loss of US$13–28 billion annually in drylands can be attributed to soil erosion (Scherr and Yadav, 1996). In Pakistan, dryland farming is practiced on 12 Mha. The area faces abject poverty and serious land degradation problems. Urbanization, deforestation, overgrazing, and improper tillage practices that leave the bare land as land cover are the major causes of soil erosion and produce serious economic loss for this area of Pakistan (Ashraf et al., 2002). The Pothwar region is the part of 12 Mha dryland farming area. This region comprises of 1.82 Mha and falls under the administrative control of Attock, Rawalpindi, Islamabad, Jhelum and Chakwal Districts. According to Oweis and Ashraf, 2012 findings in this region, at altitudes between 300 m and 700 m above sea level, the area consists of gullies (wasteland), terraced fields along hillsides, and irrigated fields. Poverty, severe erosion, and diminishing vegetation cover are the root causes of the land degradation. Different research studies have been conducted in this region related to soil erosion severity. More recently, Iqbal et al. 2015 carried out study at runoff plots in the Dharabi watershed in Chakwal Pakistan. The results indicated that cultivated slope produced highest soil loss (8.96 Mg ha^{-1}) annually as compared to both undisturbed gentle and steep slopes, viz., 2.08 and 4.66 Mg ha^{-1} respectively. Iqbal et al. 2012, conducted a study in the Dhrabi watershed of Pakistan to evaluate sediment yield associated with rainfall-runoff under various land-use practices. Terraced catchment with arable crops produced annual 4.1 t ha^{-1} of sediment as compared to 12.31 t ha^{-1} by the adjacent gully catchment. Nasir et al. 2006 carried out a study using Revised Universal Soil Loss Equation (RUSLE) and GIS at small mountainous watershed of Rawal Lake near Islamabad. The predicted soil loss ranged from 0.1 to 28 t ha^{-1} $year^{-1}$. Similarly, Ahmad et al. 1990 reported annual soil loss rates of 17-41 t ha^{-1} under fallow conditions, and at annual rate of 9-26 t ha^{-1} under vegetative cover in the Fateh Jang watershed having slope of 1%-10%. Using traditional techniques in Pothwar plateau soil loss of 3.0-4.5 t ha^{-1} $year^{-1}$ has been observed in cropped fields (Ahmed, 2002). Sarah, 2010 estimated soil erosion risk using Coordination of Information on the Environment (CORINE) model in the Rawal lake watershed. The annual soil loss ranged between 24-28 t ha^{-1} with high erosion risk (26%) in areas with steep slope and small vegetative cover. The highest estimated record of soil erosion was 150–165 t ha^{-1} $year^{-1}$ in the Dharabi watershed the part of Pothwar region (Ashraf et al., 2002). Nabi et al. (2008) reported that in the Soan River basin of Pothwar, the soil loss rates in barren and shrub land were 63.41 and 53.41 t ha^{-1} $year^{-1}$, respectively, whereas those in low- to high-cultivation land were 34.91 and 25.89 t ha^{-1} $year^{-1}$, respectively. Vegetation cover on sloped ground helps reduce soil loss; however, during field preparation and cultivation, the surface soil becomes pulverized and easily eroded, causing acute topsoil erosion because of vegetation cover removal. Therefore, during the cultivation of sloping land, measures should be adopted to stop fertile surface soil caused by substantial rainfall runoff. If such measures are not applied, the agricultural land may turn barren in only a few years (Itani, 1998). Vegetation cover is a key measure for soil protection against water erosion (Uhlirova and Podhrazska, 2007; Gordon et al., 2008; Saco et al., 2007); it reduces the flow velocity of surface runoff by increasing surface roughness, in addition to increasing the infiltration rate (Hejduk and Kasprzak, 2004, 2005) of soil.

Considerable increases in sediment yield at the expense of soil renewal pose a major threat to soil and water resources development. Although water erosion is a function of many environmental factors, its assessment and mitigation at the watershed level are complex phenomena; this is because of the unpredictable nature of rainfall along with topographic heterogeneities, climate and land use–land cover variability, as well as other catchment features for the specified areas under study (Moore and Burch, 1986). In addition, inappropriate land management practices and human activities increase the dynamics of these factors (Wischmeier and Smith, 1978). At present, many models with a broad spectrum of concepts, which were classified as spatially lumped, spatially distributed, empirical, regression, semi-distributed eco-hydrological model and factorial scoring models, are in use for modelling the rainfall-runoff-soil erosion and sediment transport processes at different scales (Vente et al., 2013). The information about existing erosion and sediment transport models was adopted from two review papers. Aksoy and Kavvas (2005) performed a review for erosion and sediment transport models developed at hillslope and watershed scales while Merritt et al. (2003) reviewed several different erosion and sediment and sediment-associated nutrient transport models with regard to many factors such as their complexity, inputs and requirements, the processes they represent and the manner in which these processes are represented, the scale of their intended use and the types of output information.

Empirical models are generally simplest, limited to conditions and parameter inputs for which they have been developed. They are particularly useful as a first step in identifying sources of sediment and nutrient generation. For example, Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) the empirical model used because of easy to apply and low data requirements but have deficiency to simulate physical processes in a watershed. The USLE computes annual soil loss. Its modified version (MUSLE) has been an attempt to compute soil loss for a single storm event. The USLE was revised (RUSLE) (Renard et al., 1991) and revisited (Renard et al., 1994) for improvement. Other empirical models are AGNPS (Young et al., 1989) an event base model uses a modified form of USLE. SEDD (Ferro and Porto, 2000) based on the empirical USLE model uses Monte Carlo technique to test the effect of uncertainty in the model parameters on sediment yield computations. In conceptual models, a watershed is represented by storage systems (flow paths). They include general descriptions of catchment processes and provides outputs on lumped scale as well as spatially distributed manner. Conceptual models play an intermediary role between empirical and physics-based models. A conceptual model such as the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) is semi distributed model that exemplifies a compromise between empirical and physical algorithms as a modified version of USLE (MUSLE) furthermore, it is considered a more suitable tool for agricultural management practices in watersheds, compared with other models (Borah and Bera, 2003). LASCAM (Viney and Sivapalan, 1999) is a conceptual and continuous (daily time interval), algorithm coupled to an existing water and salt balance model for sediment generation and transport. Some conceptual models examples are EMSS (Vertessey et al. 2001), HSPF (Johanson et al. 1980), SWRRB (USEPA, 1994). Physics-based models are based on the solution of fundamental physical equations and give the complete understanding and quantification of the physical processes. The streamflow process is described by the governing equations of conservation of mass and momentum while physically based erosion and sediment transport model use mass conservation equation of sediment. The ANSWERS model (Beasley et al., 1980) includes a conceptual hydrological process and a physically based erosion process. LISEM (De Roo et al., 1996) is one of the first models that use GIS. CREAMS (Knisel, 1980) analyzes the inter rill area and rill separately. WEPP (Nearing et al., 1989) daily continuous model to predict soil erosion and sediment delivery from fields, farms, forests, rangelands, construction sites and urban areas. KINEROS (Smith, 1981), WESP (Lopes, 1987), SEM (Storm et al., 1987), SHESED (Wicks, 1988), RUNOFF (Borah, 1989) and EUROSEM (Morgan et al., 1998) are some examples for the physically based erosion and sediment transport models.

This research study was conducted in small sub-watersheds of District Chakwal and Attock of Pothwar region. Soil erosion and water loss are extreme hazards in this area due to cultivated highland slopes where timely soil and water conservation strategies and remedial measures are the basic requirements for sustainable crop productivity. The purpose of the study was to evaluates the effectiveness of soil and water conservation structure for soil erosion control using SWAT model. Eventually, to recommend this study as a strategy to counteract the soil erosion with soil and conservation structures at a broader scale.

2 Materials and methods

2.1 Pothwar region

Determining the relationship between rainfall, runoff, and soil erosion is imperative in the Pothwar rainfed region for creating applicable soil and water conservation mechanisms, as well as for enhancing crop productivity. Considering the long-term sustainability and productivity of eroded land, the present study focused on Chakwal and Attock districts of Pothwar plateau between 32°-30' to 34° North Latitudes and 71°-45' to 73°-45' East Longitude as shown in Fig.1. The region has an arid to semiarid climate with hot summers and cold winters, according to a soil survey report (Ali, 1967) and Zakaullah et al., 2014. Generally, the plateau land comprises broken gullies, low hill ranges, and a flat to gently undulating topography. The textural classification varies from sandy to silt and clay loam, and the land consists of poor to fertile soil derived from sandstone and loess parent material (Nizami et al., 2004). The rainfall pattern is unpredictable with high intensity; 60–70 % of the total rainfall occurs during the monsoon season (from mid-June to mid-September). The average annual rainfall varies from 250 mm to 1675 mm, with decreasing trend from North to South. After the rains, soil crusting decreases the infiltration rate and aeration and increases soil strength, which reduces plant emergence and exposes the soil surface to erosion (Shafiq et al., 2005). The soil loss rate becomes more deleterious with higher intensity rainfall runoff over greater slope lengths and steepness levels (Rai and Mathur, 2007). Out of total 1.82 Mha of Pothwar region, about 0.77 Mha (43%) are cultivated and the remaining is mostly grazing land. While of the cultivated area only 4 percent is irrigated, while remaining (96%) is under rain-fed agriculture (Khan 2002). The rainfall plays an important role in crop, the principal crops of the area are wheat, maize, bajra, barley, pulses, groundnut, fruits and vegetables. Without adequate protection, the effects of erosion on this highly erodible soil are extensive fertile soil and vegetation loss, endangered soil and water conservation structures, and reservoir depletion through sedimentation. Moreover, it causes doubts about the viability of existing and future soil and water conservation schemes. The high rate of erosion is creating silting problem in small dams of Pothwar area. For sustainable agricultural and socioeconomic development of the region, the Government started various projects for watershed development in the upstream of storage reservoirs such as Watershed Management Programme by Pakistan, Water and Power Development Authority (WAPDA). Similarly, soil and water conservation activities have also been carried out in Pothwar region for erosion control and land development through series of Barani Areas Development Projects. The application of loose stone structures project of SAWCRI (Soil and Water Conservation Research Institute, Chakwal) with ICARDA (International Center for Agricultural

Research in the Dry Areas, Syria) for erosion control has resulted in development of some environmental friendly and cost-effective resource conservation technologies.

2.2 Soil and water conservation structures

In Pothwar region, the terrace land use system along with wide and deep gullies are being used for field crop production. The agriculture fields are usually not flat but various field terraces are situated at different elevation levels (Fig. 2). Farmers make earthen contour embankments (bunds) to retain rainwater and conserve soil moisture. The terrace land use system fails due to breaching of field embankments/bunds, when heavy rainstorm occurs. This is mainly caused by hydraulic shear failure of the soil under saturated conditions. The disturbance of soil organisms can aggravate the impact. Fig. 3 show such terrace failures which cause an increase of surface runoff and soil erosion especially in the pothole area. The moving runoff from higher to lower fields not only takes with it top fertile soil but also essential nutrients and organic carbon thereby reduces productive capacity of soils. If the breached bund is not repaired before next rainy season, it leads to formation of gullies and rendering area out of plough, a great national loss. Crop yield on such eroded lands are poor and livelihood of resource-poor farmers is affected adversely. To reduce this problem, the eroded areas need sustainable rehabilitation to ensure food security in the region. The long-term international collaboration of SAWCRI with ICARDA has resulted in development of some environmental friendly and cost-effective resource conservation technology “loose stone structures” based on principal approach of “Catch water where it drops” and only allow surplus water to dispose-off safely. The loose stone structures were designed and installed in clusters with the help of farmers in the upper, middle, and lower parts of terraced catchments as shown in Fig.4 and 5.

The idea is to retain water in the terrace until a certain rainfall amount (without overboarding the terrace) and then to divert the excess rainfall in a non-erosive way. Firstly, this increases the infiltration and improves the amount of plant available water and secondly it reduces the soil erosion by reducing amount and kinetic energy of runoff. On average a water height of approximately 10-15 cm can be hold back in the fields. The crest of structure is kept 6-9 inches raised from soil surface to encourage in situ rainwater conservation. Height of side walls of a structure should be equal to height of field bund/embankment where structure is to be installed. The cross-section and pictorial view of these structures is shown in Fig. 6 and 16.

2.3 Study watersheds description

The soil and water conservation structures were installed in small terraced agriculture fields in Chakwal and Attock districts by SAWCRI Chakwal department. Out of which six small sites were selected to evaluate the effectiveness of these structures on soil erosion control. The description of these sites is given in Table 1 and location map is shown in Fig.1. For model calibration and validation, one subcatchment (Catchment-25) of the Dharabi watershed was selected as shown in Fig.7. Catchment-25 is an agricultural watershed consisting of deep gullies and having an area of 2 ha and elevation ranging from 527.15 to 539.78 m above sea level. The average land slope is 10.5%. It has well-defined boundaries and wide gully beds that mimic the full representation of the study area. The soil texture class is sandy loam. Catchment-25 was selected for model calibration and validation because this subcatchment is equipped with measuring system of rainfall (rain gauge), runoff (water level recorder) and sediment yield (stilling basin) at the outlet point, having coordinate 32.8946380 N and 72.7094070 E, as shown in Fig. 8. The SAWCRI department install and manage these instruments and collect the data for the period of 2009-2011. The model was calibrated and validated for this time span due to data availability. The experimental setup for the measurement of runoff and sediment yield is shown in Fig.8. The detailed description for collection of runoff and sediment data are given in (Nadeem et al., 2012). The other selected sites of district Chakwal are also located in Dharabi watershed. Dahrabi watershed comprises an area of 196 km² between latitudes 32°42′36″N to 32°55′48″N and longitudes 72°35′24″E to 72°48′36″E in District Chakwal, Pothwar Pakistan. The rainfall is the main sources of freshwater in the watershed. The undulating and uneven topography has deep to shallow gullies, large to small terraces and low to medium hills between elevations of 465 to 919 m above sea level. Slope steepness varies from 2% in the areas of the plain to more than 30% along the hillsides. The soil is sandy loam type having low (less than 1%) organic matter. Generally, the climate is hot in the summer season and cold during the winter. The summer season extends from April to September, with the highest temperatures occurring during June and July (30-35 °C). The winter season spans the months of October to March, with the coldest temperatures occurring in December and January (0-5 °C). The rainy summer season (July to September) delivers about 65-70% of the annual rainfall while about 30-35% of the annual rainfall occurs during the winter rainy season (December to March). The average annual rainfall is about 630mm (Oweis and Ashraf, 2012). The major landuse classifications of this area are: Agricultural Land (22%; 43 km^2), Barren Land with Shrubs and Bushes (32%; 62 km^2), Fallow/Range Land with Range Grasses (33%; 65 km^2), Residential Areas (4%; 9 km^2), Water Bodies (3%; 7.0 km^2) and Forests (6%; 11 km^2). The location map of the area is shown in Fig.1 and 7.

2.4 SWAT model description

SWAT (Soil and Water Assessment Tool) is a conceptual, continuous time basin scale hydrological model deal with land-soil-water-plant system (Arnold et al., 1998; Neitsch et al. 2001). It was developed in the early 1990s to assist water resource managers in assessing the impact of management and climate on water supplies and non-point source pollution in watersheds and large river basins (Arnold and Fohrer, 2005). SWAT can be used in small agricultural watersheds to simulate water and soil loss (Tripathi, 2003; Zabaleta et al., 2014; Lemann et al., 2016; Roth and Lemann, 2016). Similarly, Setegn et al., 2010 used SWAT to simulate the sediment yield simulations for the Anjeni, a small watershed in the northern highlands of Ethiopia. Neitsch et al. (2001) discussed the model's development, operation, assumptions, and limitations in the SWAT theoretical documentation and user's manual available on the SWAT website (USDA-ARS, 2002). SWAT is a watershed-scale ecohydrological model tested for a wide variety of watershed scales and environmental conditions worldwide (Gassman et al. 2007, 2014; DouglasMankin et al. 2010; Tuppad et al. 2011; Krysanova and White 2015; Bressiani et al. 2015). Srinivasan et al. (1998) reviewed the SWAT model simulation and application for streamflow, sediment, and nutrient transport along with the effects of management practices. The SWAT model simulation and application for streamflow, sediment and nutrient transport with effects of climate change, land use change and management practices has been reviewed by researchers and scientist all over world from last 30 years. SWAT literature data base consist of total 1,700 papers, and Gassman et al., 2014 structured these database studies in four major categories (i) hydrologic foundations, (ii) sediment transport and routing analyses, (iii) nutrient and pesticide transport, and (iv) scenario analyses.

ArcSWAT, as an ArcGIS interface (Olivera et al., 2006), uses GIS spatial algorithms to spatially link multiple model input data, such as watershed topography (DEM), soil, land use, land management and climatic data. During watershed delineation, the entire watershed is divided into different sub-basins. Then, each sub-basin is discretized into a series of Hydrologic Response Units (HRUs) as the smallest computation unit of a SWAT model, which are characterized by homogeneous soil, land use and slope combinations. Daily climate input data for defined locations are spatially related to the different sub-basins of the model using a 'nearest neighbor' GIS algorithm. Different model outputs, such as surface runoff, sediment yield, soil moisture, nutrient dynamics, crop growth etc., are simulated for each HRU, aggregated and processed to sub-basin level results on a daily time step resolution. The surface runoff computation is performed using a modified USDA-SCS Curve Number method (USDA-SCS, 1972) or the Green and Ampt infiltration method (Green and Ampt, 1911). Sediment yield levels from each HRU are estimated using the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977) written as a mass balance equation as follows:

$$S.Y = 11.8\left(Q_{surf} \times q_{peak} \times area_{hru}\right)^{0.56}.K_{USLE}.C_{USLE}.P_{USLE}.LS_{USLE}.CFRG \quad (1)$$

where S.Y = sediment yield (t ha^{-1}); Q_{surf} = surface runoff (mm ha^{-1}); q_{peak} = peak discharge (m^3 s^{-1}); and $area_{hru}$ = area of hydrological response unit (ha). K_{USLE}, C_{USLE}, P_{USLE}, and LS_{USLE} are USLE parameters and are presented in Table 5.

Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1965) was developed for estimation of the annual soil loss from small plots of an average length of 22 m, its application for individual storm events and large areas leads to large errors (Hann et al., 1996; Kinnell, 2005). Also, there is no direct consideration of runoff, although erosion depends on sediment being discharged with flow and varies with runoff and sediment concentration (Kinnell, 2005). Later, Williams & Berndt (1977) introduced sediment yield estimation model (MUSLE) on a storm event basis based on runoff characteristics, as the best single indicator for sediment yield prediction (ASCE, 1970; Williams, 1975; Sadeghi et al., 2004; Hrissanthou, 2005). In this model runoff shear stress effects were taken into account in terms of the product of runoff volume and peak discharge, on soil detachment for single storms.

The sediment yield level at a watershed outlet is affected by two principal channel processes: sediment aggradation and degradation. The sediment transport capacity is a direct function of the channel peak velocity, which is used in the SWAT model as shown in Eq. (2):

$$T_{ch} = \alpha v^{b} \quad (2)$$

where T_{ch} (t m^{-3}) = transport capacity of a channel; v (m s^{-1}) = channel peak velocity; and α and b = constant coefficients.

The channel peak velocity is calculated using Manning's formula in a reach segment as presented in Eq. (3):

$$v = \frac{1}{n} R_{ch}^{2/3} S_{ch}^{1/2} \quad (3)$$

where n = Manning's roughness coefficient; R_{ch} (m) = hydraulic radius; and S_{ch} (m m^{-1}) = channel bed slope.

Channel aggradation (Sed_{agg}) and channel degradation (Sed_{deg}) in tons are computed in the channel segment using the criteria presented in Eqs. (4) and (5):

$$if\ sed_i > T_{ch}:\quad Sed_{agg} = (sed_i - T_{ch}) \times V_{ch}\ \ \& Sed_{deg} = 0 \tag{4}$$

$$if\ T_{ch} < sed_i:\quad Sed_{deg} = (T_{ch} - sed_i) \times V_{ch} \times K_{ch} \times C_{ch}\ \ \& Sed_{agg} = 0 \tag{5}$$

where sed_i (t m^{-3}) = initial concentration of sediment; C_{ch} = channel cover factor; K_{ch} (cm h^{-1} Pa^{-1}) = channel erodibility factor; and V_{ch} (m^3) = channel segment water volume.

(Sed_{out}) in tons is the total sediment transported out of the channel segment, which is computed using Eq. (6):

$$Sed_{out} = \left(sed_i + Sed_{deg} - Sed_{agg}\right) \times \frac{V_{out}}{V_{ch}} \tag{6}$$

where V_{out} (m^3) = volume of water leaving the channel segment at each time step.

Soil erosion is a direct function of slope length and steepness, because of direct increases in flow velocity (van Vliet and Hall, 1995).

2.5 Model input

To model sediment yield and runoff, two types of input data were required: (1) spatial raster data, include slope data, digital elevation model (DEM), land use, and soil data and (2) daily meteorological and climatic data in a lookup table and observed runoff and sediment data. For this study, Catchment-25 was used for sediment yield evaluation because of the similar characteristics of its selected small watersheds. This catchment was used for model calibration and validation because of data availability as discussed in section 2.3. The model input data source is given in Table 2.

A physical topographical survey of the catchment was conducted using a global positioning system (GPS) and total station. DEM was generated using point-source elevation data in a geographic information system by applying the inverse distance weighting method (IDW) as shown in Fig.9. The soil textural classification analysis was performed by collection of soil samples at different locations in the catchment as shown in Table 3. The raster map of soil layer was created using IDW interpolation method. The catchment consists of three types of texture i.e. sandy loam, clay loam and sandy clay loam. The catchment features deep gullies with scrub trees, bushes, and grasses on top. The land cover map for this research was produced by reconnaissance survey and google earth survey. The study catchment consists of four major landuse classes (Fig.9). The percentage distribution of area according to landuse class is given in Table 4. Climate input data required by SWAT includes daily precipitation, maximum and minimum temperature, relative humidity, wind speed and solar radiation. Required daily precipitation and maximum/minimum air temperature data was collected for the period of 2009–2011 from the Soil and Water Conservation Research Institute (SAWCRI), Chakwal District Department. The observed runoff and sediment data were also collected from SAWCRI department.

2.6 Model setup, calibration and validation

After the SWAT model established, the first step in measuring the catchment's topography was physiographic analysis. ArcSWAT9.3 was used to delineate subwatersheds automatically and generate a stream network based on the DEM. Appropriate database of sub-basin parameter and comprehensive topographic report of the catchment was generated. The subwatersheds topographic report was rechecked for area, slope, location of outlet, soil textural class according to physical characteristics to make the appropriate database changes. SWAT coding conventions were used to reclassify land use and soil maps. According to Mamillapalli, 1998, the model's predictions are highly sensitive to HRU distribution levels; therefore, the distribution levels were set to 0 %, and the watershed was classified into HRUs based on the unique land use and soil and slope class in the overlaying section. The weather station location table and lookup tables of daily precipitation and temperature (maximum and minimum) data were loaded to link them with the required files. The model was initially simulated using default parameter values for surface runoff and sediment yield using the step by step algorithm (Fig.10) Different calibration approaches can be used in SWAT with respect to frequency and quantity of observation data available for model calibration. Nevertheless, the most powerful calibration is usually achieved through following a specific calibration order as suggested by Arnold et al., 2012. In particular, streamflow data at the sub-basin or watershed level are required to perform accurate model hydrologic balance and streamflow calibration, followed by calibration of different pollutants such as sediment load, nutrient yields and other water quality variables. The calibration procedure is typically based on initial sensitivity analysis results (using a set of sensitive parameters) and is executed either manually or automatically (Arnold et al., 2012; Moriasi et al., 2007). Calibrations can be performed manually, which can be important for clearly understanding some processes (Arnold et al., 2012). In the present study, the entire simulation period is limited to field observation data from 2009 to 2010 (calibration) and 2011 (validation). The SWAT manual calibration criteria of Santhi et al. (2001a) was adopted as shown in Fig.11. using daily surface runoff and sediment yield recorded at the outlet of the watershed for both calibration and validation of the model. The manual calibration helper tool of Arc SWAT was used as an iterative approach for manual calibration, involving the following steps: (1) perform the simulation; (2) compare observed and simulated values; (3) assess if reasonable results obtained; (4) if not, adjust input parameters based on expert judgment and other guidance within reasonable parameter value ranges; and (5) repeat the process until it is determined that the best results have been obtained.

2.7 Model performance evaluation

Efficiency criteria are defined as a mathematical measure of how well a model simulation matches corresponding observed data (Moriasi et al., 2007). In the present study, the goodness of the model fit related to surface runoff and sediment yield was assessed based on root mean squared error (RMSE), Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS), coefficient of determination (R^2) and percent difference (d).

2.7.1 Root mean square error (RMSE)

The root mean square error (RMSE) has been used as a standard statistical metric to measure model prediction error in meteorology, air quality, and climate research studies; a smaller RMSE value indicates better model performance (Chai and Draxler, 2014). Although RMSE is sensitive to outliers as it places a lot of weight on large errors, it has been developed to confirm the reliability of models (Hernandez, 2006). The RMSE does not provide information about the relative size of the average difference and the nature of differences comprising them (Willmott, 1982). The RMSE is calculated with the following equation:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(E_i - O_i)^2\right]^{1/2} \tag{7}$$

2.7.2 Nash-Sutcliffe Efficiency (NSE)

The Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) is a normalized statistic that determines the relative magnitude of the residual variance (“noise”) compared with the measured data variance (“information”). The Nash-Sutcliffe efficiency is calculated as:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(E_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{8}$$

The range of NSE lies between -∞ and 1.0 with NSE=1 describing a perfect fit. Values between 0-1.0 are generally viewed as acceptable levels of performance, whereas values <0.0 indicate that the mean observed value is a better predictor than the model (Krause et al., 2005). The simulation results are considered good if the NSE value is >0.75 and satisfactory if the NSE is in the range 0.36–0.75 (Motovilov et al., 1999). The model prediction is considered unacceptable if the NSE value is negative or nearly 0 (Santhi et al., 2001a).

2.7.3 Percent bias (PBIAS)

Percent bias (PBIAS) is defined as the average tendency of the observed data compared with their simulated counterparts (Gupta et al., 1999). The negative values of PBIAS indicate model overestimation bias, and positive values indicate model underestimation bias. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation (Moriasi et al., 2007). PBIAS is calculated with the following equation:

$$PBISA = \left[\frac{\sum_{i=1}^{n}(O_i - E_i) \times 100}{\sum_{i=1}^{n}(O_i)}\right] \tag{9}$$

2.7.4 Coefficient of determination (R^2)

The coefficient of determination R^2 is defined as the squared value of the coefficient of correlation (Stigler, 1989). It is calculated as follows:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i-\bar{O})(E_i-\bar{E})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(O_i-\bar{E})^2}}\right]^2 \quad (10)$$

where, n is the number of observations or samples; Oi are observed values; Ei are estimated values; Ō is mean of observed values; Ē is the mean of estimated values; i is counter for individual observed and predicted values.

The range of R^2 lies between 0 and 1, and describes how much of the observed value is explained by the predicted value (Krause et al., 2005). A value of 1 means the predicted value is equal to the observed value, where a value of zero means there is no correlation between the predicted and observed values.

2.7.5 Percent difference (d)

The percent difference (d) measures the average difference between the simulated and measured values for a given quantity over a specified period (usually the entire calibration or validation period) and it is calculated using equation. A value close to 0% is best for percent difference (d).

$$d = \frac{|O_i-E_i|}{\frac{(O_i+E_i)}{2}} \times 100 \quad (11)$$

3 Results and discussion

In the research study area, erratic and intensive rainfalls during the rainy season generate several peak runoff events (Fig. 13), exposing steep sloped areas to potentially severe soil erosion (Fig. 14). The best fit relation between rainfall and measured runoff and sediment yield were drawn for the observed study period (2009-2011) as shown in Fig. 12. In 2009, a total rainfall of 400 mm was observed to accumulate from 11 erosive rainstorms. The maximum rainstorm (108 mm) occurred on July 29, producing a 46.2 mm runoff and a 6.86 t ha−1 sediment yield. The total measured runoff was 95.5 mm, and the runoff values ranged between 0.24 and 46.2 mm (Fig. 13a). The total sediment yield was 13.2 t ha−1, and the yield values ranged between 0.003 and 6.86 t ha−1 against the corresponding events (Fig. 14a). From February to September 2010, 13 erosive storms occurred with a total rainfall of 528.3 mm. The observed overall runoff during the 2010 measuring period was 129.53 mm, with runoff events ranging from 0.31 to 31.5 mm (Fig. 13a). The maximum rainstorm (122.3 mm) occurred on the same date as the previous year, generating a 25.9 mm surface runoff and 7.75 t ha−1 sediment yield. The rainfall event on July 29 (122.3 mm) and August 24 (62.8 mm) produced relatively low runoff values of 25.9 and 20.3 mm, as well as low erosion rates of 7.75 and 5.15 t ha−1, respectively. By contrast, the rainfall event on July 20 (59.9 mm) produced a maximum amount of runoff (31.5 mm) and sediment yield (9.04 t ha−1), although the soil was not wet from a prior rainfall event, whereas for the other two storms, the soil was wet from prior rainfall events (Fig. 13a and Fig. 14a). The total soil loss during the 2010 investigation period was 31.13 t ha−1, with the loss values ranging between 0.016 and 9.041 t ha−1. During the 2011 period, 12 erosive rainfall events occurred with a total rainfall amount of 262 mm, which produced an overall runoff of 28.34 mm and sediment yield of 2.59 t ha^{-1}. The maximum rainstorm (39.6 mm) occurred on August 12, causing a 7.48 mm runoff and 0.598 t ha^{-1} soil loss, as illustrated in Fig. 13b and Fig. 14b. The observed runoff and soil loss during the 2011 period were lower because of light rainstorms.

3.1 Model sensitivity analysis

The determination of the most sensitive parameters is the first step in SWAT for model calibration and validation. The user determines which variables to adjust based on sensitivity analysis. Sensitivity analysis is the rate of change in model output values with respect to changes in model input parameters (Arnold et al., 2012). For determining the most sensitive parameter for model calibration the parameter sensitivity analysis was done using the Arc SWAT interface. The sensitivity analysis was made using a built-in SWAT sensitivity analysis tool that uses the Latin Hypercube One-factor-Ata-Time (LH-OAT) algorithm (Van Griensven 2005). Sensitivity analysis was performed using five parameters for sediment yield and list of parameter ranking was found in sensout.out file which is given in Table.6 with default and value used for sediment yield calibration. The sensitive parameters ranking from high to low for sediment are given in Table.6. USLE_P factor was found most sensitive as compared to the others. It indicated that sediment loading is affected by the change in landuse change practice factor. USLE_LS factor has value 2.36. The value of soil erosion parameters used during calibration were similar as recommended by Klik et al. (2012).

3.2 Model calibration and validation results

Calibration involves the adjustment of parameters in watershed modeling; model predictions obtained without calibration may differ substantially from observed data. Both calibration (2009-2010) and validation (2011) were performed manually on daily basis by using soil erosion parameters values as given in Table.6. For the calibration process, the parameter ranges were referenced from Neitsch et al. (2001) and the calibration criteria followed those of Santhi et al. (2001a) as shown in Fig.11.
Table 7 presents the model performance in terms of surface runoff and sediment yield, as evaluated using statistical indicators discussed in model performance evaluation section. This table indicates satisfactory model fit according to the assessment criteria suggested by (Moriasi et al., 2007; Moriasi et al., 2015). for the small watershed (Catchment-25) in the Pothwar region. Furthermore, high R^2 values were observed, indicating a strong correlation between the observed and simulated runoff and sediment yield. NSE values signifying the observed and predicted runoff and sediment yield plots fit the 1:1 line well. The calibration and validation results for surface runoff are illustrated in Fig. 13a and b, respectively, and those for sediment yield are illustrated in Fig. 14a and b, respectively.
According to the comparisons of the simulated and measured sediment yield and runoff during the calibration and validation periods (Fig. 13a and b and Fig. 14a and b), the average simulated runoff (6.73 mm) was close to the average observed runoff (7.04 mm), whereas the average simulated sediment yield was nearly equal to the average observed sediment yield (1.30 t ha^{-1}). Furthermore, the mean values and standard deviations revealed good agreement between the simulated and observed

sediment yield and surface runoff values for the calibration and validation periods. The validated model was subsequently used to assess model applicability for soil erosion estimation with conservation structures under various scenarios.

SWAT studies for smaller watersheds in the northeast and northwest of Ethiopia tend to show weaker hydrologic results (Schmidt and Zemadim, 2015; Yesuf et al., 2015), which is an indication that it may be difficult to accurately represent processes and thus obtain better results for smaller watersheds. Nevertheless, obvious correspondence of the hydrographs of observed and simulated surface runoff (Fig. 13) for both, the calibration and validation period, indicates that SWAT is capable to simulate the hydrological regime of small watershed (catchment-25) of Pothwar region. Similarly, the sediment simulation results by Betrie et al., 2011 reported that the fit between the model daily sediment predictions and the observed concentrations showed good agreement as indicated by very good values of the NSE=0.88 for the calibration period and NSE=0.83 for the validation period at El Diem gauging station.

4 Model application with conservation structures

After the model validation with adjusted soil erosion parameters, the model was applied to the aforementioned small watersheds of district Chakwal and Attock. These small watersheds already have existing soil and water conservation structures for control of soil erosion. The crests of the structures play a major role in reducing the flow velocity that creates ponding and results in sediment deposition (erosion reduction) upstream of the structures, whereas the downstream sections of the structures prevent channel or gully development. For model applicability, the first step was the demarcation of all watershed boundaries. Using a GPS and total station (Fig. 16), the boundaries of all watersheds were marked; because of the complex topography of the small watersheds, considerable effort was required to accurately delineate the watershed area for estimating the HRU and subbasins (for example, at the Khokar Bala site). The point elevation data inside the marked boundaries of all watersheds were collected and converted into DEM as shown in Fig.15. The location of each soil and water conservation were marked and used for correct delineations of subbasins. The landuse classification was used winter wheat soil types was sandy loam for all small watersheds based upon soil textural analysis and type cropping practice. After preparation of the requisite data file for SWAT model input, the model was run for all the selected sites for 6 years from January 2010 to April 2015. First the model was simulated with validated parameters without consideration of soil and water conservation structures and then intervention of soil and water conservation structures were made by modifying the surface runoff and sediment yield parameters. The topography of the region consists of permanent gullies where farmer used these gullies for cultivation of crops. The farmers managed the gullies in a terraced landuse system by making the field boundary bunds. During the monsoon season, the heavy rainstorm causes the shear failure of terraces edge (field bunds) due to heavy surface runoff. This problem creates loss of soil and also damage the crops. To reduce this problem, soil and water conservation structures were installed to retain water in the terrace until a certain rainfall amount (without overboarding the terrace) and then to divert the excess rainfall in a non-erosive way. These structures looks like stone bunds type.

SWAT provides various options to consider soil and water conservation structures impacts (Neitsch et al., 2005) including: (1) surface runoff may be modified through the adjustment of the runoff ratio (Curve Number) and/or the consideration of a micro-pond (pothole) at the related HRU level, which will also impact soil erosion, and (2) impacts on sediment yield levels via adjustment of the support practice factor (P-factor) and/or the slope length factor (LS) of the MUSLE (Williams, 1975). The ideal factors that describe the effect of stone bunds are the USLE support practice factor (P-factor), the Curve Number and average slope length (SLSUBBSN). In this study, the SLSSUBSN value was modified by editing the HRU (.hru) input table, whereas the P-factor and Curve Number values were modified by editing Management (.mgt) input table. Three more parameters were modified, namely average slope steepness (HRU_SLP) of the HRU input tables and two basin parameters (SPCON and SPEXP) representing the general watershed attributes in the Basin (.bsn) input files.

4.1 Soil erosion estimation and effect of conservation structures

The validated model was run without and with conservation structures separately for each selected site. Sediment yield results were compared under each condition, as shown in Table 9, by modifying the SWAT parameters representing the conservation structures, as shown in Table 8. The six parameters were modified according to the slope characteristics of the small watersheds and field conditions, in addition to being modified according to the terraced and contoured section of the SWAT user's manual (Neitsch et al., 2005) and a literature review (Addis et al., 2016, Betrie et al., 2011; Herweg and Ludi, 1999; Hurni, 1985). Soil and water conservation structures, such as stone bunds, act as imperative measures in the reduction of flow velocity, surface runoff, soil erosion, and slope length in a watershed system (Bracmort et al., 2006). Apposite parameters that signify the effect and importance of loose stone structures are the average slope length (SLSUBBSN), land management practice parameter (USLE_P), and curve number (CN2) for rainfall runoff conversion (Betrie et al., 2011). As described by Bosshart,1997, soil and water conservation impacts of stone bunds are mainly related to the reduction of surface runoff and sediment yield.

The impact of stone bund soil and water conservation structures was simulated through reduction of the Curve Number (CN_2) for surface runoff ratio modification as well as the adjustment of the support practice factor (P-factor) to account for the amount of trapped sediments at the stone bunds. Table 9 presents a significant sediment yield reduction achieved by incorporating the parameter values recommended for stone structures. The average annual sediment yield reduction varied from 40 to 90 % in the analyzed sites; the Khokar Bala site showed the maximum reduction. The average 5-year sediment yield reduction engendered by structures at various sites was revealed to vary from 54 to 98 %; these results are relatively comparable to the findings of various scientists (e.g., Betrie et al., 2011; Gebremichael et al., 2005; Herweg and Ludi, 1999). Betrie et al. (2011) indicated 6–69 % sediment reductions in the Upper Blue Nile River basin caused by stone bunds. A field-scale study in the northern part of Ethiopia by Gebremichael et al. (2005) indicated a 68 % sediment yield reduction engendered by stone bunds. In addition, Herweg and Ludi (1999) conducted a study at plot scale in the Eritrean highlands and Ethiopia and reported 72 – 100 % sediment yield reductions engendered by stone bunds. Based on the plot experiments carried out in 2013 (Rieder et al., 2014) stone bund structures were found to reduce surface runoff by approximately 60% to 80% and sediment yield between 40% to 80%. This is consistent with other plot experimental findings reported by Adimassu et al., 2012, where stone bunds reduced sediment yield by roughly 50% compared to untreated plots. However, plot experiments tend to reflect optimized stone bund conditions for just a very limited area. The effect of conservation structures on sediment yield reduction is elucidated by Oweis and Ashraf (2012) in the Dhrabi watershed, the average soil loss rates in 2009 without and with structures were calculated as 47 and 37.98 t ha^{-1} $year^{-1}$, respectively, with a 20 % reduction. However, the maximum soil loss rates without and with structures were 2716.17 and 1731 t ha^{-1} $year^{-1}$, respectively, with a 37 % reduction. Similarly, a 31 % reduction in average soil loss and a 36 % reduction in maximum soil erosion were reported for the year 2010 in the same catchment (Klik et al., 2012).

The large variation in sediment reduction with conservation structures was observed due to watershed topography and numbers of soil and water conservation structures. For example, the Khokar Bala site showed the maximum 98% reduction because this site has 90% area in 0-10% slope (Table.11) and 7 soil and water conservation structures.

4.2 Soil erosion estimation under different scenarios

In addition to evaluating the effectiveness of the soil conservation structures as presented in Table 9, this study developed various scenarios to estimate the further reduction in soil erosion associated with land use change. The scenarios were developed according to the scientific literature of land use and vegetation cover importance to assess soil erosion and farmer's common cropping practices in the study region. Vegetation cover increases the infiltration rate (Hejduk and Kasprzak, 2004, 2005), reduces the erosive velocity of surface runoff, and plays a key role in resisting water erosion. A trivial variation in vegetative cover can produce considerable effects in overland flow (Wei et al., 2011). Vegetation cover is a key factor in controlling and reducing surface runoff and water erosion on agricultural land (Hofman et al., 1985).

The scenarios were also developed based upon the common practice which is adopted by the farmers in this area. This area is rainfed agriculture, where the agriculture totally depends upon the precipitation. The common practice for agriculture is the sowing of one or two crops a year. Other than the sowing period the fields remain uncultivated as fallow land. Based upon this practice, the scenario related to land cover change was adopted that is winter wheat to fallow land change. The other management practice is conservation structures which is used by the farmers for soil-water conservation and to meet the crop water requirement. These structures safely pass the overland flow during the monsoon season and minimize the damages of the terrace ridges and bunds.

The SWAT model was applied on the basis of four scenarios at the Dhoke Mori (Khaliq and Ashraf Gulli) and Khandoya catchment sites. The scenarios are described as follows:

Scenario 1 (S1): The model was applied for soil erosion estimation on land without structures under the following conditions: the land use type was determined to be winter wheat; for overland flow, Manning's n = 0.15 (for short grass), and for channel flow, Manning's n = 0.025 (for natural, earth uniform streams).

Scenario 2 (S2): The model was applied for soil erosion estimation on land with structures under the same conditions as S1.

Scenario 3 (S3): The model was applied for soil erosion estimation on fallow land without structures. Manning's n = 0.09 for overland flow. Crop residue and channel flow conditions remained the same.

Scenario 4 (S4): The model was applied for soil erosion estimation on land with structures under the same conditions as S3.

The analysis of the various scenarios (Table 10) revealed that the sediment yield level was higher in S1 and S2 than in S3 and S4. This indicates that the sediment yield level is higher on agricultural land than on fallow land with crop residue. In the comparative analysis of S1 and S2, the average sediment yield decreased to 1.25 t ha^{-1}, whereas in S3 and S4 (fallow land with crop residue), the average sediment yield decreased to 0.85 t ha^{-1}. The results reveal that land use change facilitates sediment yield reduction, in addition to soil conservation structures.

Notably, a visual observation of the various structures revealed that the effects of the structures on soil erosion control generally extended to a 4 to 5 m radius from the center of the structure crests during high flow seasons; the water accumulated and sediment was deposited upstream of the structures.

4.3 Spatial analysis of slope ranges for Attock and Chakwal districts

As reported by various researchers, soil loss is minimal on sloping land with vegetation cover; however, when the available vegetation cover is removed, soil loss becomes more significant as a function of slope length and slope steepness. The stream power (ƮU) as a function of shear stress and flow velocity and the shear stress caused by flowing water are the basic criteria for assessing erosion of soil particles caused by overland flow. Shear stress and flow velocity are directly proportional to slope steepness. This means that the steeper the land slope is, the greater the shear stress becomes, consequently increasing the potential for soil erosion.

Additionally, when soil conservation structures are installed in a field, farmers focus on cultivating agricultural crops in the areas above and below such structures. Considering these factors, this section estimated the potential area that would benefit from the installation of structures in Chakwal and Attock. Accordingly, the suitable slopes for stone structures and agricultural practices were analyzed on district level based on slope characteristics of selected sites. The areas under various slopes in the small watersheds were calculated and are shown in Table.11. All selected sites in the catchment were depicted as having a maximum slope area of less than 5 %. This is because the selected sites were used for agricultural production. Farmers have graded the land as suitable for crop production and generating less surface runoff. The agriculture practices are only possible on soil that has a slope of less than 8 %; otherwise, land grading must be carried out. The same has been suggested by various authors; a USLE experiment conducted at the SAWCRI office concluded that only a slope of less than 10% is acceptable for agricultural practices under rainfed conditions.

The slope classification analysis was performed to check the areal installation applicability of soil and water conservation structures on district level as shown in Table.12. The maximum proportions of the areas in Attock and Chakwal district with less than 20% slope were 94 and 94.5 %, respectively. The table shows that approximately 60% area of Attock and Chakwal district lies in a slope range of 0–4 %, whereas 30% lies in a slope range of 4–10 %. The minimum slope areas were considered according to Betrie et al. (2011), who recommended that stone bunds should be applied in low-slope areas for soil conservation. However, the effectiveness of the structures depends on the local topography and soil and land use–land cover conditions. Considering topographic conditions, considerable potential exists for implementing soil conservation measures through the installation of stone structures. However, appropriate maintenance of the structures is crucial for sustaining effectiveness.

5 Conclusions and Recommendations

In this research, SWAT watershed modeling was performed to describe the driving hydrological and sediment transport related processes of a 2.0 ha catchment in the Dharabi watershed district Chakwal Pothwar region. Based on calibrated and validated SWAT model, the average annual runoff at the outlet was predicted to be 80 mm. The model predicts 15.5 t ha^{-1} as an average annual sediment yield. The effectiveness soil and water conservation structures for soil erosion control was assessed with SWAT model application in selected small watershed of district Chakwal and Attock. The stone bund type structures intervention was done in the model through modification of USLE support practice factor (P-factor), the Curve Number and average slope length (SLSUBBSN). The model results reveal that 40–90 % sediment yield reduction could be achieved using soil conservation structures. Soil and water conservation structures are effective options for soil erosion control in rainfed areas. The land use change scenarios result reveal that vegetation cover facilitates sediment yield reduction, in addition to soil conservation structures. An all-inclusive interpretation of the quantitative model results may be misleading because no model can simulate all physical processes of soil and water interactions in a real sense. Some assumptions were made during modeling; however, the results suggest to policymakers and planners that more than 60 % of the area in Attock and Chakwal districts has potential for soil and water conservation structures.

The following recommendations can be drawn:

1. The conservation structures require regular maintenance because nonmeshing can cause stones to slide, which may lead to the displacement of whole structure.
2. The structures were not designed according to the hydraulic characteristics of surface flow. Downstream damage of the structures was common because of the nonavailability of downstream energy dissipation arrangements.
3. Considering the topographic conditions, loose stone structures should be installed in areas with a slope range of 0–10 %.
4. Wire-meshed stone structures should be installed in areas with a slope range of 6–10 %. Proper energy dissipation arrangements should be implemented to prevent downstream erosion.

Acknowledgments

This study is part of a research project under the CGIAR Research Program (CRP on Dryland Systems) carried out through cooperation between University of Engineering and Technology, Centre for Excellence in Water Resources Engineering, The

International Center for Agriculture Research in the Dry Areas, and Soil and Water Conservation Research Institute. The authors particularly thank all colleagues involved in the fieldwork. This manuscript was edited by Wallace Academic Editing.

Author contributions

Ghulam Nabi was in charge of designing the study and wrote the paper. Fiaz Hussain performed the analysis and produced the results. Ray-Shyan Wu helped in strengthening the quality of the work in terms of data management and result evaluation. The authors Vinay Nangia, Riffat Bibi, and Abdul Majid contributed to the preparation and review of the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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Table 1. Study watersheds sites description

Site Name	District	Land use System	Area (ha)	Main Land Slope (%)
Kohkar Bala	Chakwal	Winter wheat and fallow land	2.75	7.15
Khandoya			5.37	4.35
Dhoke Mori (Khaliq Gully, Ashraf Gully)			1.25, 2.64	3.75, 3.52
Chak Khushi			2.33	2.31
Dhoke Dhamal	Attock	Winter wheat and fallow land	7.03	3.86
Dhoke Hafiz Abad			3.22	4.80

Table 2. Model input data source

Data Type	Source	Data Description and Properties
Topography (DEM)	Surveying Using GPS and Total Station (SAWCRI, Chakwal)	Point elevation data interpolated using IDW method for using as Digital Elevation Model
Soil Map	Soil Textural Analysis by SAWCRI, Chakwal	Samples at different locations were taken physical properties of soil determined
Landuse Map	Google Earth	Classification were done based upon reconnaissance survey and google earth survey
Climate Data	Automatic weather station and water level recorder installed by SAWCRI Chakwal	Daily data of Precipitation, Temperature, Wind speed, Relative Humidity, Solar Radiation and Flow data
Sediment Data	An experimental setup for measurement of sediment load by SAWCRI Chakwal Department.	Event based sediment data

Table 3. Soil textural classification in catchment-25

Sample Location	% Sand	% Silt	% Clay	Texture Class
UG	15	17.5	67.5	Sandy Loam
MG	20	10	70	Sandy Loam

LG	25	22.5	52.5	Sandy Clay Loam
W25 B	27.5	27.5	45	Sandy Clay Loam
W25 F	27.5	30	42.5	Clay Loam

Table 4. Land use classification of catchment-25

Processed Land use	SWAT Class	Percentage of Catchment Area
Agricultural Land	Agricultural Land Generic (AGRL)	14.19
Fallow/Range Land	Crop Land/Grass land Mosaic (CRGR)	24.54
Mixed Trees/ Forest	Forest Mixed (FRST)	1.49
Barren Land with Shrubs and Bushes	Mixed Grass Land/ Shrubs (MIGS)	59.78

Table 5. Soil erosion estimation parameters used in ArcSWAT

S. No.	Parameter	Description
1	USLE_P	USLE conservation practice factor
2	USLE_C	Cover and management factor in USLE
3	USLE_K	USLE Soil erodibility factor
4	SPCON	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing
5	SPEXP	Exponent parameter for calculating sediment re-entrained in channel sediment routing
6	CH_EROD	Channel Erodibility factor
7	CH_COV	Channel Cover factor

Table 6. Soil erosion parameters ranking and values used during model calibration and validation

Parameter	Default Value	Value Used	Ranking
USLE_P	0 to 1	0.65	1
SPEXP	1.0 to 2.0	1.0	2
SPCON	0.0001 to 0.01	0.0032	3
USLE_C	0.001 to 0.5	0.182	4
USLE_K	0 to 0.65	0.246	5

Table 7. SWAT model performance evaluation

Surface Runoff		
Parameter	Calibration	Validation
d(%)	1.91	5.68
R^2	0.84	0.81
EN-S	0.81	0.78
PBISA	1.89	-5.85
RMSE	2.63	0.80
Sediment Yield		
d(%)	0.26	2.1
R^2	0.82	0.79
EN-S	0.79	0.76
PBISA	-0.26	2.1
RMSE	0.85	0.14

Table 8. SWAT parameters used to represent conservation structures

Parameter Name (input file)	Modified Value
SLSUBBSN (.hru)	60
HRU_SLP (.hru)	0.016
CN2 (.mgt)	65
USLE_P (.mgt)	0.11
SPCON (.bsn)	0.001
SPEXP (.bsn)	1.25

Table 9. Effect of stone structures on sediment yield reduction

Sediment Yield (t/ha) Reduction due to Stone Structures															
	Khaliq Gully			Ashraf Gully			Khokar Bala			Chak Khushi			Dhoke Dhamal		
Year	W.O.S	W.S	% Red	W.O.S	W.S	% Red	W.O.S	W.S	% Red	W.O.S	W.S	% Red	W.O.S	W.S	% Red
2010	59.3	30.3	49.0	25.0	10.4	58.5	37.6	0.9	97.6	1.6	0.8	49.4	15.3	8.3	45.7
2011	25.8	15.3	40.6	10.7	2.6	75.8	21.9	0.4	98.1	0.9	0.4	58.8	6.7	2.3	66.3

2012	2.3	0.0	100	0.9	0.0	100	3.9	0.1	98.5	0.0	0.0	100	0.6	0.0	98.2
2013	32.9	14.6	55.7	14.0	3.5	75.2	28.7	0.7	97.7	1.1	0.2	78.2	8.9	2.2	75.0
2014	27.6	11.9	57.0	11.6	2.2	81.1	13.8	0.2	98.6	0.8	0.2	69.7	7.4	1.8	75.4
2015	34.0	25.2	25.9	14.5	3.0	79.0	21.1	0.3	98.8	0.9	0.1	92.1	9.4	0.9	90.3
Ave.	-	-	54.7	-	-	78.3	-	-	98.2	-	-	74.7	-	-	75.2

Table 10. Effect of different scenarios on sediment yield reduction

Catchment Name	S1 (t/ha)	S2 (t/ha)	S.Y Reduction	S3 (t/ha)	S4 (t/ha)	S.Y Reduction
Ashraf Gully	10.95	10.15	0.80 t/ha	7.91	7.04	0.86 t/ha
Khaliq Gully	25.98	24.75	1.23 t/ha	17.10	16.5	0.60 t/ha
Khandoya	48.75	47.0	1.75 t/ha	42.28	41.18	1.1 t/ha

Table 11. Area under different slopes in small watersheds of Chakwal and Attock districts

	Ashraf Gully	Khaliq Gully	Chak Khushi	Dhok Dhamal	Khokar Bala	
Slope (%)	Area (%)	Area (%)	Area (%)	Area (%)	Slope (%)	Area (%)
0-2	63	50	97	81	0-5	65
2-5	30	42	3	17	5-10	25
>5	7	8	-	1	>10	10

Table 12. Slope classification analysis of Chakwal and Attock districts

Slope Category	Chakwal		Attock	
	Area	Area	Area	Area
(%)	km^2	(%)	km^2	(%)
0-4	4095	60	3918	61
4-10.1	1913	28	1786	28

10.1-20	547	8	472	7
20.1-40	233	3	165	3
40-90	75	1	55	1

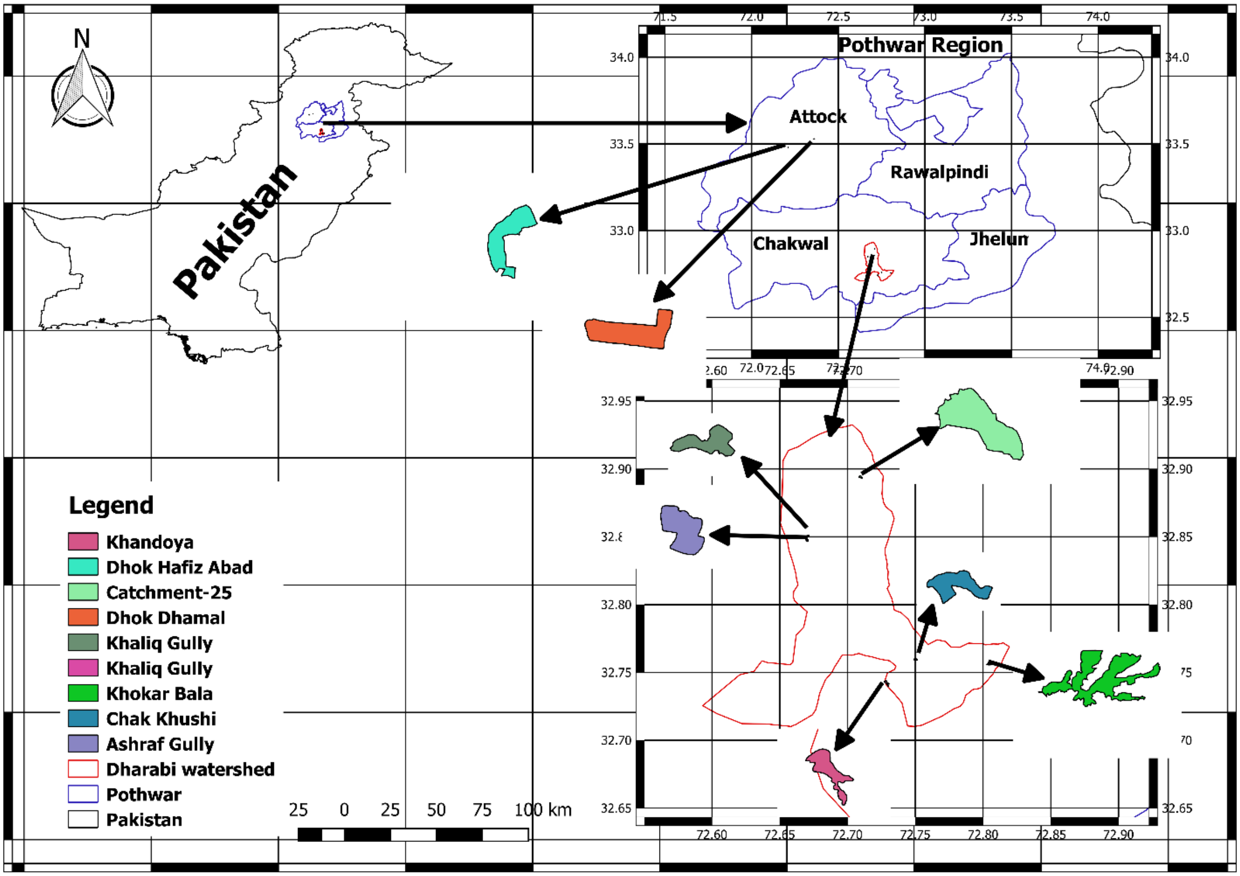


Figure 1. Location map of Pothwar region, Dharabi watershed and small catchment and watersheds.

Figure 2. Terraced cultivated lands in Pothwar

Figure 3. Breached terrace bund/embankment

Figure 4. Loose stone structures system

Figure 5. A loose stone structure in the field

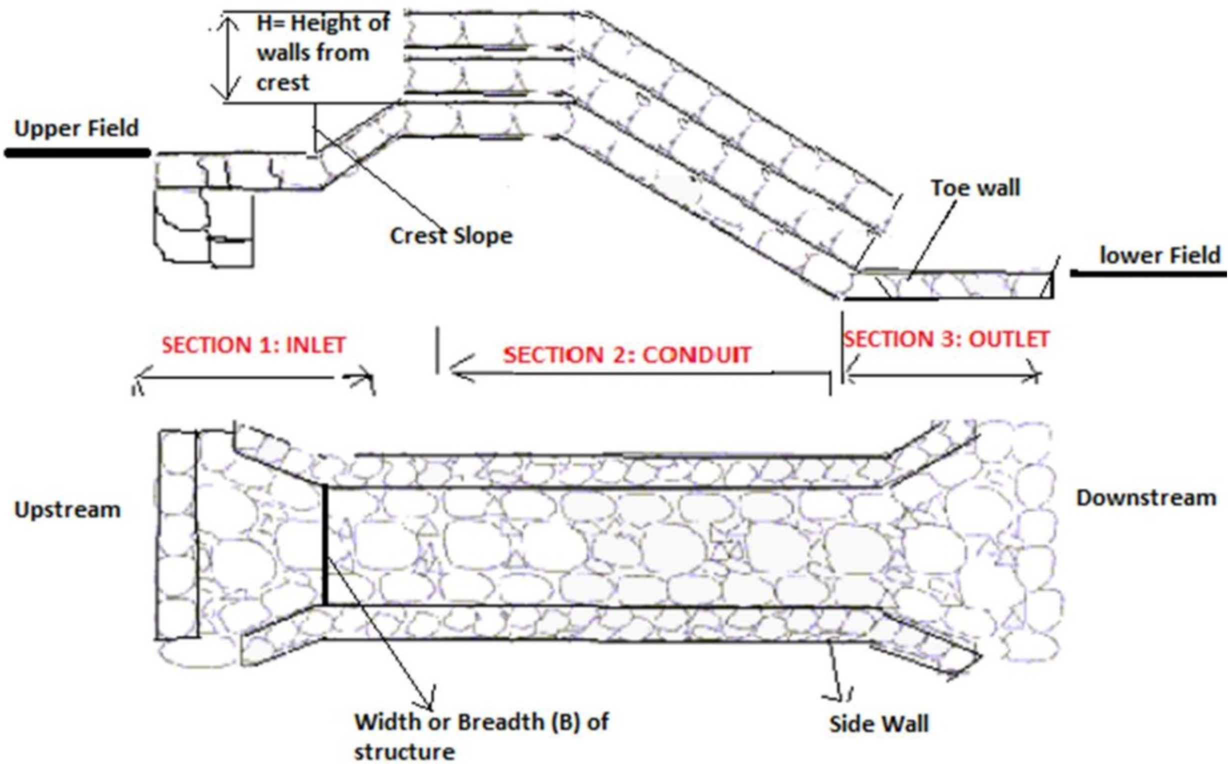


Figure 6. Cross-section of a loose stone structure

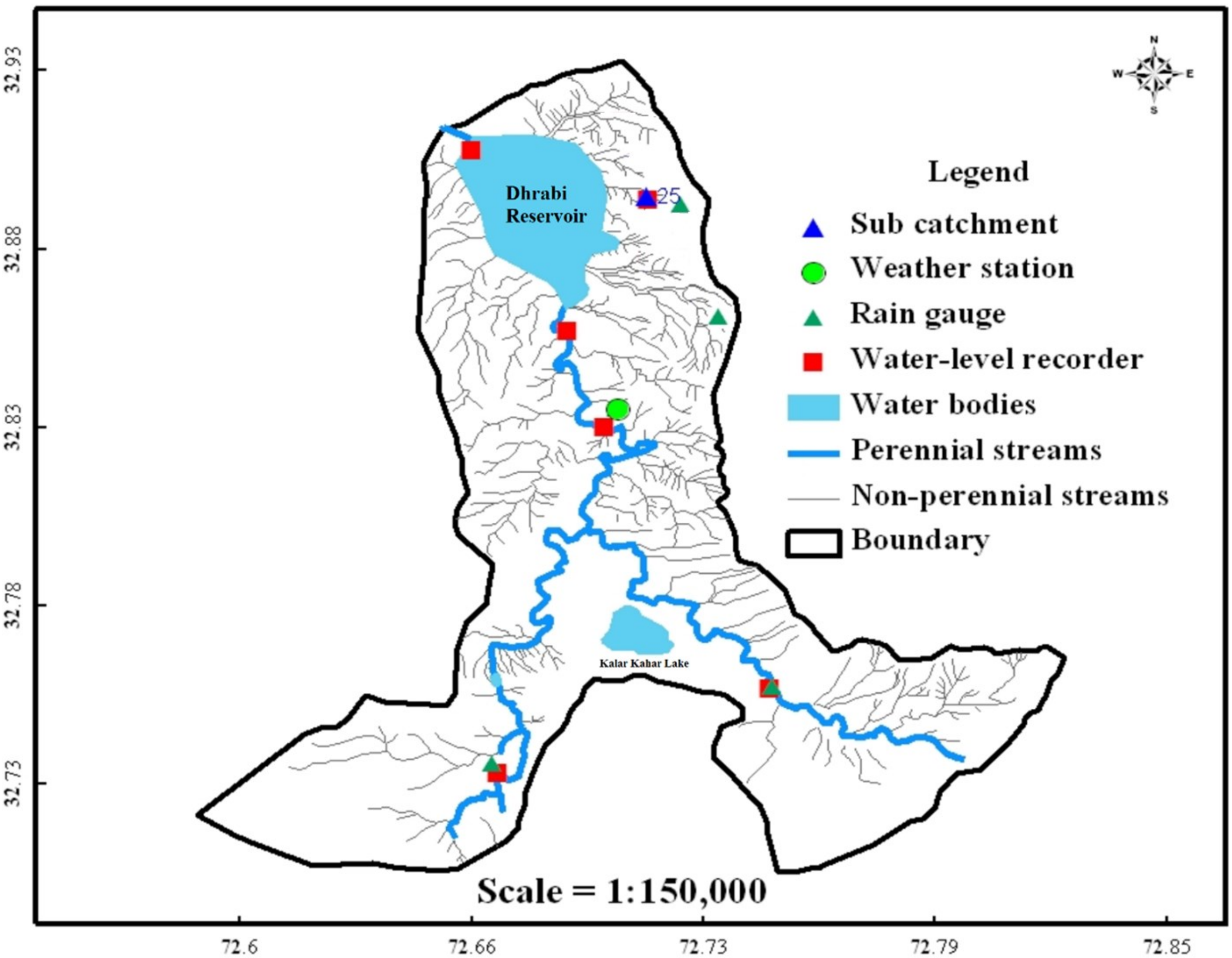


Figure 7. Location of Catchment-25 of Dharabi watershed used for model calibration and validation.

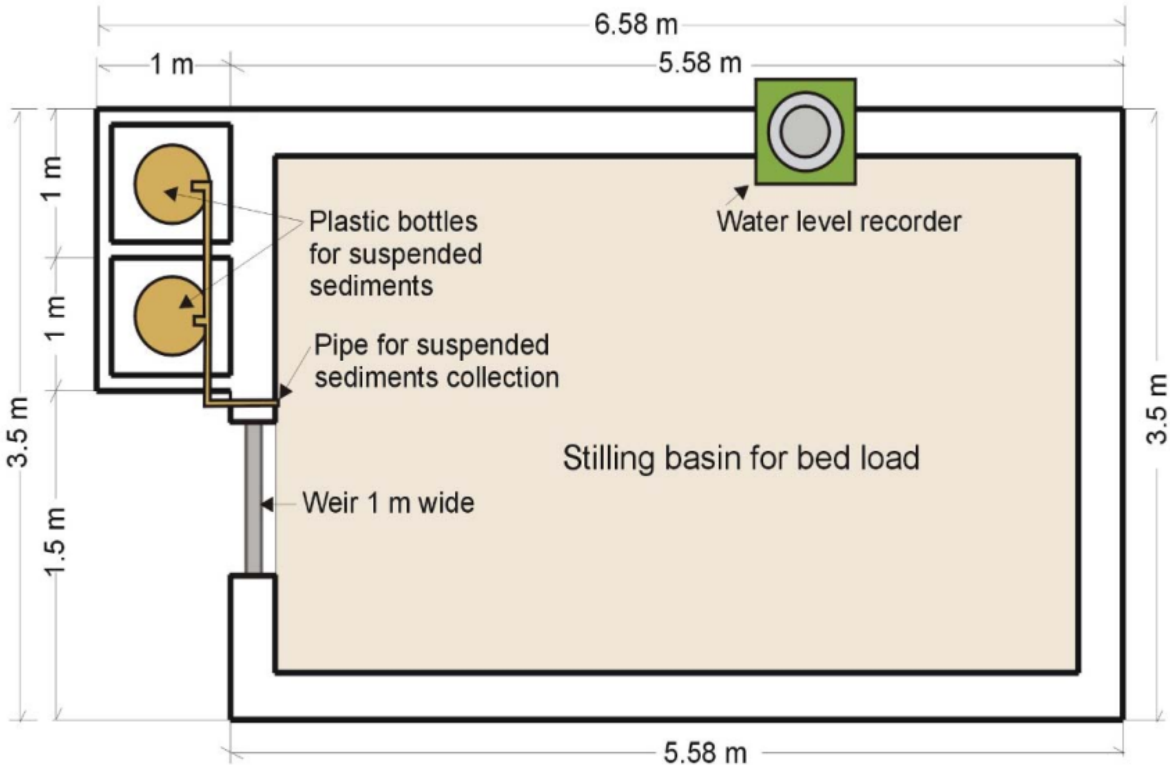


Figure 8. A schematic showing the arrangement for the collection of sediment and runoff

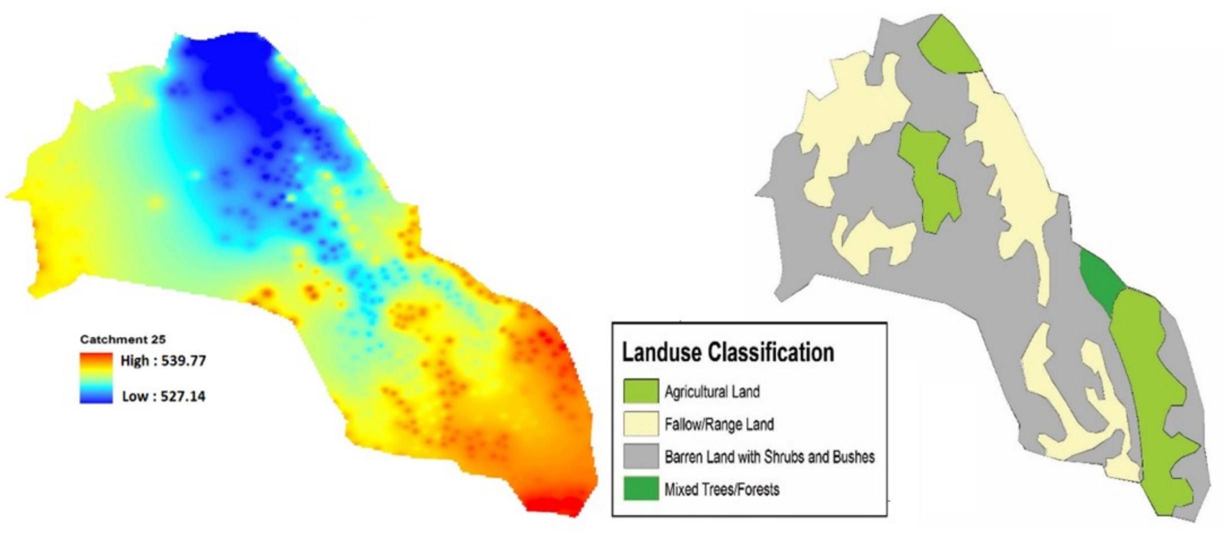


Figure 9. Digital Elevation Model (DEM) and Land use classification of Catchment-25

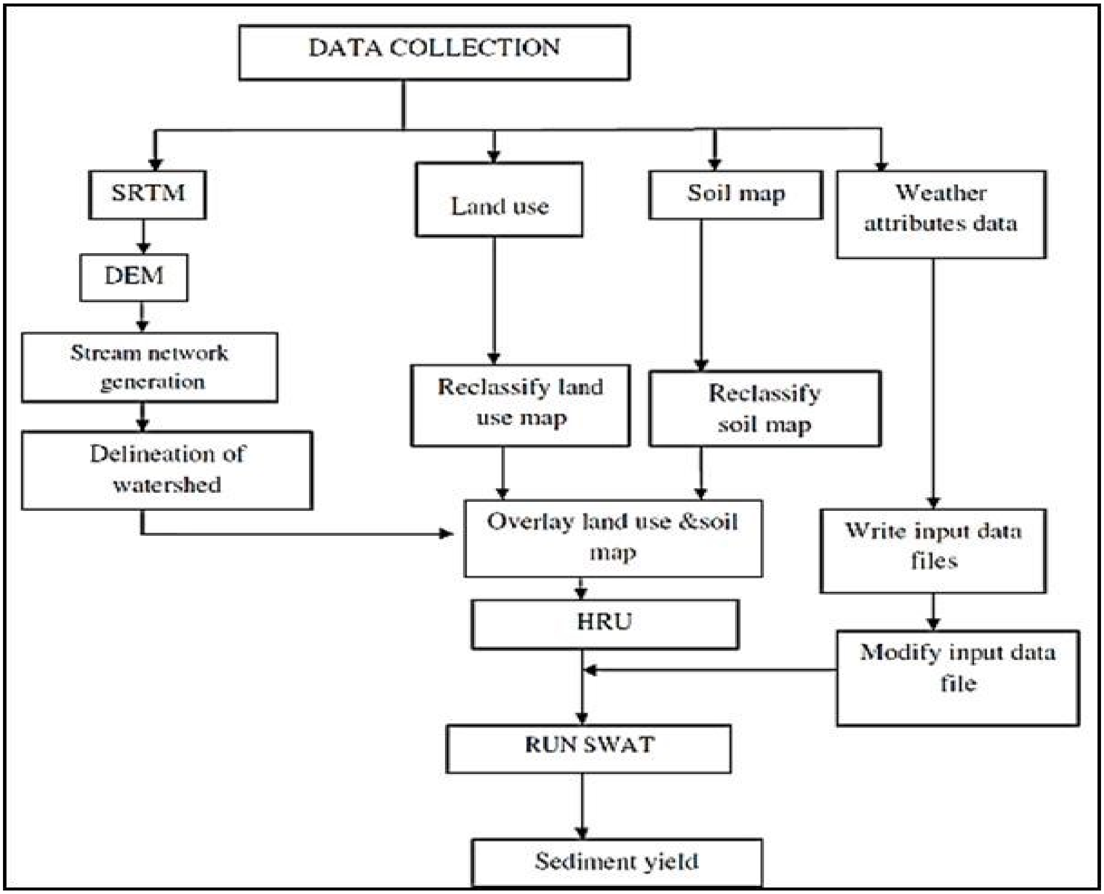


Figure 10. General algorithm used for sediment yield simulation in Arc SWAT

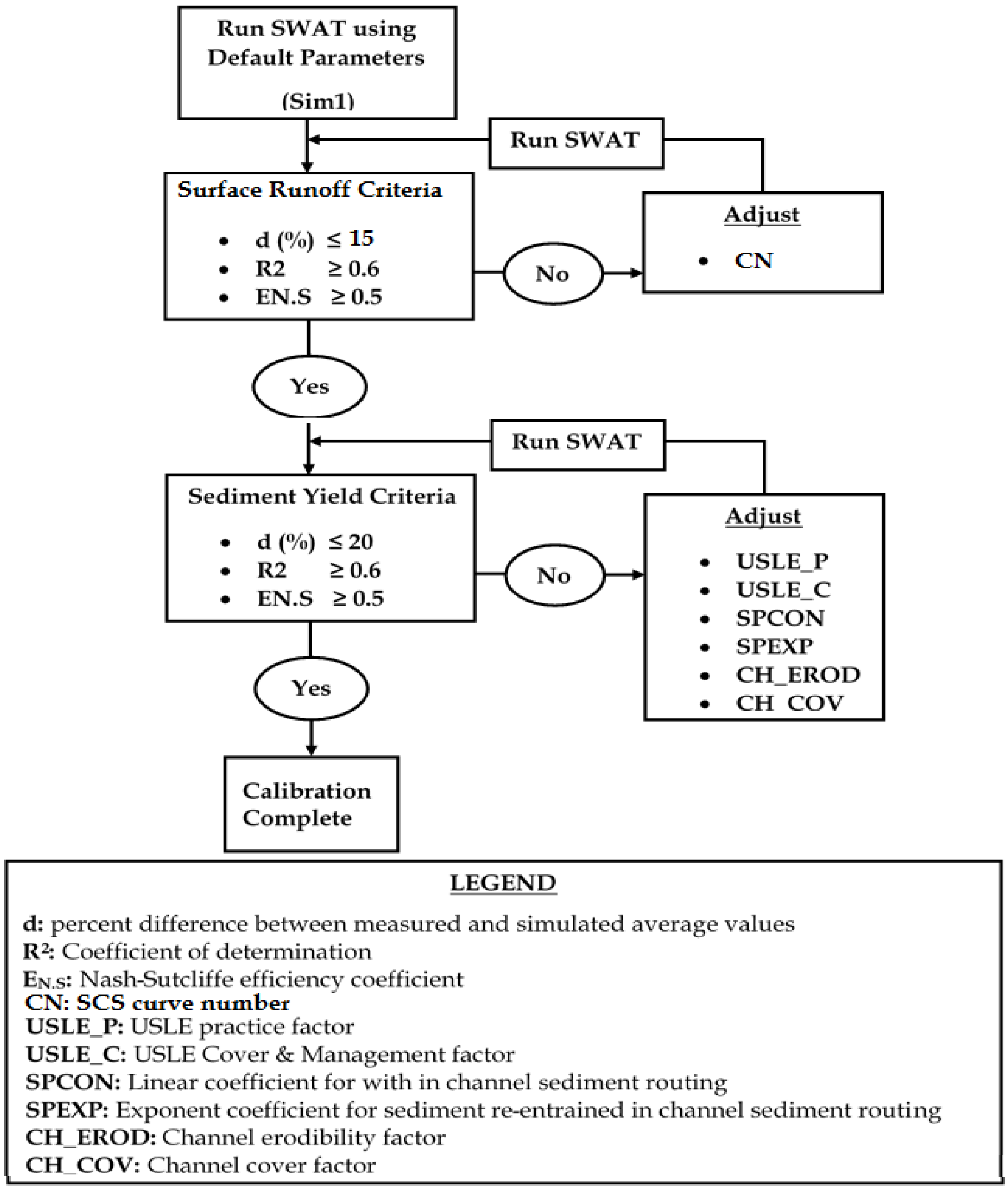
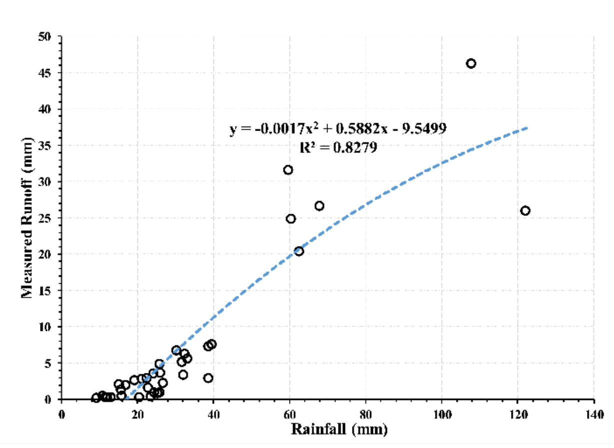


Figure 11. SWAT manual calibration flowchart for surface runoff and sediment yield (from Engel et al., 2007; adapted from Santhi et al., 2001)



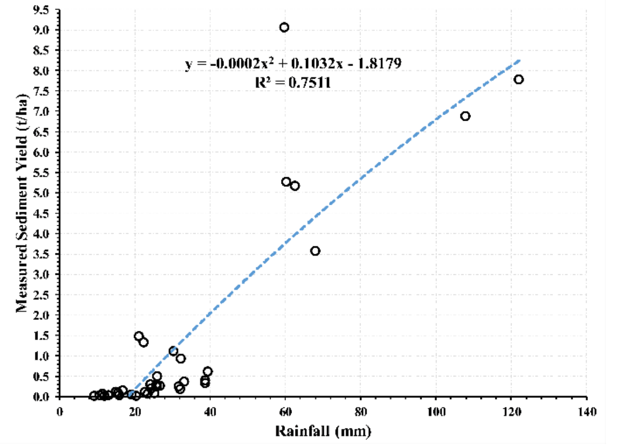


Figure 12. The best fit relation between rainfall-runoff and sediment yield for observed data (2009-2011)

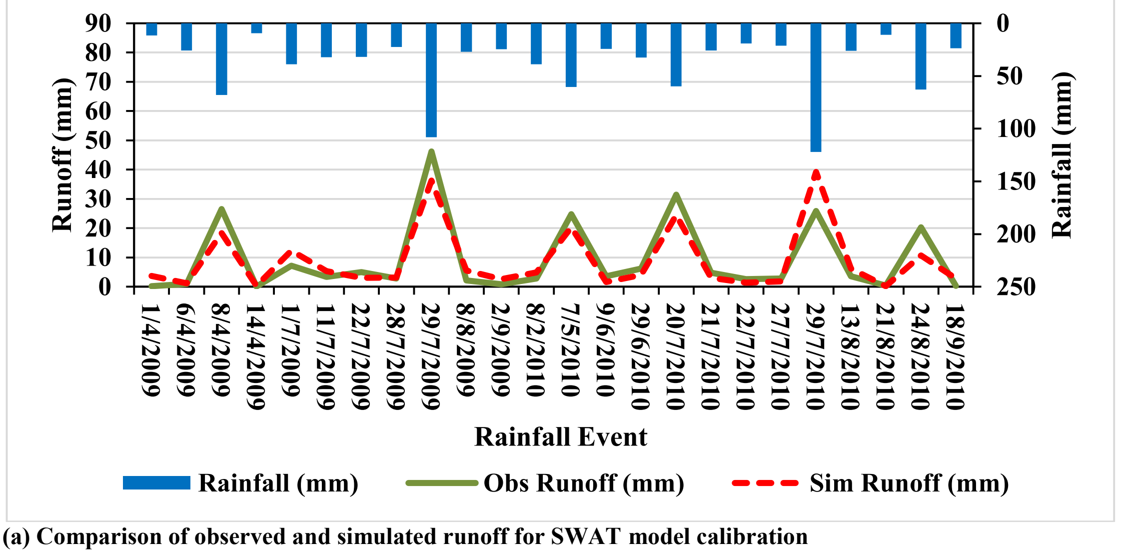


Figure 13. (a) Comparison of observed and simulated runoff for SWAT model calibration

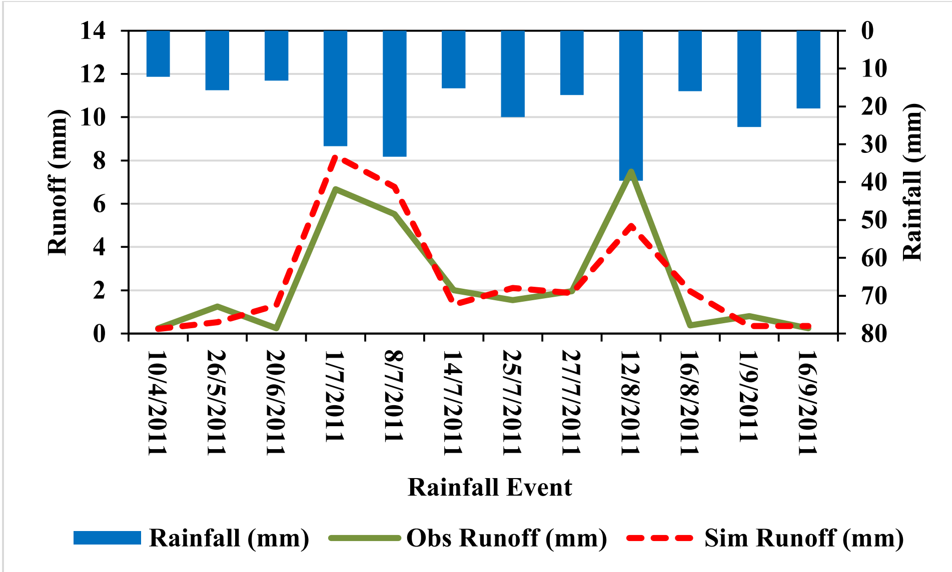


Figure 13. (b) Comparison of observed and simulated runoff for SWAT model validation

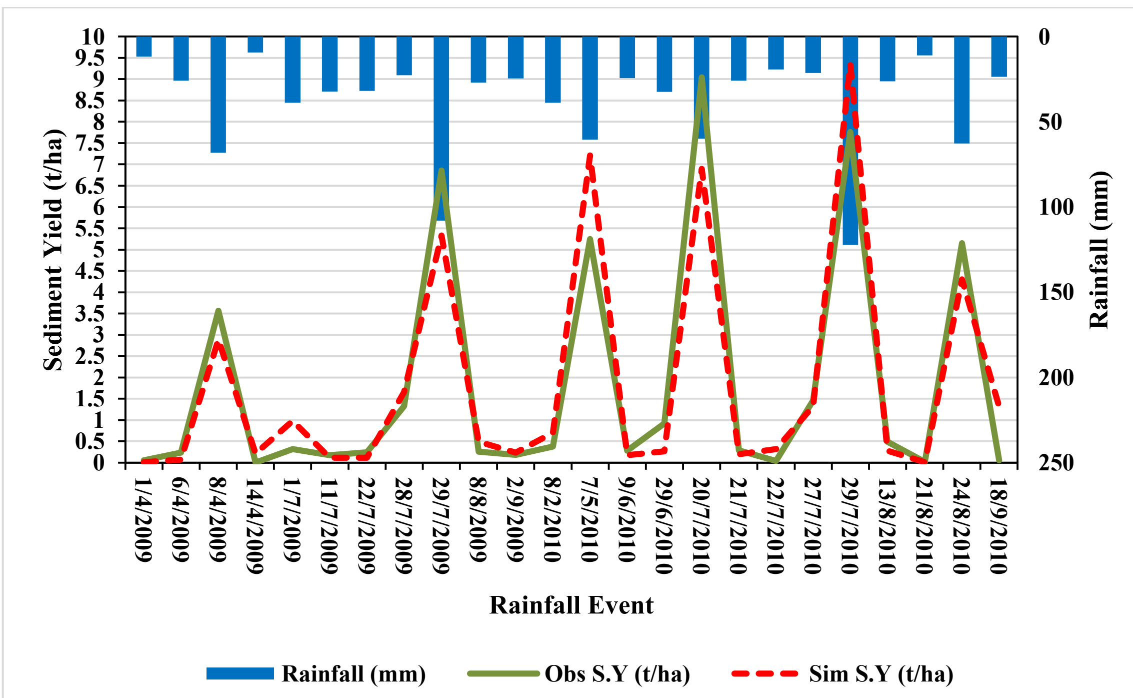


Figure 14. (a) Comparison of observed and simulated sediment yield for SWAT model calibration

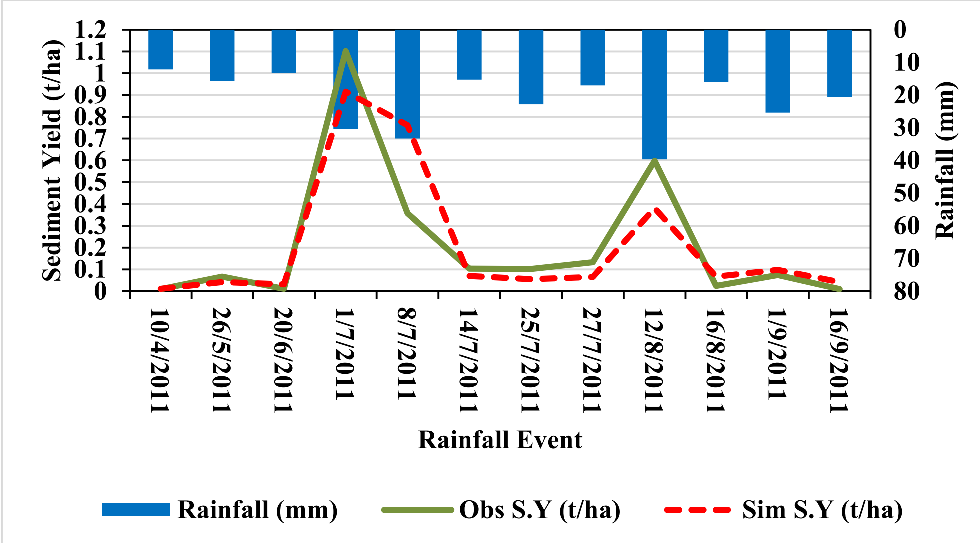


Figure 14. (b) Comparison of observed and simulated sediment yield for SWAT model validation

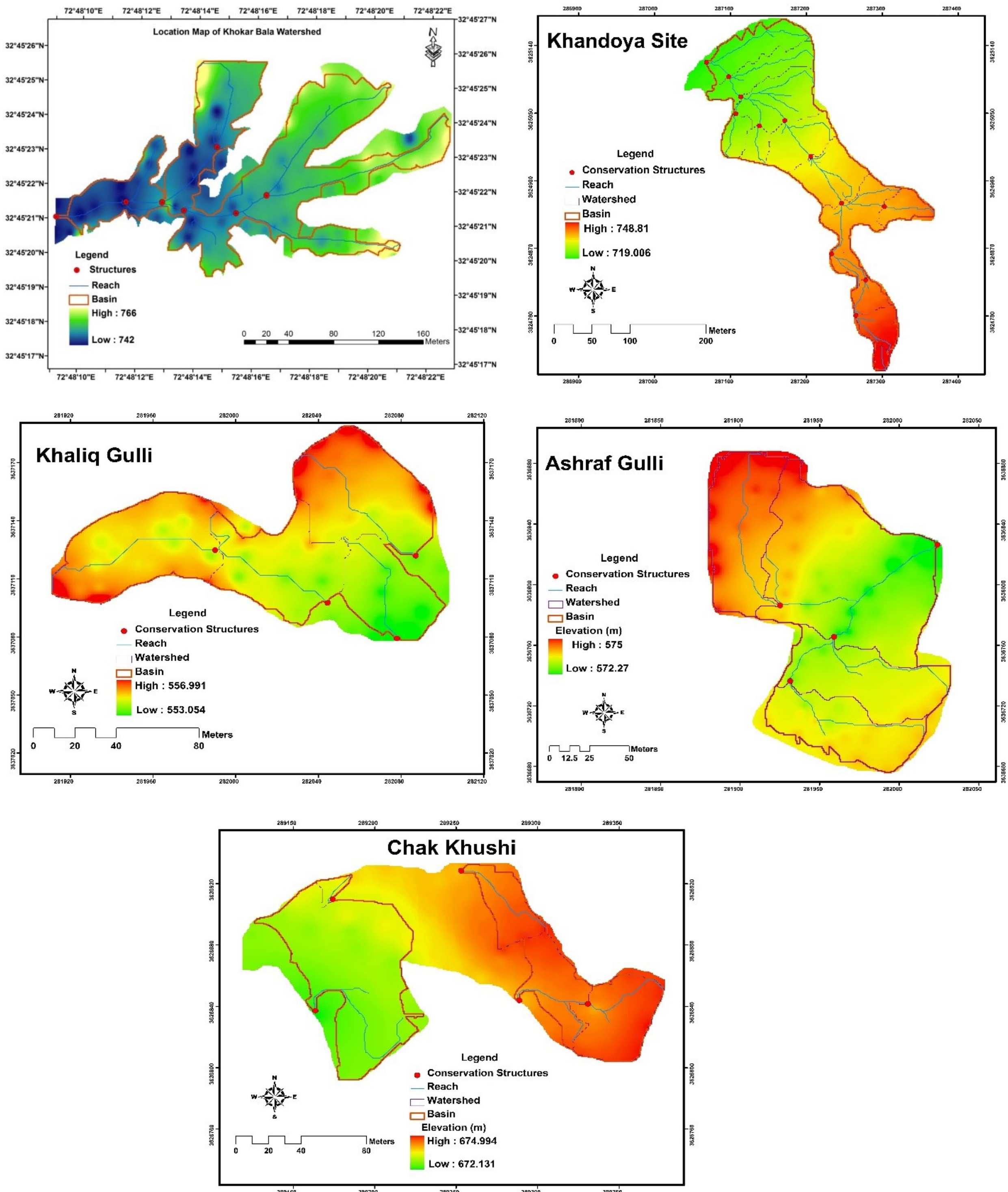


Figure 15. (a) Topographic maps of selected small watersheds in Chakwal District for model application.

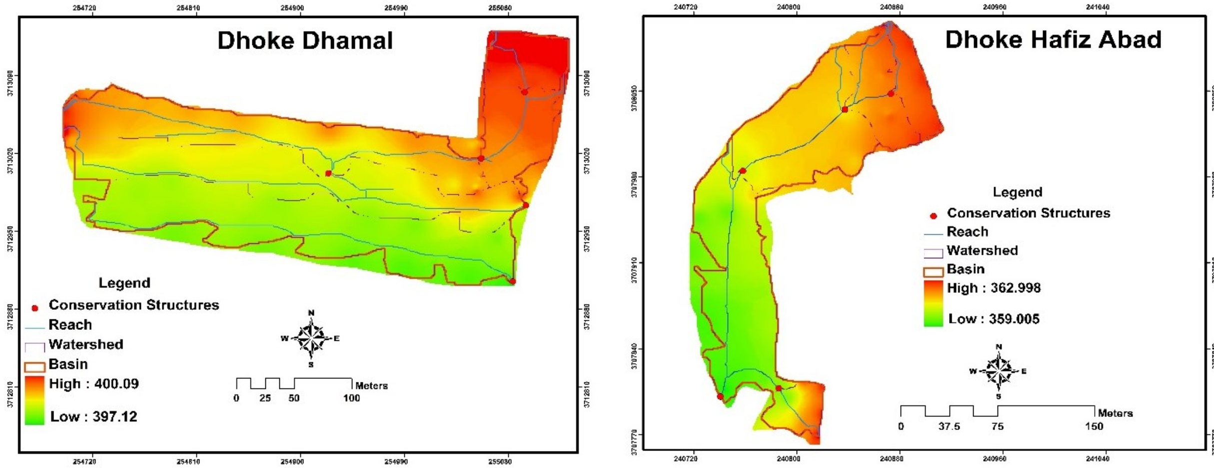


Figure 15. (b) Topographic maps of selected small watersheds in Attock District for model application

Figure 16. Pictorial view of data collection and conservation structures at different locations