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Runoff and Soil Erosion Assessment for Watershed Conservation Planning - A Case Study of Asan Watershed

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Abstract

Runoff is the most important hydrological component for a design of any hydrologic structure and especially in the area of water scarcity. However, in pursuance of comfort and self-prevention, humankind is modifying the land use/land cover (LULC) which impacts hydrology of the area. The consequent impact of such degradation of forest is high erosion in the watershed. Moreover, the excessive soil erosion impairs the soil productivity capability and reduces the water availability in reservoirs. Watershed management or protection implies the proper use of all land and water resources for optimum production with minimum hazard to natural resources as watershed conservation planning. Therefore, it is necessary to study runoff and soil erosion simultaneously. In the present study, Asan watershed has been taken as the study area, which is located in Dehradun valley of Uttarakhand State, India.

In this study, the Natural Resource Conservation Services Curve Number (NRCS-CN) method is used to assess the runoff, and the Modified Morgan Finney (MMF) model is used to assess soil erosion rate. Based on the estimated runoff and soil erosion, the watershed conservation measures are suggested. In this regard, LULC map has been derived from Landsat TM data of 2010. The soil map has been procured from NBSS&LUP. The slope map has been derived from ASTER GDEM data. Rainfall data of Forest Research Institute which lies within the watershed has been utilized. With the help of LULC and HSG map, CN map has been derived, which is further corrected for slope. Finally, the runoff depth in mm has been estimated. In MMF model, parameters such as annual rainfall, soil moisture content at field capacity, bulk density, effective hydrological soil depth, soil detachability index, slope, interception capacity, canopy cover, ground cover, plant height, crop cover management factor and ratio of actual and potential evapotranspiration have been derived for soil erosion computation.

The results show that there is runoff of 816.34 mm out of 2173 mm rainfall. The runoff coefficient is around 37.56 %. The relationship between rainfall and runoff is polynomial second order, and runoff will occur when rainfall per day is greater than 18 mm. The study results also show that average raindrop detachability is 120 tons/ha/year, and the average detachability by runoff is 6.70 tons/ha/year. The average soil detachability is 126.8 tons/ha/year. The average transport capacity by runoff is 335.90 tons/ha/year. Average annual soil loss of 68 tons/ha/year has been estimated. For water conservation measure, 22 suitable sites were identified for water harvesting structure as check dam and soil conservation measure, agronomical measure, contour bunding and bench terrace.

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1. Introduction

Watershed is defined as a geo-hydrological unit draining to a common point by a system of drains. All lands on earth are part of one watershed or other. Watershed is thus the land and water area, which contributes runoff to a single point. Watershed can be only a few hectares as in case of small pounds or hundreds of square kilometres as in case of river. All watersheds can be divided into smaller sub-watersheds and each watershed or sub-watershed is an independent hydrological unit. According to main objective of watershed management, there should be a proper use of all land and water resource of a watershed for optimum production with minimum hazard to natural resources; any modification of land use in the watershed or sub-watershed will reflect on the runoff as well as sediment yield of the watershed (Water Resources Division, IIRS, 2007). Soil erosion by water is a major hazard of a watershed, assessment and inventory on surface runoff, and soil erosion are essential for formulation of effective watershed conservation plans of a watershed for sustainable development (Bhatt et al., 2011).

Morgan et al. (1984) presented a simple empirical model for predicting annual soil loss from field-sized areas on hill slopes. The MMF model used the concepts proposed by Meyer and Wischmeier (1969) and Kirkby (1976) to provide a stronger physical base than the USLE (Wischmeier and Smith, 1978), yet retain the advantages of an empirical approach regarding ease of understanding and availability of data. The model was validated by the authors (1984) using erosion plot data for 67 sites in 12 countries and then applied to simulate erosion over a 100-year period in Malaysia under shifting cultivation. Since then, several researchers have used the model successfully in a wide range of environments ranging from Indonesia (Besler, 1987) to Nepal (Shrestha, 1997) and the Rocky Mountains (Morgan, 1985).

Natural Resources Conservation service Curve Number method (NRCS-CN), USDA (formerly known as Soil Conservation Services method) is widely used to estimate surface runoff because of its flexibility and simplicity. The method combines watershed parameters and climatic factors in one entity called the Curve Number (CN). Mishra and Singh (2002) modified this method for long-term hydrology simulations by incorporating an evapotranspiration component, modifying the initial abstraction estimation techniques and extending it for computation of infiltration and runoff rates. Bhuyan et al. (2001) used the modified CN technique for predicting surface runoff by adjusting the CNs based on the estimated antecedent moisture condition (AMC) ratios. It was shown that the CN approach could be used for accurate prediction of runoff depths from storm events over ungauged watersheds. Bhuyan et al. (2003) studied events based watershed scale AMC values to adjust field-scale CNs, and to identify the hydrological parameters that provide the best estimate of AMC. The AMC condition of the watershed refers to the 5 days preceding rainfall, in which conditions I, II and III denote the low, medium and high runoff potentials, respectively. Many researchers (Pandey and Sahu, 2002; Nayak and Jaiswal, 2003; Zhan and Huang, 2004; Gandini and Usunoff, 2004) have utilized the Geographic Information System (GIS) technique to estimate runoff CN value throughout the world. Therefore, the use of a GIS is preferred over the traditional techniques such as quantify surface runoff by storing and analysing the factors responsible for runoff. The estimation process becomes more efficient, interactive and less cumbersome when the GIS is used for storing, interpreting and displaying the data required in CN-based runoff estimation techniques.

In this study, the main objectives are 1) to assess runoff by using NRCS-CN method with the help of remote sensing and GIS techniques. 2) to assess annual rate of soil erosion with the help of remote sensing and GIS techniques using MMF model approach. And 3) to propose the watershed conservation plans.

2. Study Area

Asan watershed, Dehra Dun district, Uttarakhand State, India has been selected for the present study. It covers an area of approximately 654.47 km^2 and lies between latitudes 30^o 14” 14’ N to 30^o 29” 54’ N and longitudes 77^o 39’’ 42’ E to 78^o 05’’ 30’ E (Figure 3-1). It is bound in the north by the Lesser Himalayan range and in the south by the Siwaliks. It forms an asymmetrical synclinal valley. This watershed is occupied by the Asan river which flows north-westwards and joins the Yamuna river. All these physiographic units are extended NW-SE to ENE-WSW. The major drainage present in the area is parallel to sub-parallel, sub-dendritic, trellis, angular, rectangular, intermittent and braided.

Climate of the study area is sub-tropical to temperate on higher elevation (more than 1,800 m.) It varies greatly from tropical to severe cold depending upon the altitude of area. The average annual temperature is 21^o C in summers to 5^o C in winters. Most of the annual rainfall in study area received during the months from June to September, July and August being rainiest. The mean annual rainfall in the watershed is around 1,917 mm. Relative humidity is recorded as 91% in January. There are three distinct seasons of Monsoon, winter and summer. The extreme temperature was recorded in the area as 0^o to 42^o C during the winter and summer season respectively.

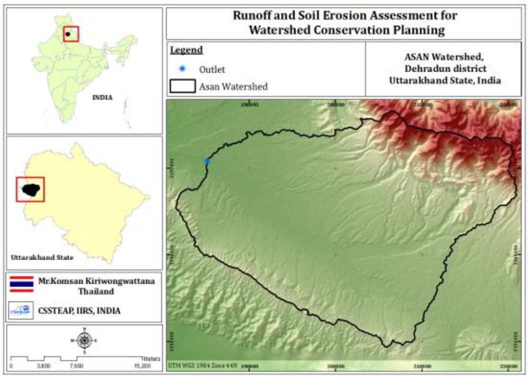

Fig. 1. Location map of Asan watershed

3. Materials And Methodology

In the present study, the Natural Resource Conservation Services Curve Number (NRCS-CN) method is used to assess runoff and the Modified Morgan Morgan Finney (MMF) model is used to assess soil erosion rate. Based on the estimated runoff and soil erosion, the watershed conservation measures are suggested. In this regard, LULC map has been derived from Landsat TM data of 2010. The soil map has been procured from NBSS&LUP. The slope map has been derived from ASTER GDEM data. Rainfall data of Forest Research Institute lies within watershed has been utilized. With the help of LULC and HSG map, CN map has been derived, which is further corrected for slope. Finally, the runoff depth in mm has been estimated. In MMF model, parameters such as annual rainfall, soil moisture content at field capacity, bulk density, effective hydrological soil depth, soil detachability index, slope, interception capacity, canopy cover, ground cover, plant height, crop cover management factor and ratio of actual and potential evapotranspiration have been derived for soil erosion computation.

3.1 Methodology for runoff estimation

For runoff estimation, there are numerous runoff models that could be selected. The Natural Resource Conservation Service Curve Number (NRCS-CN) model (USDA, 1972) has been selected as it requires few parameters and is both realistic and robust. This method is also known as the Hydrological Soil Cover Complex

Method. This is based on some empirical formula and basis inputs like CN, slope, land use and land cover, hydrological soil group, etc. In this model, there are developed relationships between rainfall and runoff. Curve number is the watershed coefficient, which is an index that represents the combination of hydrological soil group and land use/land cover (Chow et al., 1988 and Mishra et al., 2006). The main criticism of the curve number method was that the amount of simulation runoff was not sensitive to rainfall intensity (Terzoudi et al., 2007)

The empirical NRSC-CN model was developed by studying runoff in many small experimental watersheds. In the NRCS-CN runoff equation, the ratio of amount of actual retention to watershed storage is assumed to be equal to the ratio of actual direct runoff to the effective storm rainfall. The assumed relationship in mathematical form is:

$$\frac{F}{S} = \frac{OF}{P - I} \tag{1}$$

Where

F is actual retention (mm);
S is initial abstraction and maximum losses after overland flow begins (mm);
OF is the overland flow in a rainfall event or actual direct runoff (mm);
P is total rainfall (mm); and I initial abstraction (mm).
I is initial abstraction (mm).

Overland flow (OF) to be computed using the following equation:

$$OF = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (P > 0.2S) \tag{2}$$

Since overland flow (OF) will occur when P exceeds 0.2S value (P being the rainfall per rain day or month), the following is applied when this occurs. The parameter S is related to CN by US Soil Conservation Services Model (Murth, 2004):

$$S = \frac{25400}{CN} - 254 \text{ (mm)} \tag{3}$$

Where, CN is the runoff curve number

The CN is a dimensionless runoff index determined based on HSG, land use, land treatment, hydrologic conditions and antecedent moisture condition (AMC). The CN method is able to reflect the effect of changes in land use on runoff. The CN values range between 1 and 100. Higher values of CN indicate higher runoff. The NRCS runoff equation is widely used in estimating direct runoff because of its simplicity, flexibility and versatility.

AMC is an indicator of watershed wetness and availability of soil storage prior to a storm. Moisture content at the time of rainfall plays a very important role for determining OF, and the moisture conditions are expressed as AMC I for dry (wilting point), AMC II for normal (average moisture condition); and AMC III for wet (field capacity) conditions). In NSCS model, slope correction was done using the Slope Corrected Empirical Formula as bellow:

$$CN_{2s} = 1/3\ (CN_3 - CN_2)[1 - 2\exp(-13.86S)] + CN_2 \tag{4}$$

Where

CN_{2s} is the moisture condition II curve number adjusted slope;
CN_3 is the moisture condition III curve number for the default 5% slope;
CN_2 is the moisture condition II curve number of the default 5% slope;
S is the average slope (in percent).

For AMC class I $$CN_{1s} = \frac{(4.2 * CN_2)}{(10 - 0.058 * CN_2)} \quad (5)$$

For AMC class III $$CN_{3s} = \frac{23 * CN_{2s}}{(10 + 0.13 * CN_{2s})} \quad (6)$$

In this study, mean daily runoff to be computed by using AMC was derived from daily rainfall data of Forest Research Institute (FRI). Classification of antecedent moisture classes for the NRCS-CN method of rainfall abstraction is shown in Table 1

Table 1. Antecedent moisture condition classes

AMC Condition	AMC (mm)		Runoff producing condition
	Dormant Season	Growing season	
I	<12.5	<35	Dry soil but not the wilting point; Lowest runoff potential
II	12-27.5	35-32.5	Average condition; Moderate runoff potential
III	>27.5	>52.5	Saturated soil; heavy rainfall or light rain; Highest runoff potential

Sources: E.M. Tideman, 2000

Moisture content at the time of rainfall plays a very important role for determining the runoff, and the moisture conditions are expressed as AMC I, II and III.

CN is an index that represents the combination of HSG and land cover (Chowl et al., 1998 and Mishra et al., 2006). HSG depends upon soil texture, soil depth, drainage, permeability and water table depth. In this study, HSG is derived by using geomorphology, soil texture and depth of the study area. Standard HSG according to soil texture (Chowl et al., 1988).

Geomorphology, soil texture and soil depth of the area has been crossed with each other, and HSG is assigned for the study area. After assigning, the HSG to soil texture was merged with land cover map to prepare hydrological soil cover complex and assigned the CN.

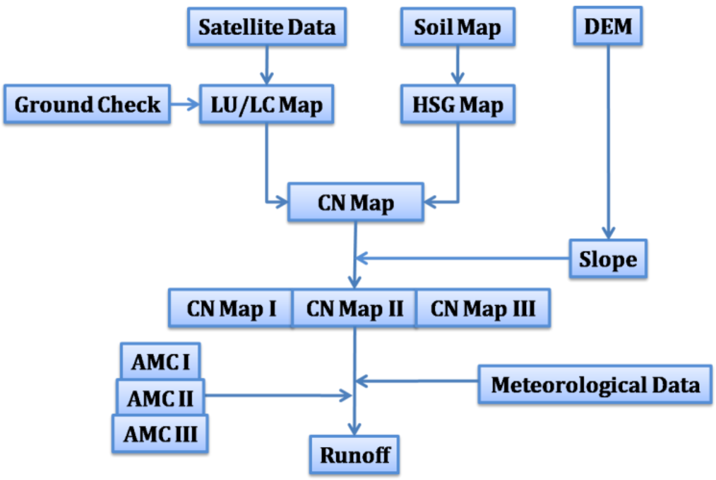

Fig. 2. Flowchart of the methodology for NSCS Curve Number Model

3.2 Methodology for soil erosion estimation

Soil erosion is a general term for a complex set of process, and there are no united models that consider all its aspects. Remote sensing lends itself to water erosion more than wind erosion because there are no currently available techniques for estimating rainfall. In this study, the following Morgan-Morgan-Finney (MMF) model was applied to Asan watershed for soil erosion estimation.

The MMF model separates the soil erosion process into two phases: the water phase and the sediment phase. The water phase determines the energy of the rainfall available to detach soil particles from the soil mass and the volume of runoff. In the erosion phase, rates of soil particle detachment by rainfall and runoff are determined along with the transporting capacity of runoff. Using the procedure proposed by Meyer and Wischmeier (1969), predictions of total particle detachment and transport capacity are compared, and erosion rate is equated to the lower of the two rates.

3.2.1 Estimation of rainfall energy

The procedure for calculating the energy of rainfall is revised from that in the original version of the model to take account of the way rainfall is partitioned during interception and the energy of the leaf drainage. The model takes the annual rainfall total (R; mm) and computes the proportion (between 0 and 1) which reaches the ground surface after allowing for rainfall interception A to give the effective rainfall (ER):

$$ER = R*A \qquad (6)$$

The effective rainfall (ER) is then split into that which reaches the ground surface as direct throughfall (DT) and that which is intercepted by the plant canopy and reaches the ground as leaf drainage (LD) The split is a direct function of the percentage canopy cover (CC):

$$LD = ER*CC \qquad (7)$$

$$DT = ER - LD \qquad (8)$$

The kinetic energy of the direct throughfall (KE(DT) ; Jrm2) is determined as a function of the rainfall intensity (I; mm/h) , using a typical value for the erosive rain of the climatic region. The original version of the MMF model used the relationship (Wischmeier and Smith, 1978):

$$KE(DT) = DT*(11.9 + 8.7\log I) \qquad (9)$$

The kinetic energy of the leaf drainage (KE(LD) ; Jrm2) is dependent upon the height of the plant canopy (PH; m) as proposed by Brandt (1990):

$$KE(LD) = (5.8*PH^{0.5})-5.87 \qquad (10)$$

Where yields a negative value, the energy of the leaf drainage is assumed to be zero. The total energy of the effective rainfall (KE/ Jrm2) is obtained from:

$$KE = KE(DT) + KE(LD) \qquad (11)$$

3.2.2 Soil particle detachment by raindrop impact

In the revised MMF model, rainfall interception is allowed for in the estimation of rainfall energy. It is therefore removed from the equation used to describe soil particle detachment by raindrop impact (F; kg/m2) which then simplifies to:

$$F = K*KE*10^{-3} \qquad (12)$$

where K is the erodibility of the soil (g/J).

3.2.3 Soil particle detachment by runoff

The procedure for estimating the annual runoff (Q; mm) remains unchanged. It is based on the method proposed by Kirkby (1976) which assumes that runoff occurs when the daily rainfall exceeds the soil moisture storage capacity (Rc); mm and that daily rainfall amounts approximate an exponential frequency distribution. The annual runoff is obtained from:

$$Q = R*\exp(-Rc/Ro) \quad (13)$$

where Ro = the mean rain per rain day (mm.) (i.e. R/Rn, where n s the number of rain days in the year).

The soil moisture storage capacity is estimated from:

$$Rc = 1000*MS*BD*EHD*E_t/E_o \quad (14)$$

where MS = the soil moisture content at field capacity (% w/w) BD = the bulk density of the soil (Mg/m), EHD = the effective hydrological depth of the soil (m) and E_t/E_o = the ratio of actual to potential evapotranspiration. The term, EHD, replaces the rooting depth (RD) used in the original model and indicates the depth of soil within which the moisture storage capacity controls the generation of runoff. It is a function of the plant cover, which influences the depth and density of roots, and, in some instances, the effective soil depth; for example, on soils shallower than 0.1 m or where a surface seal or crust has formed. Table 4-9 gives some guide values for EHD for use with the revised MMF model.

The revised model includes a new component to estimate the detachment of soil particles by runoff. Based on the experimental work by Quansah (1982), this is considered as a function of runoff (Q), slope steepness (S) and the resistance of the soil (Z). The detachment by runoff (H; kg/m^2) is estimated from:

$$H = Z*Q^{1.5*}\sin S(1-GC)*10^{-3} \quad (15)$$

For loose, non-cohesive soils, Z = 1.0. Based on a simplification of the work of Rauws and Govers (1988) the cohesion of the soil (COH; kPa) was emphasized as an important component of its resistance to erosion:

$$Z = 1/(0.5*COH) \quad (16)$$

3.2.4 Transport capacity of runoff

The method for estimating transport capacity of the runoff (TC; kgrm2) remains unchanged from that used in the original version of the model, so that:

$$TC = C*Q^2*\sin S*10^{-3} \quad (17)$$

where C is the crop or plant cover factor, taken as equal to the product of the C and P factors of the Universal Soil Loss Equation, and S is the slope angle. The C factor can be adjusted to take account of different tillage practices and levels of crop residue retention.

3.2.5 Estimation of erosion

The estimates of soil particle detachment by raindrop impact and by runoff are added together to give a total annual detachment rate. This is then compared with the annual transport capacity and the lesser of the two values is the annual erosion rate (Meyer and Wischmeier, 1969).

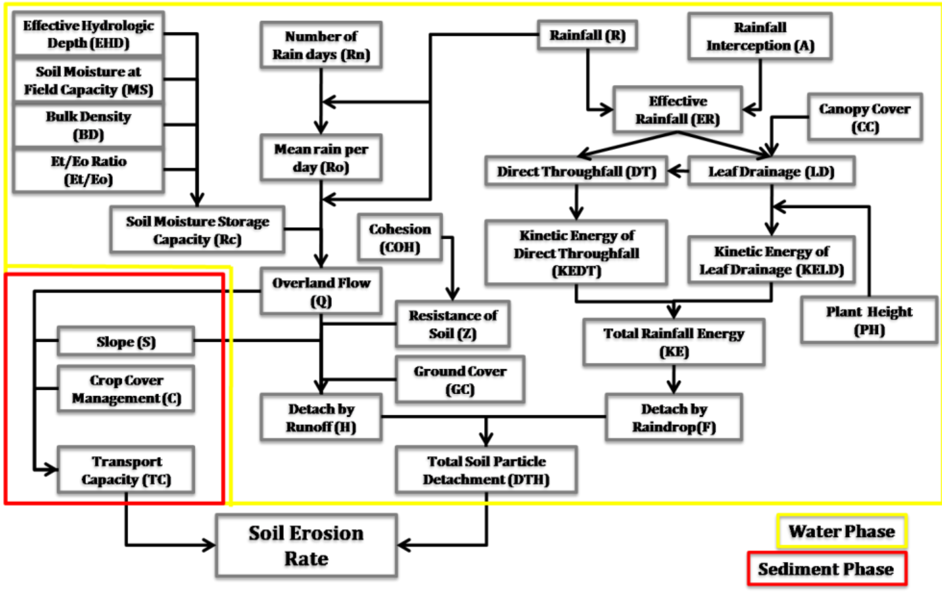

Fig. 3. Flowchart of the methodology for calculated annual soil erosion rate by MMF model

3.3 Watershed conservation planning

In this study, agronomical measure, contour bunding and terracing were suggested for watershed conservation measures. The conditions of those measures have been explained as follows:

3.3.1 Agronomical measures

- Slope should be between 5 – 8%
- Soil erosion rate should be more than 5 tons/ha/year
- Land use land cover should be agriculture

3.3.2 Contour bunding

- Slope should be between 8 – 15%
- Soil erosion rate should be more than 5 tons/ha/year
- Land use land cover should be agriculture

3.3.3 Bench terraces

- Slope should be greater than 15%
- Soil erosion rate should be more than 5 tons/ha/year
- Land use land cover should be agriculture

3.3.4 Check dam

- Should lie on hydrologic soil group (HSG) class C and D
- Slope should be between 8 – 15%
- Stream order 1 – 3 order
- Within 2 km. from agriculture area

Base on those conditions of watershed conservation measure, the site suitable has been derived using main parameters as slope, soil erosion, land use land cover, soil and stream orders map.

4. Results And Discussion

In the present study, watershed conservation planning for Asan watershed has been studied. In this regard, runoff was estimated using NRCS CN method, and erosion has been estimated using MMF model as described in the previous chapter.

4.1 Runoff

In the NRCS CN method, the initial step is to find out CN. CN is based on LULC and HSG. Based on the hydrological soil group, all of the soil units in the study area were grouped into 2 HSG classes namely C and D, as shown in Figure 6(a). The maximum area in Asan watershed was observed to be under hydrological soil group B (64.56%) followed by group C (35.44%).

Table 2. Hydrological Soil Group classes of Asan watershed

No.	**Hydrologic Soil Group (HSG)**	**Area (km)**	**Area (%)**
1	B	422.55	64.56
2	C	231.91	35.44
	Total	**654.45**	**100.00**

By intersection the land use land cover and hydrologic soil group (HSG), the curve number was assigned to each combination of land use land cover and HSG group. Relationships between land use/land cover classes, and HSG and runoff curve number for AMC II are given in following table (Table 5-2). In order to estimate runoff, slope map was used to adjust runoff CN value.

By using NRCS-CN method, the initial abstraction and infiltration of water in soil layer are governed by the antecedent moisture condition (AMC). AMC refers to the moisture content present in the soil at the beginning of rainfall-runoff event under consideration. Curve number map for AMC class II are shown in Fig 7. From the AMC classes and precipitation, the direct runoff for the study area was computed. The rainfall-runoff relationship is shown in Fig 4, and runoff coefficient is shown in Fig 5

Table 3. Relationship between land use and land cover, HSG and CN

No.	**Land use/Land cover class**	**HSG**	
		B	**C**
1	Density Pine Forest	55	70
2	Moderate Pie Forest	66	77
3	Density Sal Forest	55	70
4	Moderate Sal Forest	66	77
5	Grass Land	58	71
6	Agriculture	58	88
7	Fallow Land	86	91
8	Plantation	66	77
9	Settlement	85	90
10	Dry Riverbed	86	91
11	Water	100	100

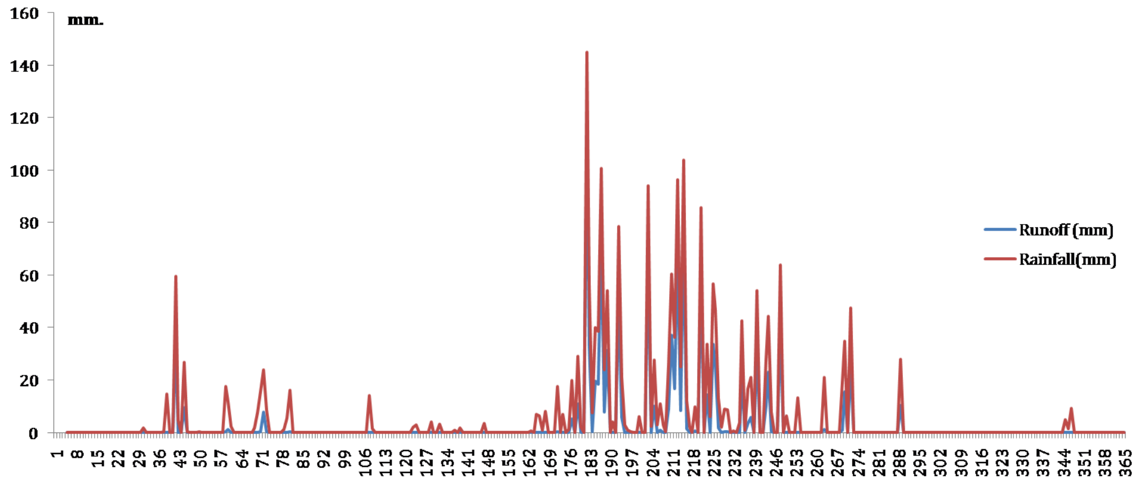

Fig. 4. Rainfall-runoff relationship in Asan watershed

4.2 Soil erosion analysis

Based on numerous input data, the detachment capacities by raindrop and runoff have been calculated. The average raindrop detachability is 120 tons/ha/year, and the average detachability by runoff is 6.70 tons/ha/year. The total of soil detachability was calculated by adding the detachment capacities by raindrop and runoff together. The average transport capacity by runoff is 335.90 tons/ha/year. Once the total detachment and the transport capacity of the watershed are computed, the minimum of the two was taken as the annual soil loss of the watershed. Predicted average annual soil loss from the watershed is 68.51 tons/ha/year. It was found that the highest annual soil loss occurred in urban area (with a maximum of 809 tons/ha/year).

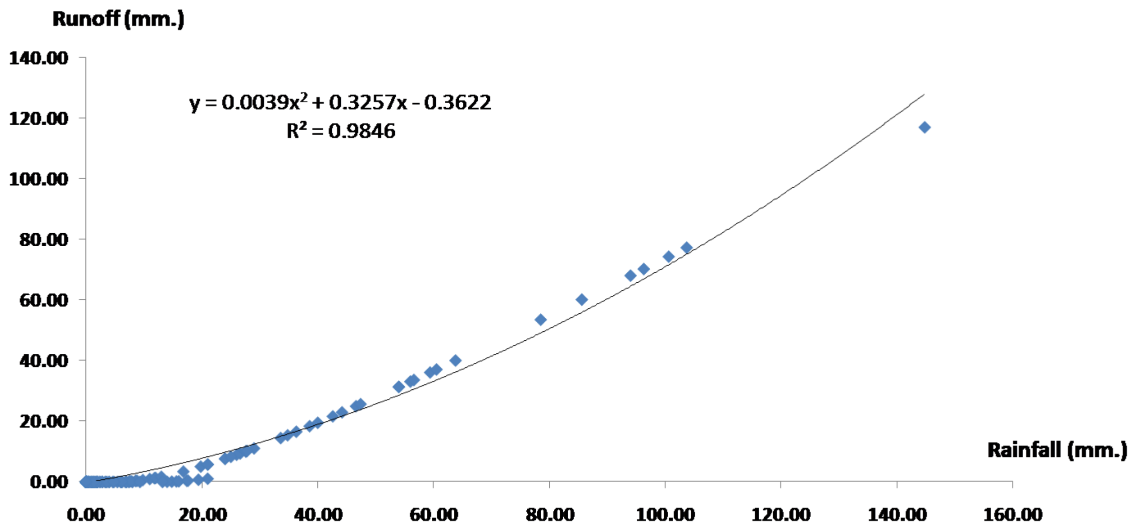

Fig. 5. Rainfall-runoff relationship in Asan watershed

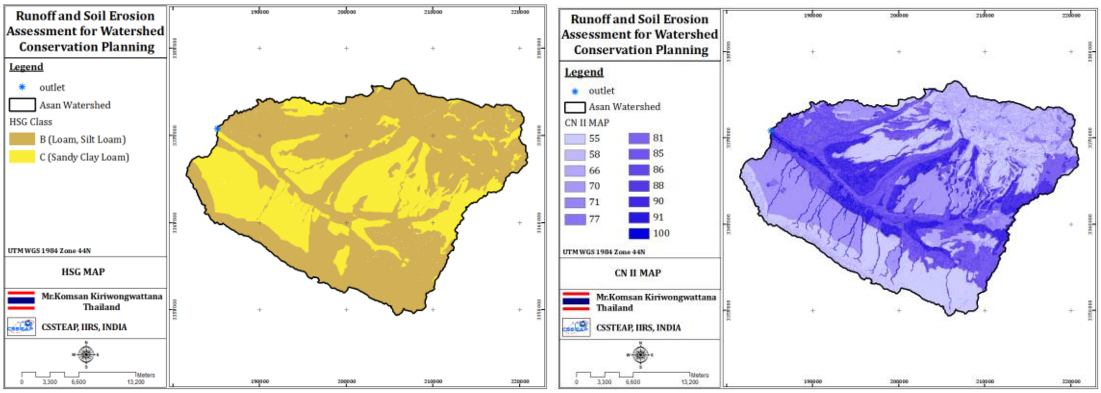

Fig. 6. (a) Hydrologic Soil Group in Asan watershed (b) Curve number II map for AMC class II in Asan watershed

For the purpose of analysis, the erosion risk is classified into five classes. According to the MMF model, 22.74% of the watershed land is under very high erosion risk**.** Moreover, class 4 (high) covers 3.30% of the area; class 3 (moderately high) covers 7.34% of the area; class 2 (Medium) covers 3.87%; class1 (low) covers 62.74%, of the watershed.

High to very high erosion risk exists in urban area and agriculture, which covers 24.29% of the watershed. The management practices which are mostly related to the nature of the crop have a major role for severe erosion in this land. Therefore, conservation strategies aiming at agronomic and structural measures should be established to reduce the risk.

Table 4. Spatial distribution of soil erosion risk severity classes of Asan watershed

No.	Erosion classes	Erosion rang	Area (km^2)	Area (%)
1	Low	0-5	410.63	62.74
2	Medium	5-10	25.34	3.87
3	Moderately high	10-25	48.05	7.34
4	High	25-50	21.59	3.30
5	Very high	>50	148.84	22.74
	Total		**654.46**	**100.00**

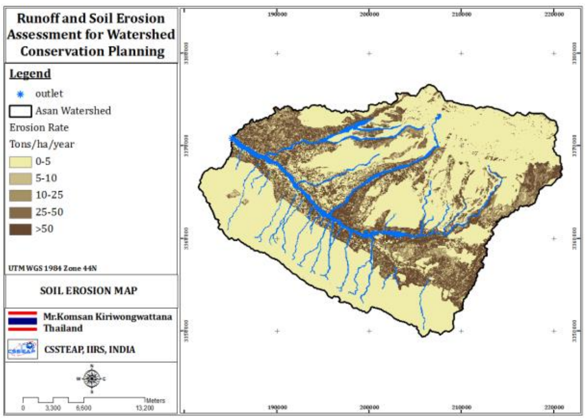

Fig. 7. Annual soil erosion rate of Asan watershed

4.3 Watershed conservation measures

It was observed that watershed has high runoff as well as high soil erosion rate; therefore, the watershed conservation measures are a must. Decision rules for locating suitable site of watershed conservation measures are explained in the previous chapter. The site suitable map of water and soil conservation measure has been derived using main input as slope, land use and land cover, stream order and soil.

For water conservation measure, 22 suitable sites were identified for water harvesting structure as check dam as shown in Fig 8(a). Whereas soil conservation measure, agronomical measure, contour bunding and bench terrace are proposed shown in Fig 8(b).

5. Conclusion

The NRSC-CN method and MMF was computed base on the prepared input parameter. The results of runoff and soil erosion were derived for rainfall data in year 2007 and land use and land cover map in year 2010. The main results obtained by this study are the following:

- The study found that there is runoff 816.34 mm out of 2173 mm rainfall. The runoff coefficient is around 37.56 %. Runoff will occur when rainfall per day is greater than 18 mm.
- The study results show average raindrop detachability is 120 tons/ha/year, and the average detachability by runoff is 6.70 tons/ha/year. The average soil detachability is 126.8 tons/ha/year.
- The average transport capacity by runoff is 335.90 tons/ha/year.
- The results of average annual soil loss from the watershed are 68.51 tons/ha/year. It was found that the highest annual soil loss occurred in the urban area (with a maximum of 809 tons/ha/year).
- The erosion risk is classified into five classes. According to the MMF model, 22.74% of the watershed land is under very high erosion risk. Moreover, class 4 (high) covers 3.30% of the area; class 3 (moderately high) covers 7.34% of the area; class 2 (Medium) covers 3.87%; and class1 (low) covers 62.74%, of the watershed.
- For water conservation measure, 22 suitable sites were identified for water harvesting structure as check dam.
- For soil conservation measure, agronomical measure, contour bunding and bench terrace are proposed.

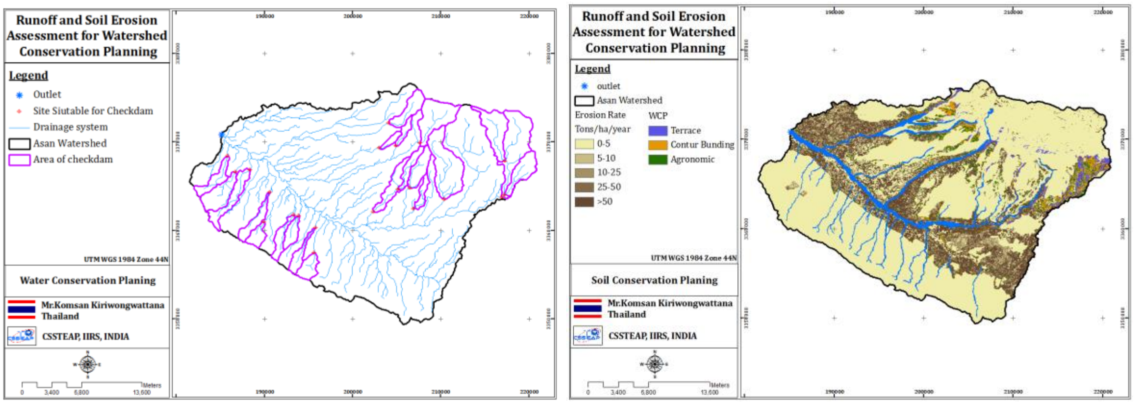

Fig. 8. (a) Suitable sites for check dam of Asan watershed (b) Suitable sites for soil conservation measures of Asan watershed

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