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Runoff and soil erosion modelling for sustained development of land and water resources under watershed concept

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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. Soil erosion assessment is a capital-intensive and time-consuming exercise. A number of parametric models have been developed to predict soil erosion prone zone at structural terrains, even though Universal Soil Loss Equation (USLE), and it's updated or modified versions are most widely used empirical equation for estimating annual soil Loss. Morgan, Morgan and Finney 1984 proposed a model on field base information and estimation had yielded point-based accuracy values.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. This study demonstrated using MMF model that the rate of soil detachment (J) varied from 0.34 – 7.91 kgm^{-2}, whereas the total average annual volume of runoff for the study area is around 94.9 mm. The estimated weighted average soil loss (G) at the outlet estimated by MMF model was 1.61 t ha^{-1} y^{-1}. Hence, introducing appropriate interventions based on the erosion severity predicted by MMFmodel in the catchment is crucial for sustainable natural resources management.

Keywords: Runoff and Soil Erosion Modelling, Development of Land and Water Resources

Introduction
Indian economy even though based on agriculture faces vagaries of monsoon in larger parts of country without irrigation facilities. The drought is a common phenomenon in one or other part of India. Arid and semi-arid regions, practicing largely rainfed agriculture are rather more prone to drought than the other climatic zones with the probability of being more than 20 percent of the years (Zhang *et al.* 2014) [9]. The arid and semi-arid regions are characterized by a climate with no or insufficient rainfall to sustain agricultural production (Ali *et al.* 2017) [2]. Most of the rainfall water through torrential downpours is lost as run-off, eroding significant quantities of precious top soil (Kalpana 2006) [3]. The current rainwater-use efficiency for crop production would be low ranging from 30 to 45 per cent leading about 300-800 mm of seasonal rainfall as unproductive (Manoj and Ram 2010) [4]. An insight into the rainfed regions shows a grim picture of water scarcity, fragility in ecosystems, recurrent drought, land degradation and low rainwater-use efficiency and indirectly negative impact due to high population pressure, poverty, and low investments in water use efficiency measures, poor infrastructure and inappropriate policies (Neelambika and Satishkumar 2016) [6].
In order to achieve the objectives of effective management of watershed activities for sustainability of land and water resources, simulation and optimization models would be required for significant representation of processes and quantification impacts of management strategies in natural watersheds (Tripathi and Woldeselassie 2016) [7]. The hydrologic models are important in addressing a range of problems related to water resources assessment, development, and management activities. However, many users may not be able to take use of modeling efforts in management decision due to lack of synergy of site specific modeling options and their applications.
A new approach based on GIS for prediction of soil losses in study area and to produce maps of soil loss the Morgan–Morgan–Finney model (MMF, Morgan, 2001) for prediction of annual soil loss by water was used in a field scaled erosion model based on GIS. Simulations of MMF model that includes estimates of rainfall energy, runoff, soil particle detachment by raindrop impact, soil particle detachment by runoff, transport capacity of runoff and estimation of erosion were performed using digital map layers in GIS. Consequently, soil losses for the study area were predicted and map of erosion was produced.

Materials and Methods

The details of methods and procedures followed in analyzing the dynamics of soil erosion under prevailing rainfall characteristics, runoff and its carrying capacity of sediment, characteristics of stream network and its influence on nature of sediment transportation and deposition in a typical micro watershed system under prevailing semi arid agro-climatic conditions are depleted.

Location of selected Patapur micro-watershed

The Patapur micro-watershed is a typical micro-watershed system under semi-arid agro climatic system having an area of 454.62 ha being located at Patapur village in Manvi taluk of Raichur district in Karnataka (Fig. 1).The Patapur study area lies between the 16˚ 07' 35.9" Latitude and 76˚ 51′ 33.3" Longitudes and 16˚ 08′ 22.3’’ Latitude and 76˚ 53′ 27.7" Longitudes with an average elevation of 447 m above the mean sea level (MSL). This watershed is located about 63 km from the Raichur city on Raichur-Lingasugur road. It finds its place toposheet No. 56 D/16 (1:50,000) of the Survey of India database.

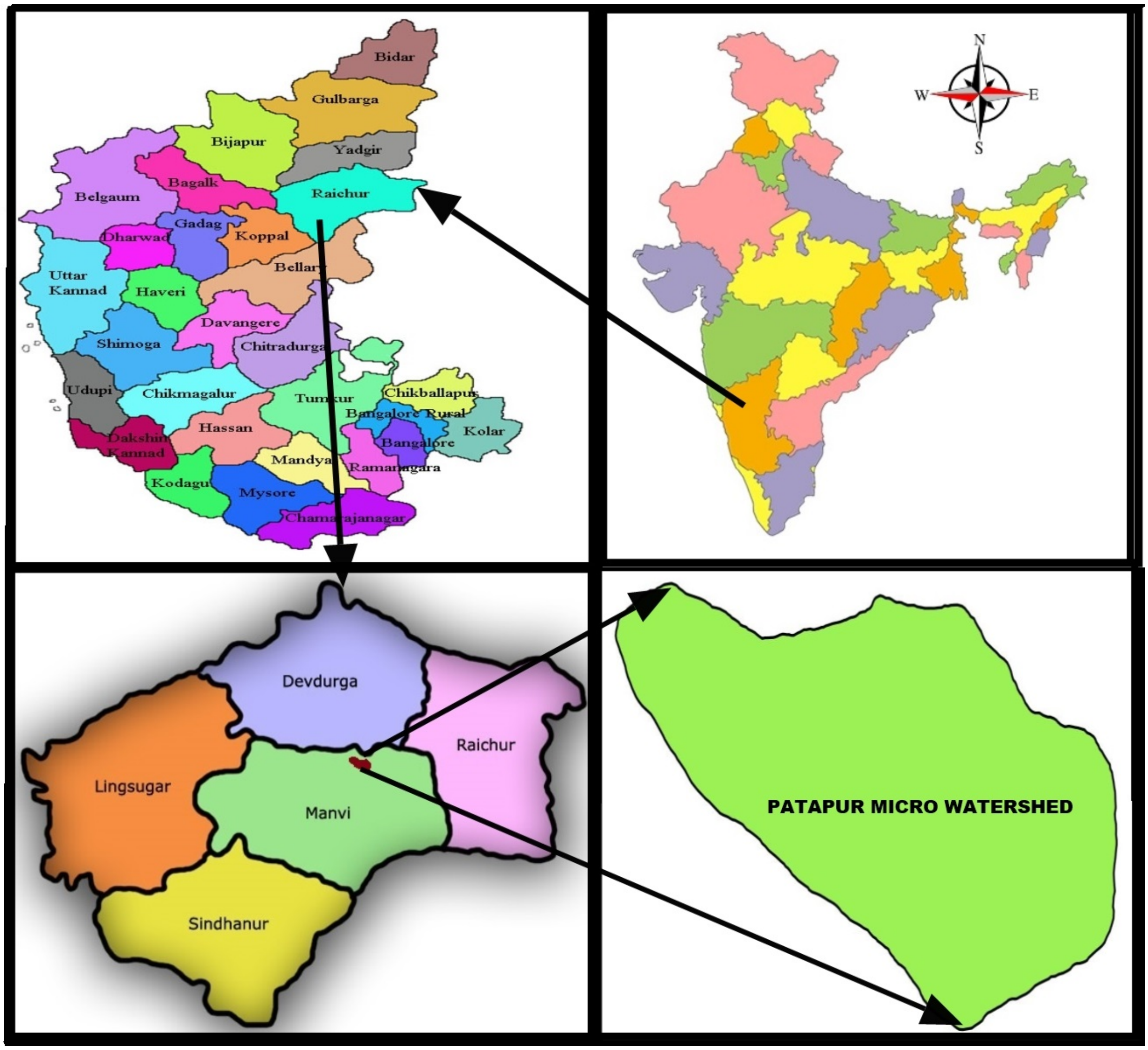

Fig 1: Identified Patapur micro-watershed in Raichur district

Morgan, Morgan and Finney (MMF) model as estimator of runoff and soil loss

MMF model was considered to predict annual soil loss from field-sized areas on hill slopes, which, while endeavouring to retain the simplicity of the Universal Soil Loss Equation, encompassed some of the recent advances in understanding of erosion processes Morgan and Duzant (2008) [5]. The model separates the soil erosion process into a water phase and a sediment phase. The sediment phase is a simplification of the scheme described by Wischmeier and Smith (1978) [8]. It considers soil erosion to result from the detachment of soil particles by raindrop impact and runoff and the transport of those particles by overland flow. The process of transport by rain splash is ignored. Thus, the sediment phase comprises three predictive equations, one for the rate of particle detachment by rain splash, one for the rate of particle detachment by runoff and one for the transport capacity of overland flow. The inputs to these equations of rainfall energy and runoff volume respectively are obtained from the water phase.

Functional components of MMF model

In the present study, estimation of soil erosion by water was modelled by using Morgan, Morgan & Finney (MMF) model. In this approach detachment of soil particles by raindrop impact and the transport of these particles by overland flow were taken into account for soil erosion assessment. The model separates the soil erosion process into a water phase and a sediment phase using six functional relations and 16 input parameters.

Operating Functions For Mmf Method

WATER PHASE

$ER = R(1-A)$

$LD = ER.\ CC$

$DT = ER – LD$

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

$KE(LD) = LD\ \{(15.8 – PH^{0.5}) – 5.87\}$

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

$Q = R \exp (-R_C/R_0)$

$R_C = 1000.\ MS.\ BD.\ EHD.\ (E_t/E_0)^{0.5}$

$R_0 = R/Rn$

Sediment Phase

$F = K\ KE\ 10^{-3}$

$H = ZQ^{1.5} \sin S\ (1 - GC)\ 10^{-3}$

$Z = 1/(0.5\ COH)$

$J = F + H$

$G = CQ^2 \sin S\ 10^{-3}$

Where,

ER = Effective Rainfall, mm

LD = Leaf Drainage, mm

DT = Direct through Fall, mm

KE = Kinetic Energy of the rainfall J/m^2

Q = Volume of overland Flow, mm

F = Annual Rate of soil particle detachment by raindrop impact kg/m^2

H = Annual Rate of soil particle detachment by runoff, kg/m^2

J = Annual Rate of total soil particle detachment kg/m^2

Z = Constant for runoff detachment; depended on soil cohesion.

G = Annual transport capacity of overland flow kg/m^2

Rc = Soil Moisture Storage Capacity, mm

R_0 = Annual rain per rain days.

Input parameters of MMF model

The MMF model uses 14 operating functions for which empirical values need to be provided for 16 input parameters categorised into 3 categories namely rainfall, soil and land use factor (Table 1).

Table 1: Input parameters to the Morgan-Morgan-Finney method of predicting soil loss

Factor	Parameter	Definition
Rainfall	R	Annual or mean annual rainfall (mm)
	R_n	Number of rain days per year
	I_t	Typical value for intensity of erosive rain (mm/hr),
	I_P	Peak Intensity of Rainfall, (mm/hr)
Soil	ST	Soil Texture
	S	Slope Steepness (rad)
	MS	Moisture Content at Field Capacity or 1/3 bar tension (wt %)
	BD	Bulk Density of the top soil layer (Mg/m^3)
	EHD	Effective Hydrological Depth of Soil (m); value depends on vegetation/crop cover, presence or absence of surface crust, presence of impermeable layer within 0.15m of the surface
	K	Soil Detachability Index (gm/J) defined as the weight of soil detached from the soil mass per unit of rainfall energy
	COH	Cohesion of the Surface Soil (KPa) as measured with a torvane under saturated conditions
Land Use & Land Cover Factor	A	Proportion of the Rainfall intercepted by the vegetation or crop cover (b/w 0 & 1)
	E_t/E_0	Ratio of Actual (E_t) to Potential (E_0) Evapotranspiration
	C	Crop Cover Management factor; combines the C and P factors of the USLE
	CC	Percentage of Canopy cover (b/w 0 & 1)
	GC	Percentage of Ground Cover (b/w 0 & 1)
	PH	Plant Height (m), representing the height from which raindrops fall from the crop or vegetation cover to the ground surface

Rainfall factor

The experiment on estimation of runoff and soil loss was conducted during the year 2016. The mean annual rainfall and number of rainy days for the year 2016 was 838.3 and 39. The intesity of erosive rain is taken as 25 mmh^{-1}(tropical climates, Morgan and Duzant 2008) [5].

Soil factor

The required soil parameters namely moisture content at field capacity (MC), bulk density (BD) and soil erodibility index (K) were estimated for Patapur micro watershed. The measured values for moisture content at field capacity (MC), bulk density (BD) and soil erodibility index (K) were reported as shown in Fig 2 to 4. The guide values of Cohesion of the Surface Soil (COH) estimated using instrument (torvane) under saturated conditions has been indicated in Fig 5. The value of EHD depends on vegetation/crop cover, presence or absence of surface crust and presence of impermeable layer within 0.15 m of the surface.The variability of EHD across different soil phase units as guide values indicated by the model architecture has been depicted in Fig 6.

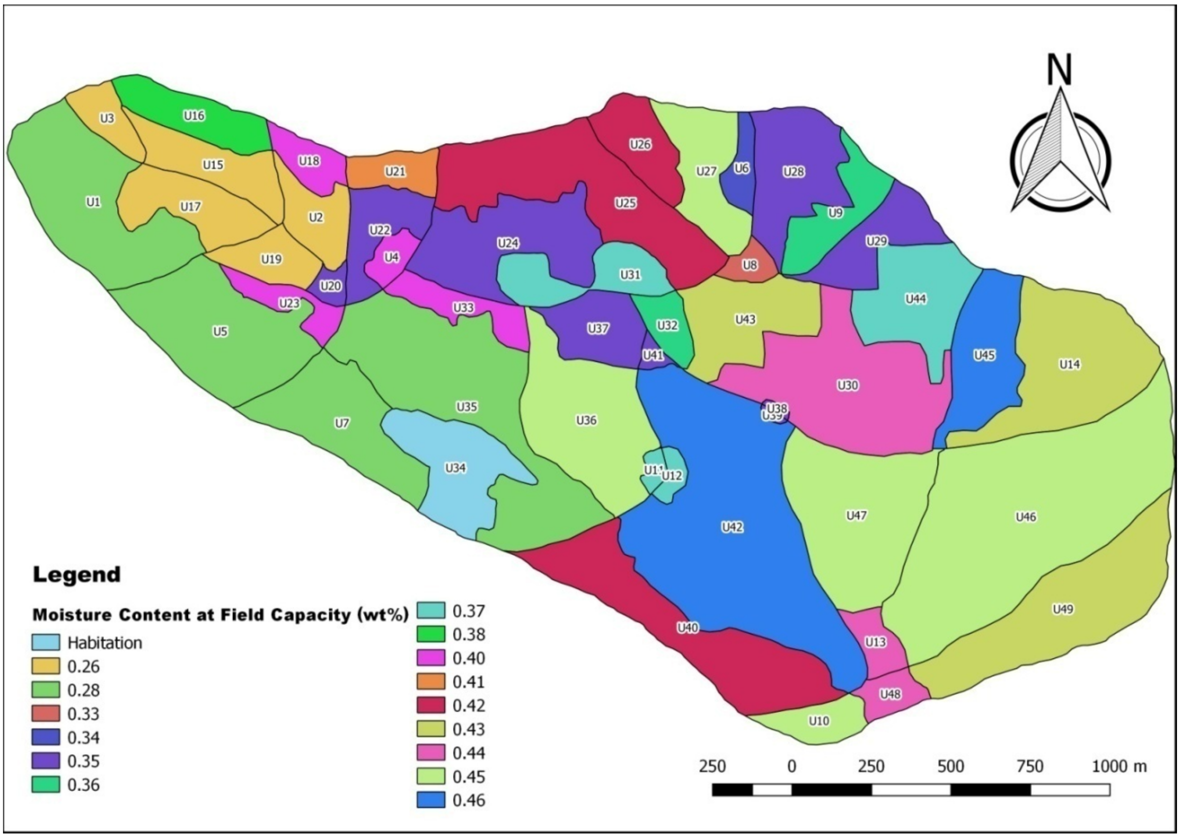

Fig 2: Variability of moisture content at field capacity of different mapping unit

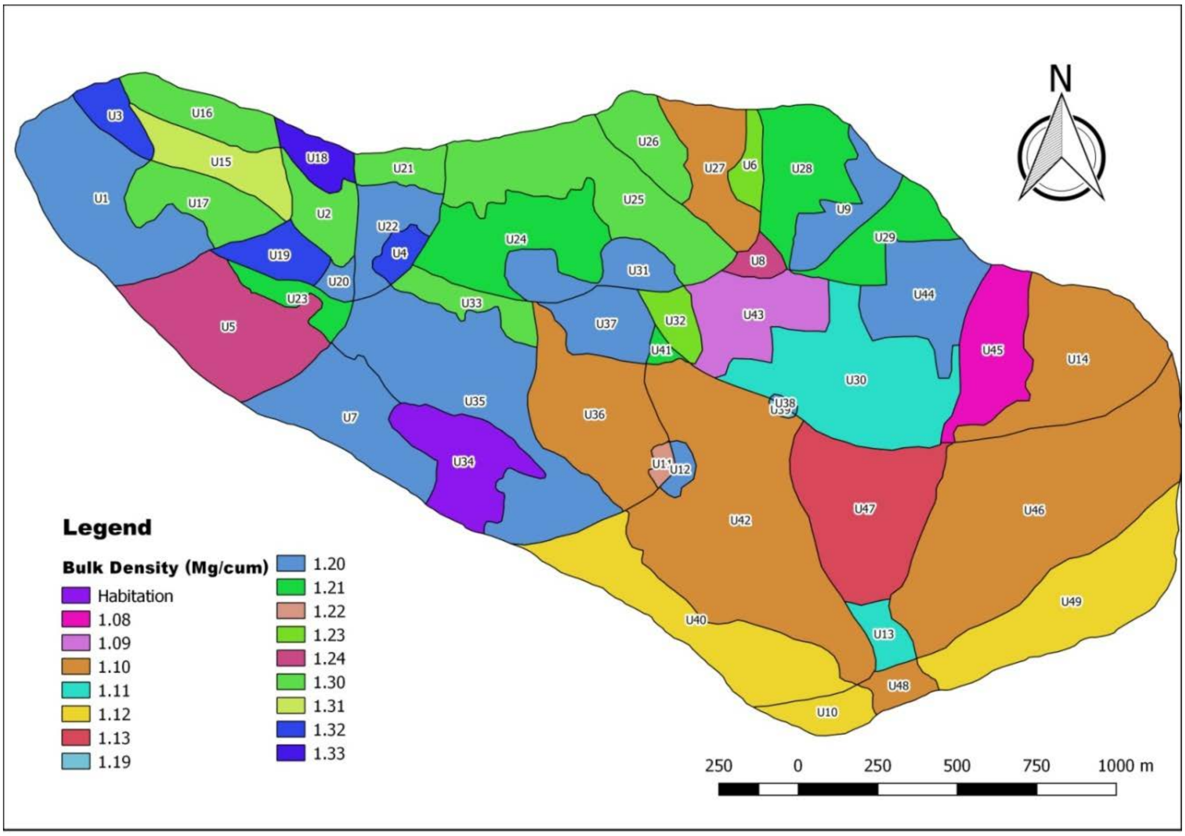

Fig 3: Bulk Density map of Patapur micro watershed

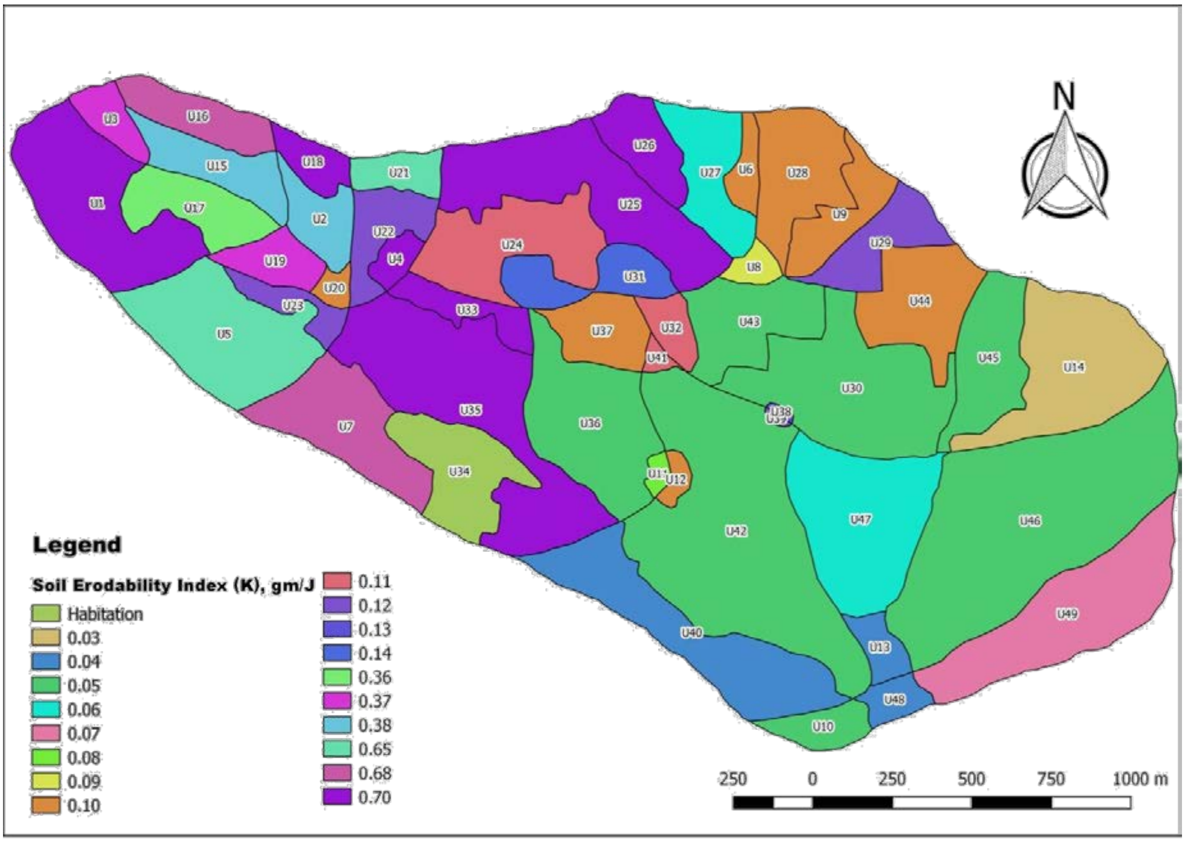

Fig 4: Variability of Soil Erodibility Index map of Patapur micro

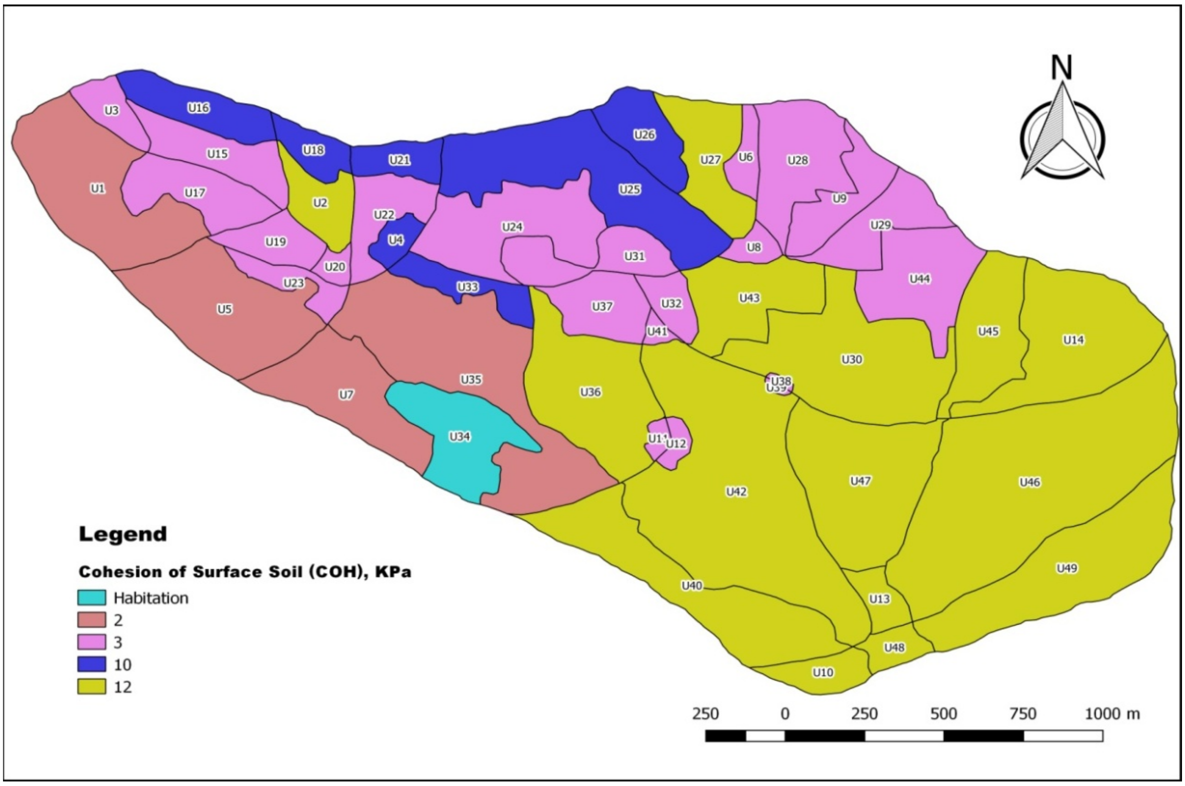

Fig 5: Variability of COH values applicable for prevailing soil of Patapur micro watershed

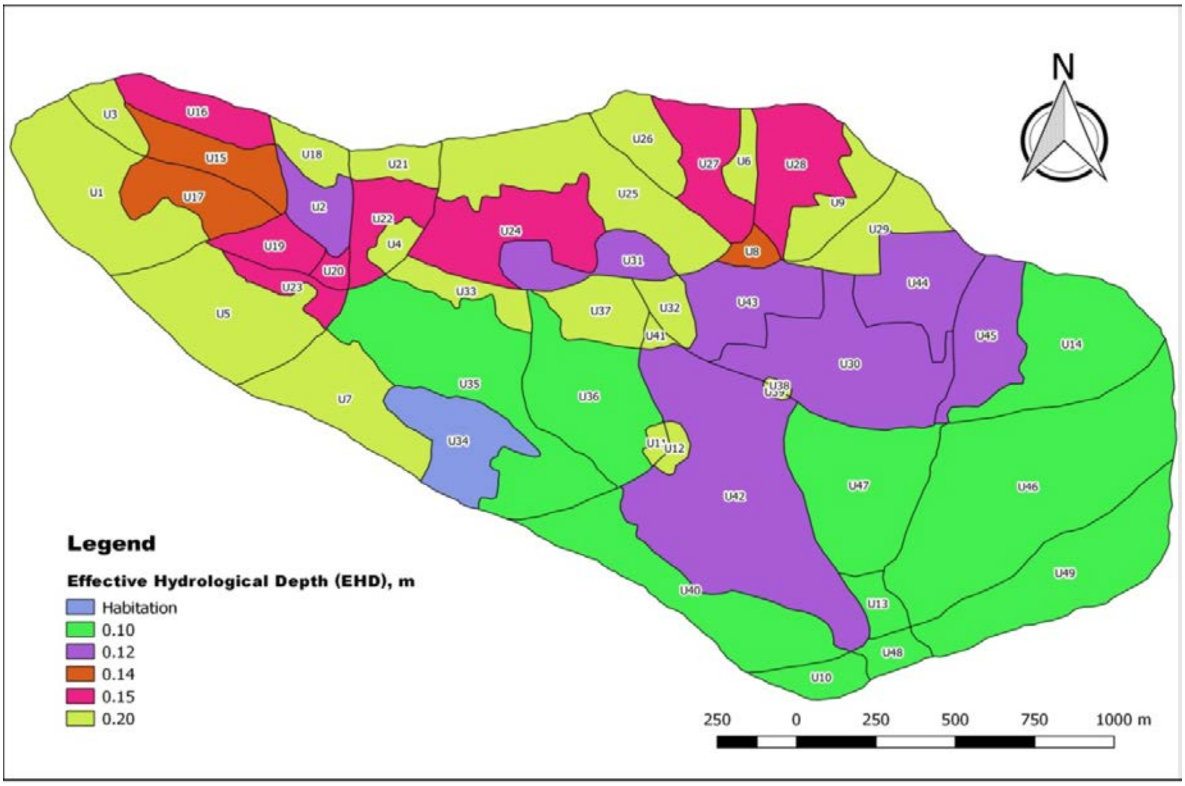

Fig 6: Variability of EHD values applicable for prevailing soil of Patapur micro watershed

Land use & land cover factor

The adopted guide values pertaining to land use and land cover factors namely proportion of the rainfall intercepted by the vegetation or crop cover (A), actual (E_t) and potential (E_0) evapotranspiration (E_t/E_0) selected were as shown in Fig. 7 and 8. Similarly Crop Cover Management factor (C), which combines the C and P factors of the USLE and Plant Height (PH), representing the height from which raindrops fall from the crop or vegetation cover to the ground surface were selected as shown in Fig. 9 to 10. The canopy cover plays a great role in the amount of sunlight that reaches the area. A classification which classify canopies as open (10-39 % of the sky is obstructed by tree canopies), moderately closed (40-69 % of the sky being obstructed by tree canopies) or closed (70-100 % of the sky being obstructed by tree canopies) were used (Abdul, 2012) [1]. The percentage of Canopy Cover (CC) in MMF model expressed as fraction ranging between 0 & 1 (Fig. 11). The measured values of percentage of Ground Cover (GC) were taken in between 0 & 1 (Fig 12).

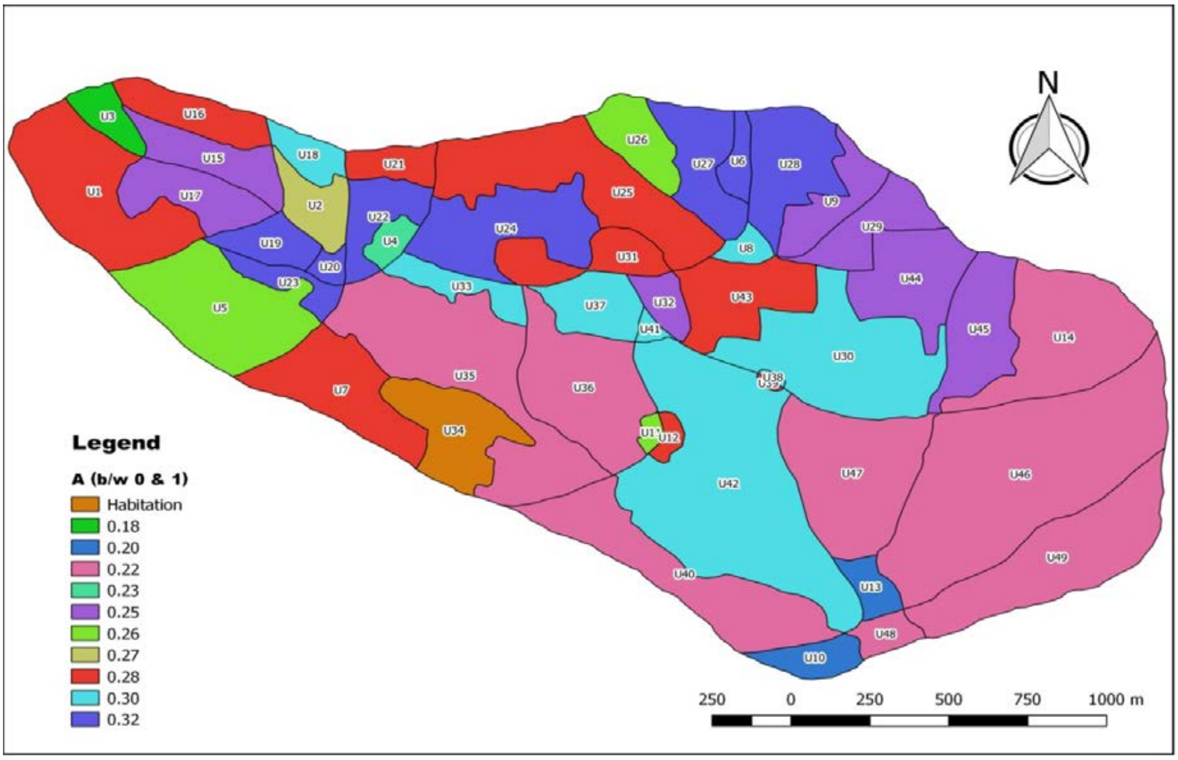

Fig 7: Applicable guide values of proportion of the rainfall intercepted by the vegetation or crop cover (A)

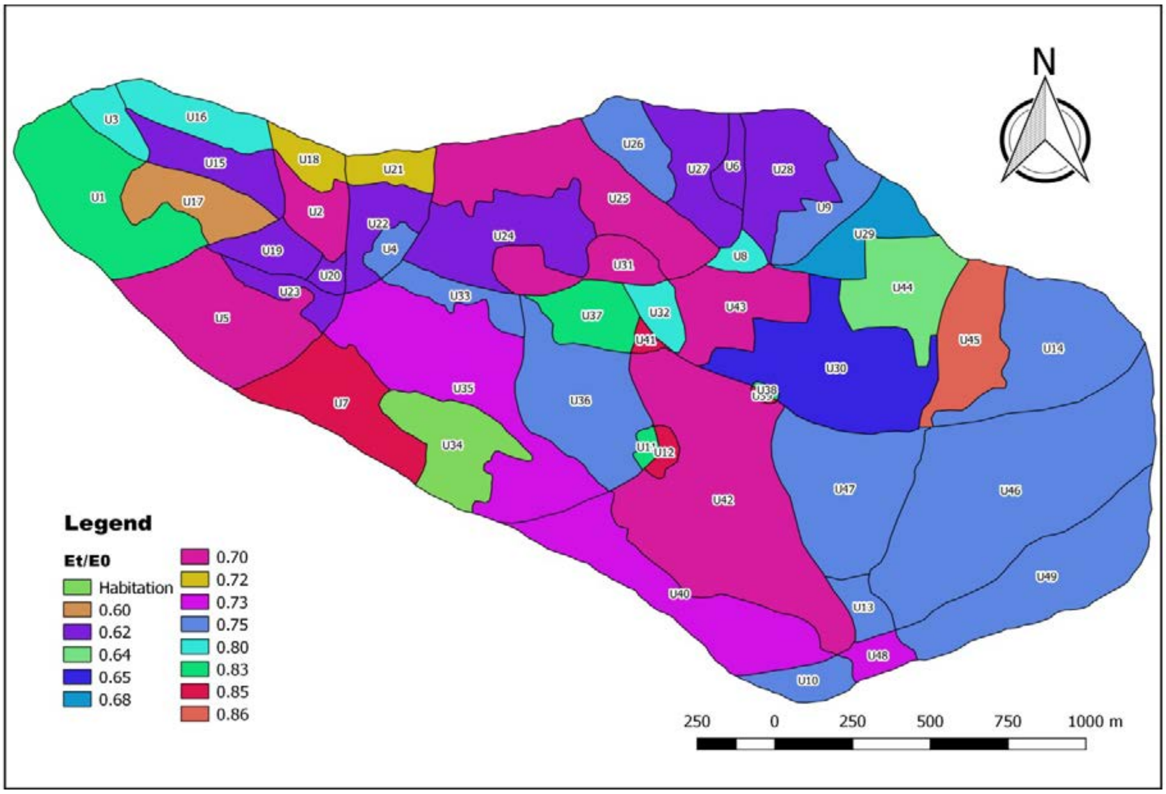

Fig 8: Applicable guide values of actual (E_t) and potential (E_0) evapotranspiration (E_t/E_0)

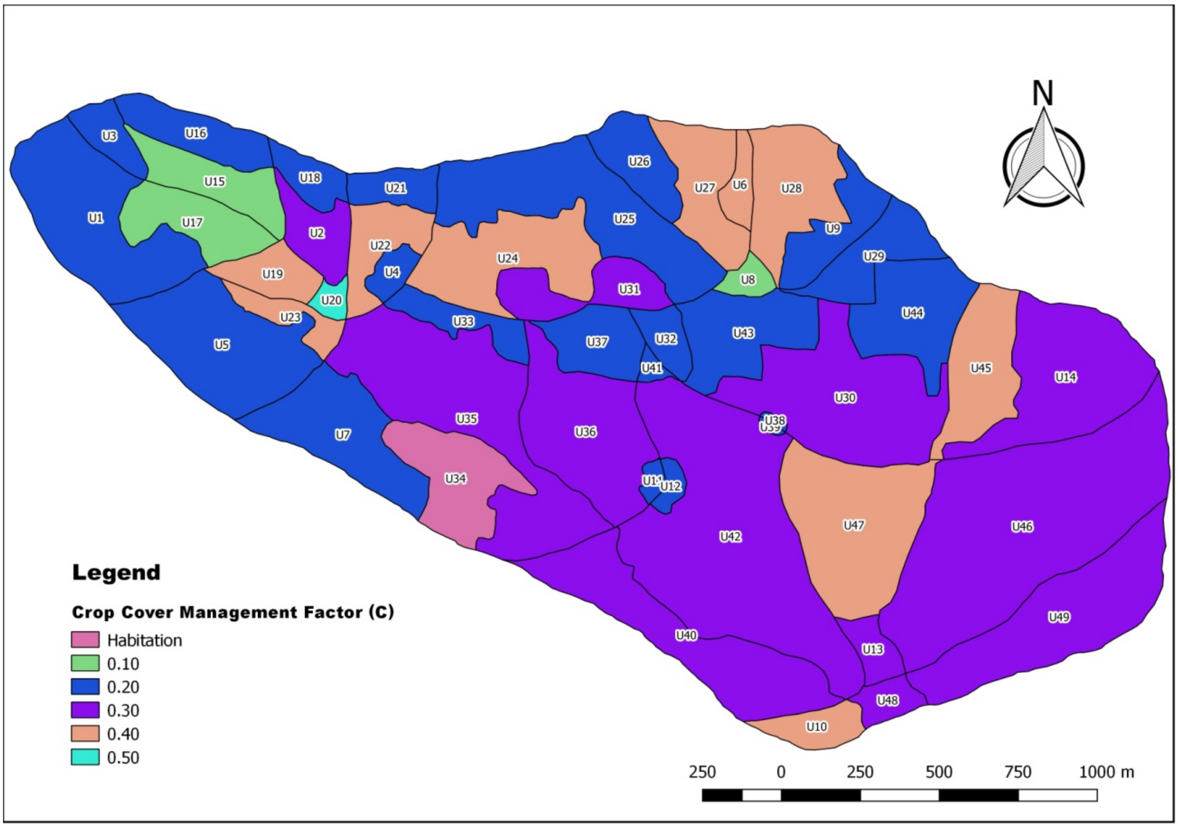

Fig 9: Variability of crop cover management factor (C) of Patapur micro watershed

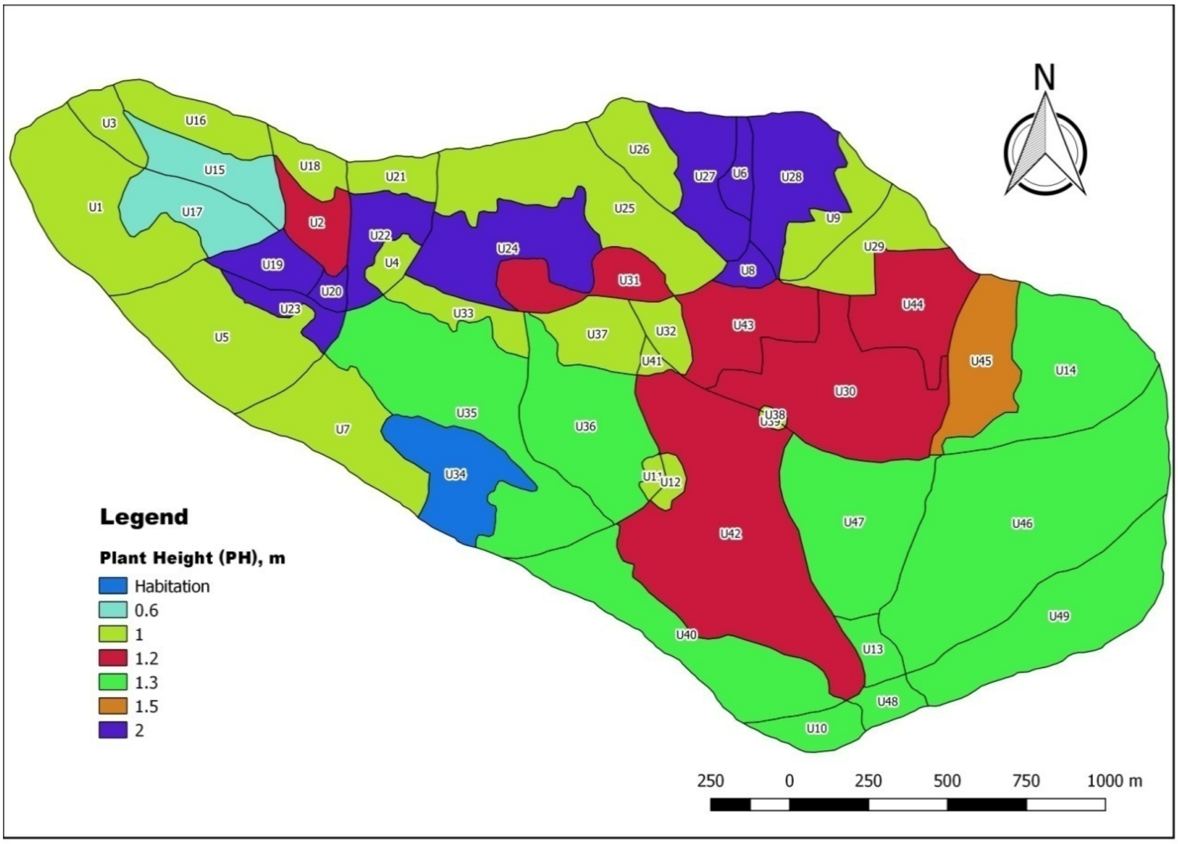

Fig 10: Variability of plant eight (PH) of Patapur micro watershed

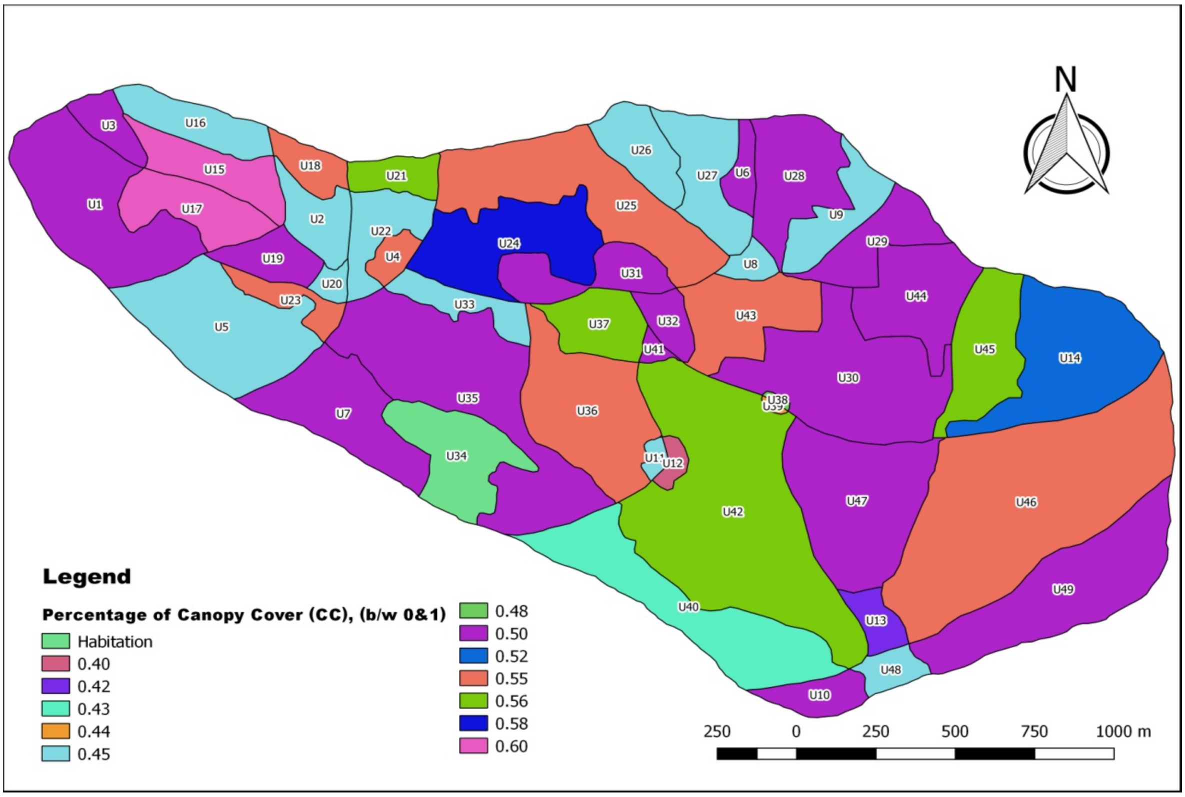

Fig 11: Variability of canopy cover of Patapur micro watershed

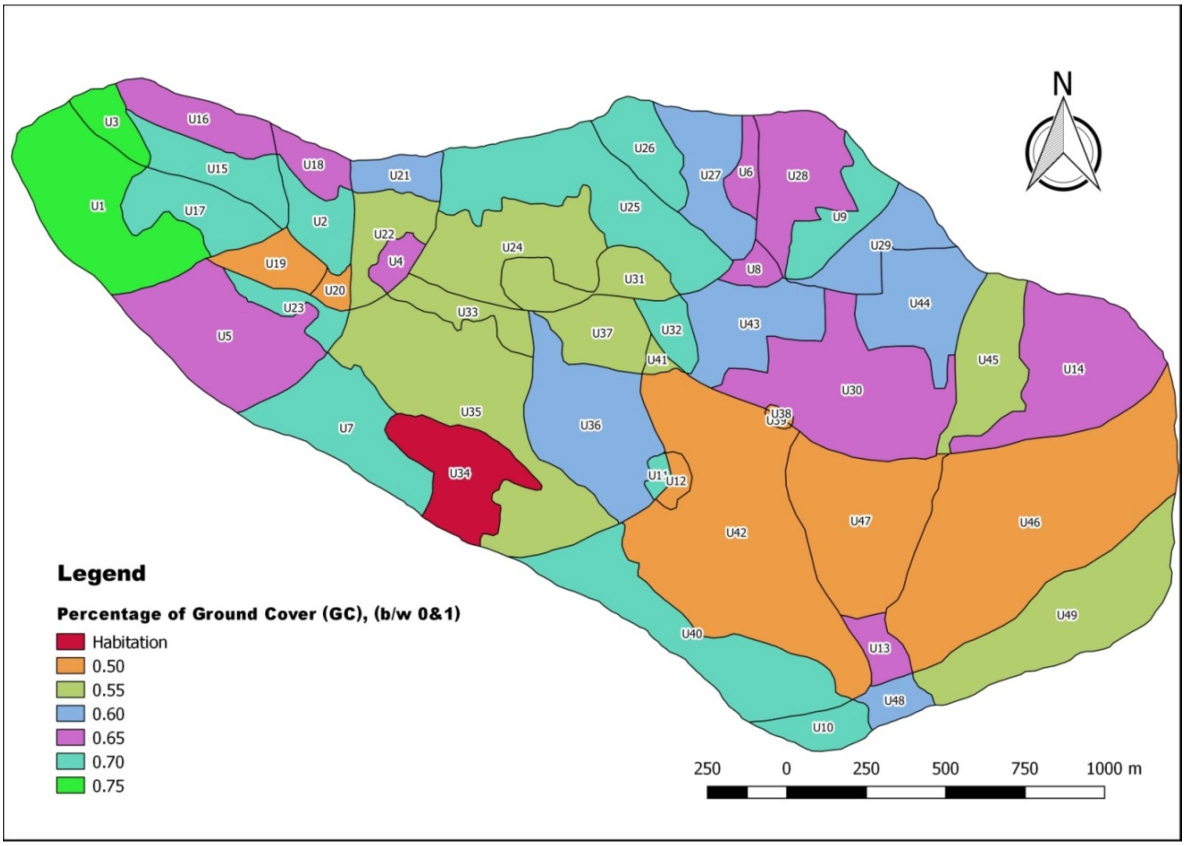

Fig 12: Variability of ground cover of Patapur micro watershed

Results

Estimated runoff and soil loss using MMF model

Spatial variability in slope, vegetation, soil texture, and land use and cover and both spatial and temporal variability in rainfall are found to be the main factors which influence on susceptibility to erosion of a catchment. The spatial runoff erosion modelling using of MMF model was to predict runoff and average soil loss. The MMF model separates the soil erosion processes into a ‘water phase’ and a ‘sediment phase’ and considers soil erosion to result from the both detachment of soil particles by raindrop impact and also from the transport of those particles by overland flow simultaneously.

The water phase comprises nine operating functions and includes rainfall energy (summation of kinetic energy of direct through fall and leaf drainage) and volume of overland flow. The basic input parameters to this phase is mean annual rainfall, rainy days per year, rainfall interception by vegetation, canopy cover, ground slope, soil moisture storage capacity, evapotranspiration etc. The sediment phase comprises three predictive equations namely particle detachment by rainsplash, particle detachment by runoff and transport capacity of overland flow (Morgan and Duzant, 2008) [5].

The model compares the predictions of detachment by rainsplash with transport capacity of the runoff and assigns the lower of the two values as the annual rate of soil loss, thereby denoting whether detachment or transport is the limiting factor (Morgan and Duzant, 2008) [5].

The results obtained pertaining to the study area is presented as below:

Water phase

The model calculates the effective rainfall (ER) out of mean annual rainfall for the year 2016 after allowing for permanent interception (A) by the vegetation cover. Variability of effective rainfall across the study area during 2016 (experimental year) is shown in Fig. 13.

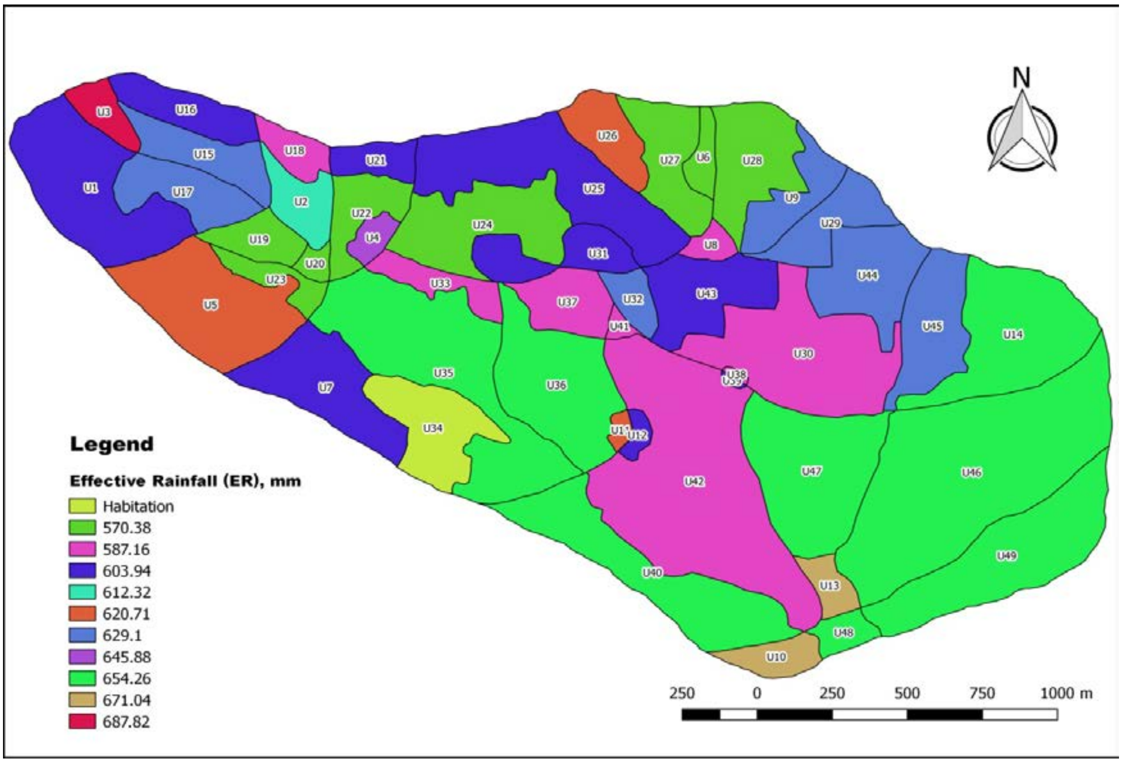

Fig 13: Depiction of variability of effective rainfall of Patapur micro watershed

The effective rainfall is divided into leaf drainage (LD), *i.e.* that reaching the soil surface as flow or drips from the leaves and stems of the vegetation. Leaf drainage is directly dependent upon the proportion of the effective rainfall intercepted by the canopy cover (CC) as shown in equation and direct throughfall (DT) i.e. that reaching the soil surface directly through gaps in the vegetation cover. The effective rainfall ranges from 573.79 to 691.92 mm.

The kinetic energy of the direct throughfall, KE (DT) is a function of the intensity of the erosive rain (I_t) and the amount of direct throughfall. Guide values are used for the intensity of the erosive rain according to geographical location; typically these are 10 mm h^{-1} for temperate climates, 25 for tropical climates and 30 for strongly seasonal climates (e.g. Mediterranean, tropical monsoon). For India tropical climates value is taken. Kinetic energy of the leaf drainage, KE (LD) is a function of the plant height (PH), which determines the height of fall of the raindrops. The total kinetic energy (KE) of the effective rainfall is a sum of both kinetic energy of the direct throughfall and kinetic energy of the leaf drainage. The total kinetic energy varies across the mapping units ranges from 12105 Jm^{-2} to 8757 Jm^{-2}. The variability of total kinetic energy for Patapur micro watershed is shown in Fig. 14.

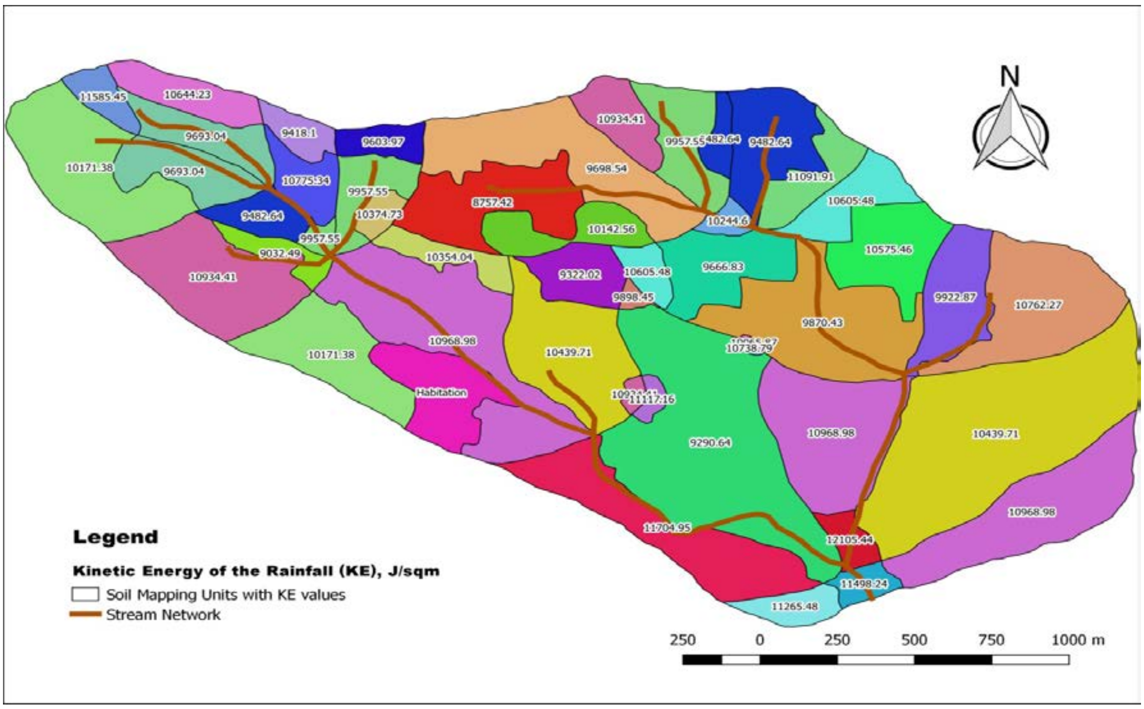

Fig 14: Soil mapping unit wise depiction of total kinetic energy of the study area

Runoff occurs when the daily rainfall exceeds the soil moisture storage capacity of the soil (R_C). The moisture storage capacity depends upon the soil moisture content at field capacity (MS); the bulk density of the soil (BD); the effective hydrological depth (EHD), defined as the depth of soil within which the moisture store controls the generation of runoff, and the loss of water from the soil through evapotranspiration, described by the E_t/E_0 ratio of the land cover.

The spatial distribution of soil moisture content at field capacity (MS) showed lower value in the hilly part of catchment as compared to that of flat to gentle slopes under similar management and cover conditions. However, regardless of the slope steepness, the highest MS was found in some sites of the study catchment such as in the closed pasture lands with relatively higher organic matter (up to 0.46 Wt%).The lowest MS (0.22 Wt%) in the catchment was associated with poor land use, and soil management systems (*e.g.*, marginal land, over grazing land, and eroded sites with shallow soil depth).

Bulk density was found to be higher (up to 1.33 Mgm^{-3}) in the steep slopes with poor vegetation cover and soil management practices and decreased to about 1.08 Mgm^{-3} around at the foot-slope of the catchment. It is possible to observe higher erosion on areas dominated by higher bulk density as they are located on the steep slopes, an increase in bulk density can negatively affect the circulation of air, water, and plant nutrients and their root system and in-turn raises rate of soil erosion. Such higher BD increases surface runoff which is the driving force for soil loss by decreasing soil infiltration and soil water holding capacity.

The effective hydrological top soil depth (EHD) spatial map indicated higher values (0.16 m) in relatively better vegetation-cover areas and stable sites, and flat to gentle slopes. The EHD values were lower around (0.12 m) in marginalized areas, cultivated and degraded grazing lands. Majority (78 Per cent) of the study catchment showed low EHD, indicating that such sites can be the source of higher runoff and soil loss.

Similarly, the higher values (0.75 to 0.85) of E_t/E_0 corresponded to scrub land, whereas lower values (0.62–0.73) corresponded to agricultural areas. The soil moisture storage capacity (R_C) calculated as a function of MS, BD, EHD, and E_t/E_0 varied spatially from 27.3 to 100.68 mm (Fig 15). Most of the small R_C values were located on steep slopes with shallow soil depth, poor surface cover, and marginal lands. Farmers who cultivated their land on steep slopes confirmed that they often face crop failure due to moisture stress related to low R_C. Generally, low R_C can be used as an indicator of a source of higher runoff. Such soil could be susceptible to soil detachment by raindrop and runoff impacts as a result of less vegetation cover. Reduction in the EHD can lead to low soil moisture storage capacity (R_C) which resulted in higher surface runoff.

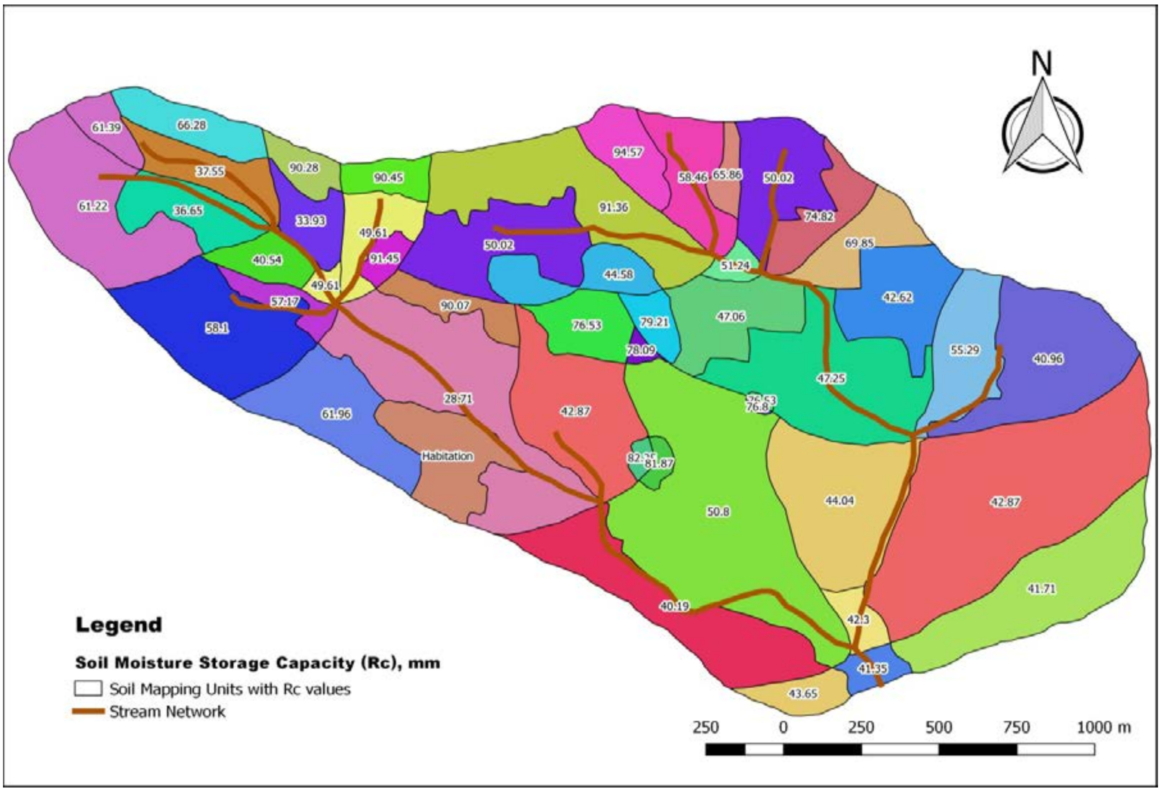

Fig 15: Soil mapping unit wise depiction of soil moisture storage capacity (R_c) of the study area

The annual rain per rain days is calculated. In a climate with variable intensity precipitation and strongly seasonal rainfall regimes, the daily rainfall amounts approximate an exponential frequency distribution and the annual runoff generated (Q) can be predicted. The distribution of runoff over a Patapur micro watershed is shown in Fig. 16. The total average annual volume of runoff for the study area for the year 2016 is around 94.9 mm.

Sediment phase

The detachment of soil particles by raindrop impact (F) is a function of the kinetic energy of the effective rainfall and the detachability of the soil (K). In order to allow for the particle-size distribution of the soil, the effective rainfall is proportioned according to the proportion of clay, silt and sand particles in the soil. Soil particles detachment by raindrop impact in the study area ranged from 0.34 to 7.91 kgm^{-2} as shown in Fig. 17.

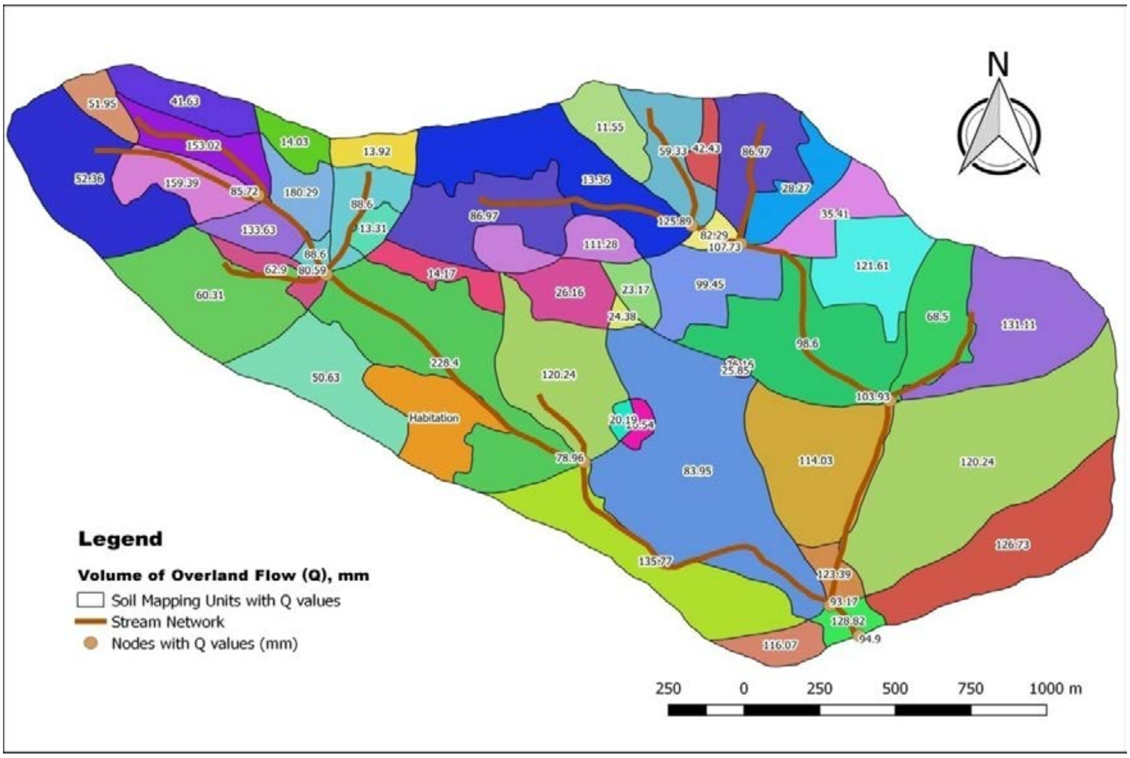

Fig 16: Soil mapping unit wise and node wise depiction of distribution of runoff of Patapur micro watershed

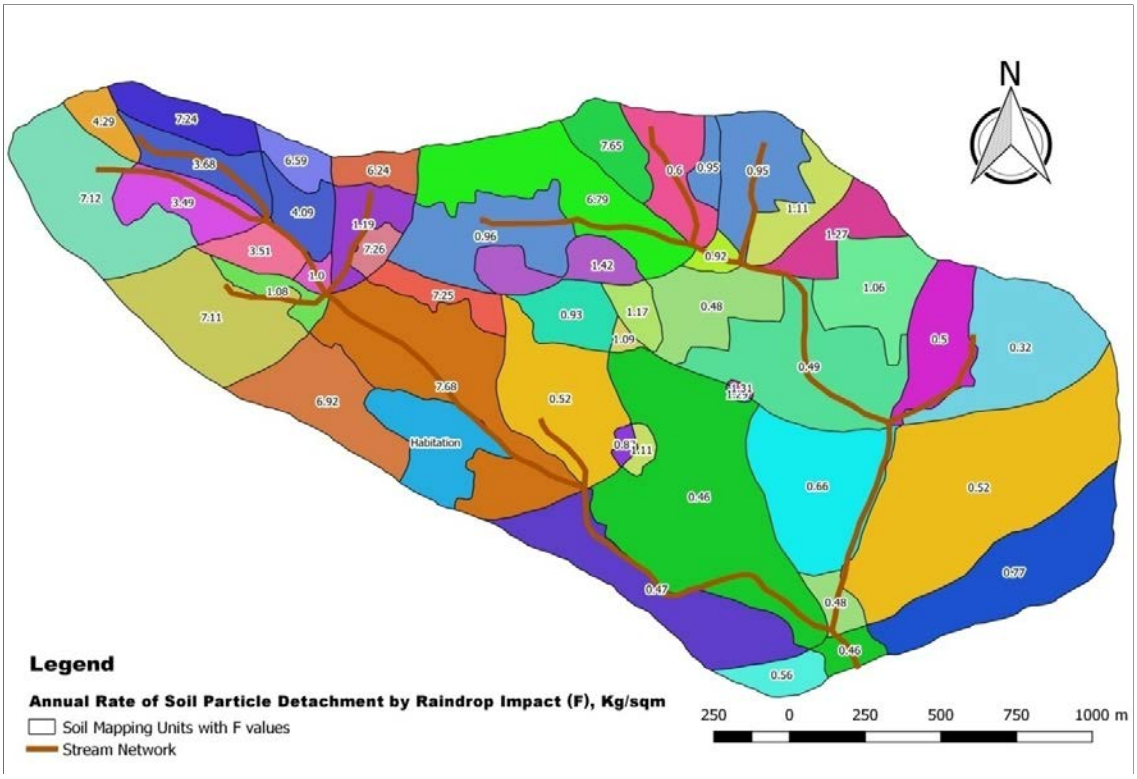

Fig 17: Soil mapping unit wise depiction of soil particles detachment by raindrop impact

The detachment of soil particles by runoff (H) is a function of the volume of runoff (Q), the detachability of the soil by runoff (Z), the slope angle (S) and the proportion of the soil covered by vegetation (GC). For estimating soil detachment rate by runoff (H), understanding the spatial distribution of slope (S), cohesion of the soil surface (COH) and fraction of ground cover (GC) are important conditions. The soil detachability by raindrop impact (F) is also influenced by the soil detachability index (K) and total kinetic energy (KE) which showed higher values (0.79–0.98 g J^{-1}) on flat areas with coarser soils and poor soil cover and lower values (0.11–0.33 g J^{-1}) on steep slope with fine soils and good vegetation cover in the study catchment (Fig. 18).

Only a proportion of the detached sediment will be delivered to the runoff for transport; the remainder will be deposited close to the point of detachment. The deposition at this point can be considered as the first phase of the depositional process. The quantity of detached soil delivered into the runoff (G) was therefore presented as the result of a balance between the amount of soil detached by raindrop impact (F) and the amount of soil detached by the runoff (H).

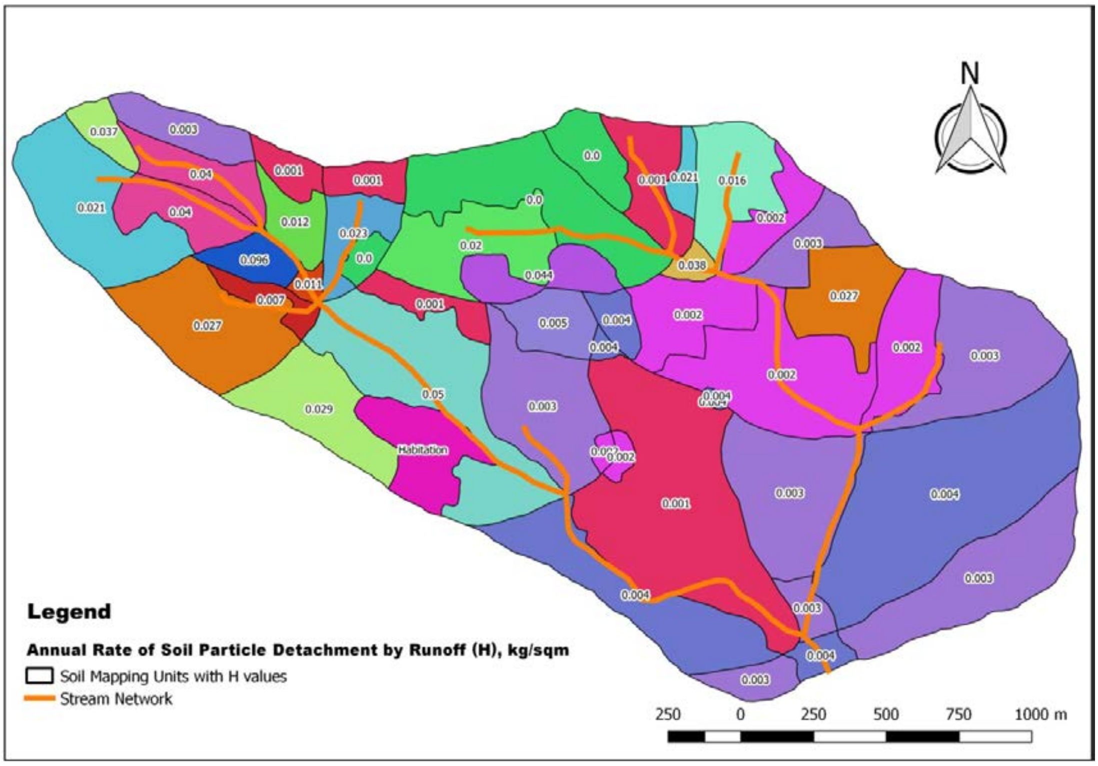

Fig 18: Soil mapping unit wise annual rate of soil particle detachment by runoff in study area

The spatial variability of the total soil detachment rate (J) as a result of the summation of F and H for the catchment is shown in Fig. 19 which ranged from 0.34 – 7.91 kgm^{-2}. The highest rate of F + H (7.91 kgm^{-2}) occurred in soil mapping unit U35 where subsoil exposed soils having low soil resistance to detaching forces. The lowest rate (0.34 kgm^{-2}) was observed in U14 where it was protected plantation area, and farm lands with high soil quality regardless of the slope steepness. This study generalized that the rate of soil loss increased with an increase of detaching forces. It was observed from the field that the process of erosion can continue until first the topsoil and finally the subsoil disappear unless suitable controlling measures are implemented. However, it is a matter of fact that all soils detached cannot be reached at the outlet of the catchment because of deposition areas on the way to the outlet. It is therefore important to have information that provides the spatial distribution of soil transport capacity of the overland flow (G) in the study catchment.

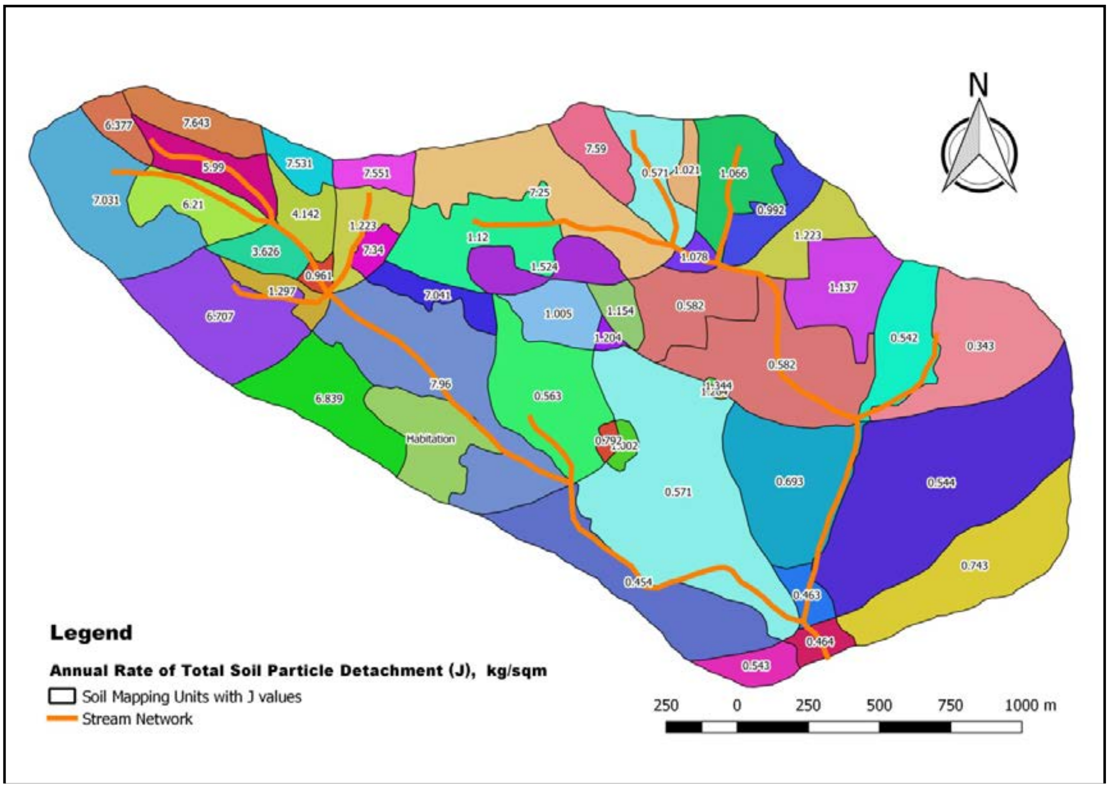

Fig 19: Soil mapping unit wise annual rate of total soil particle detachment in study area

The spatial distribution of annual soil loss (G) (Fig. 20) indicated higher value (9.74 t ha^{-1} y^{-1}) on steep slope, marginal and over grazed lands, and sites with bare soils and intensively cultivated without proper soil management and conservation measures, whereas it indicated lower value (0.01 t ha^{-1} y^{-1}) from relatively less disturbed areas (better vegetation and management practices).This indicated that annual soil loss (G) is influenced not only by slope but also by cover crop, conservation practices, and soil erodibility and erosivity conditions.

In general, the annual soil loss (G) value was lower than that of F + H which attributed to the transport of fewer amounts of detached soils by rainfall drop and runoff impacts. The estimated weighted average soil loss (G) at the outlet estimated by MMF model was 1.61 t ha^{-1} y^{-1}.

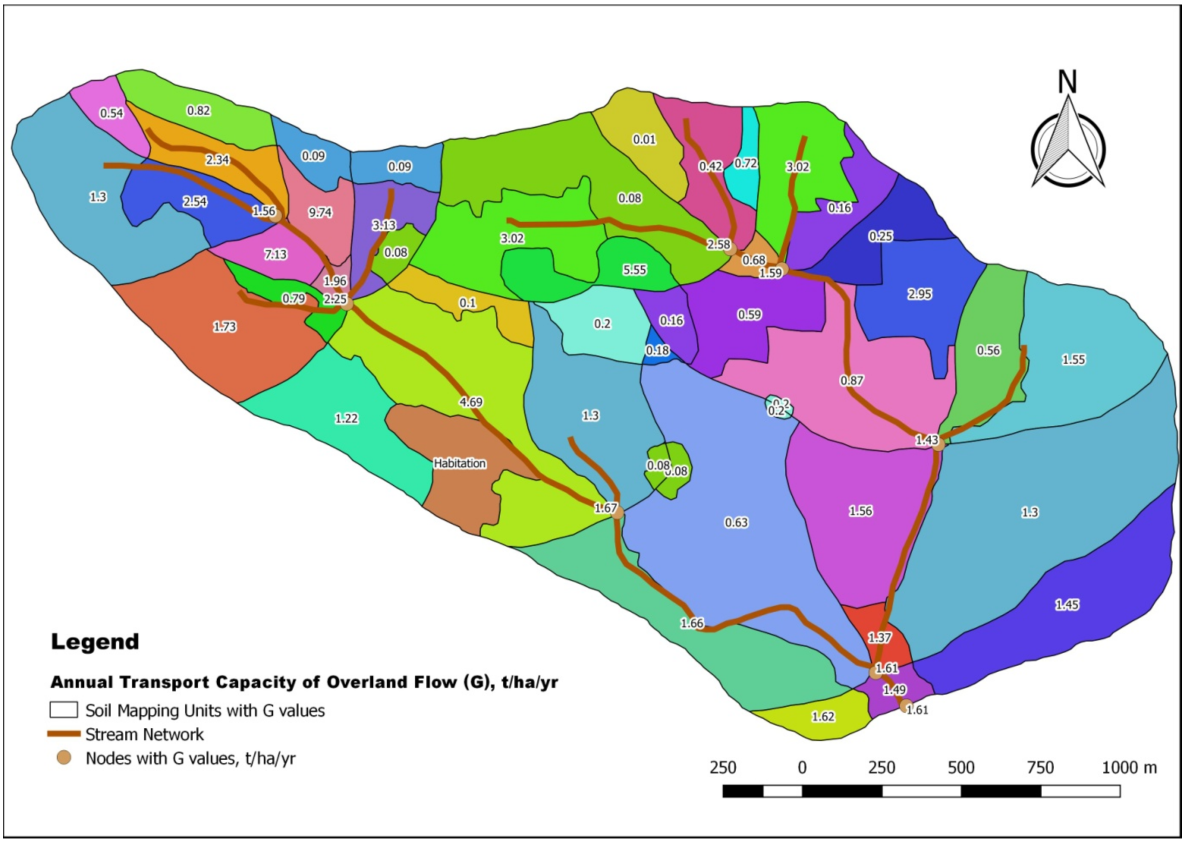

Fig 20: Soil mapping unit wise and Node wise annual soil loss in study area

Summary and Conclusion

For a given rainfall quantity, the runoff is the key process among other components of the hydrological cycle which itself presents as instantaneous responses of a catchment to rainfall events. The runoff predictive models which are capable of utilizing developed the rainfall-runoff relationship to simulate the runoff and soil loss over each storm would be a good transforming tools from a gauged to ungauged watersheds. The mathematical models which simulate significant hydrological processes occurring under watershed scale could able to quantify the impacts of natural factors and management strategies.

Following conclusions are made based on the research work undertaken:

- The annual average rainfall for the year 2016 pertaining to Patapur micro watershed was 838.38 mm with 38 rainy days. The peak intensity of erosive rain was 30 mm h^{-1} (Strongly Seasonal Climate). The total runoff measured at the watershed scale (at outlet) was 108.15 mm whereas predicted runoff by MMF Model for the study area was 94.07 mm.
- The observed data for annual soil loss at the outlet was 1.8 t ha^{-1} y^{-1} whereas predicted weighted average soil loss rate by MMF Model for the study area at the outlet was 1.5 t ha^{-1} y^{-1}.
- The MMF model estimates annual runoff and soil loss rate to an acceptable limits. The similarities between the annual measured and model simulated values at outlet were with 85 - 89 per cent accuracy.

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