MORPHOMETRIC AND HYDROLOGICAL ANALYSIS AND MAPPING FOR WATUT WATERSHED USING REMOTE SENSING AND GIS TECHNIQUES

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ABSTRACT

The study analyzes six morphometric parameters namely absolute relief, relative relief, dissection index, average slope, drainage density and ruggedness index, for better understanding of hydrologic processes in a watershed. The advanced application of Remote Sensing (RS) and Geographic Information System (GIS) techniques have lead to estimation of surface runoff and soil loss based on different parameters. Topographical map and Landsat Enhanced Thematic Mapper Plus (ETM+) satellite image are used for morphometric analysis. Land use/land cover, hydrologic soil characteristics, rainfall, curve number (CN) are used for surface runoff assessment using Soil Conservation Service (SCS) model. USLE (Universal Soil Loss Equation) model is used for soil loss estimation with the help of rainfall and runoff factor (R), soil erodibility factor (K), slope length and steepness factor (LS), crop management factor (C) and conservation practice factor (P). These parameters are obtained from monthly and annual rainfall data, soil data, topographic map, satellite image using RS and GIS techniques (with use of Normalized Difference Vegetation Index) respectively. This experimental study is carried out on Watut watershed under Morobe province of Papua New Guinea. The Watut watershed encompasses an area of about 5410.74 sq km. The average drainage density of this watershed is computed at 0.5 km/sq km with the average slope measuring about 31%. The result indicates an average of 68.23% of total rainfall flowing out as surface runoff with a concomitant wearing away of about 6579914 tons/year (12.16 tons/ha/year) of eroded soil in the Watut watershed. Wall to wall (pixel wise) spatial mapping for the entire watershed is carried out using these results. The study underscores that the integrated approach of SCS and USLE model with RS and GIS technologies have great potential for modeling of different hydrological parameters and producing risk maps in any watershed region.

KEYWORDS: *Remote Sensing, GIS, Runoff, Soil Loss, Hydrologic and Morphometric Analysis*

I. INTRODUCTION

Watershed is a natural laboratory of hydrology. It can be defined as the area that drains the entire precipitation into a particular stream outlet. In other word it is the catchment's area from which all precipitation i.e. rainfall as well as snow melt water drained into a single stream. It forms naturally to dispose the runoff as efficiently as possible. It is a natural convergent mechanism which consists of a network / branch of streamlets converging into a major stream. Studies of morphometry and hydrologic analysis on different watersheds have been carried out in many parts of the world. Relief and climate are the key determinants of running water ecosystems functioning at the basin scale (Lotspeich and Platts 1982, Frisselet al. 1986). Morphometric descriptors represent relatively simple approaches to describe basin processes and to compare basin characteristics (Mesa 2006) and enable an enhanced understanding of the geomorphic history of a drainage basin (Strahler 1964). Drainage basin morphometric parameters can be used to describe the basin characteristics. These are basin size (stream order, stream length, stream number, and basin area), basin shape factors (circularity ratio, elongation ratio, form factor and compaction ratio), basin perimeter, bifurcation ratios, drainage density, stream frequency and drainage intensity. The risk factor of flood is indirectly related with the bifurcation ratio (Waugh 1996). Quantitative expression of drainage basin shape or outline form was made by Horton (1932) through a form factor. The unit hydrograph, a method for estimating storm runoff, was proposed by Sherman in 1932 and since then it has been considered as a significant concept. Runoff is one of the most important hydrologic variables used in most of the water resources applications. Reliable prediction of quantity and rate of runoff from land surface into streams and river have been difficult and time consuming task especially for un-gauged watersheds. However this information is needed in dealing with many watershed development and management problems (Kumar et.al., 1991). Soil erosion is a complex dynamic process by which productive surface soil is detached, transported and accumulated at a distant place culminating in dual predicament – severe loss of agricultural productivity through the exposure of subsurface soil as well as siltation in reservoirs and natural streams elsewhere (Kandrika and Venkataratnam, 2005). Soil erosion is a major problem throughout the world. Globally, 1964.4 M ha of land is affected by human-induced degradation (UNEP, 1997). Of this, 1,903 M ha are subjected to aggravated soil erosion by water and another 548.3 M ha by wind. The Revised Universal Soil Loss Equation (RUSLE) calculates the long term average annual rate of erosion on a field slope based on rs (Drainage density, average slope, absolute relief, relative relief, dissection index, and ruggedness index mapainfall pattern, soil type, topography, crop system and management practices. RUSLE only predicts the amount of soil loss that results from sheet or rill erosion on a single slope and does not account for additional soil losses that might have occurred from gully, wind or tillage erosion. Economically, the soil loss results in the depletion of arable land and its quality by wearing away the top fertile soil and thereby affecting the land productivity as a whole. The present study is carried out with a view to preparing a land use map of Watut watershed. This will lead to the computation of the runoff volume by developing a suitable hydrological model, thereby enabling us to estimate soil loss by using RUSLE Equation using digital remote sensing data. Finally different hydro-geomorphological maps were developed for mophometric analysis.

II. STUDY AREA AND MATERIALS USED

The Watut watershed is situated in Morobe province. Sixty percent (60%) of the study area is covered by Bulolo districts, twenty one percent area (21%) in Hunon district, fifteen percent(15%) area in Menyamya district and the remaining four percent (4%) in Markham districts. The basin area is bounded within 145° 58' 45.92" E to 146° 53' 22.66" E longitude and 6° 36' 03.09" S to 7° 31' 15.69" S latitude. The basin area (Figure 1) is about 5410.74 sq km. Papua New Guinea's climate is tropical, as one would expect in a country located just south of the Equator. Port Moresby, the capital, and other towns on the coast are quite hot in the summer months; temperatures are considerably cooler in the Highlands. Average temperature is 27 °C while total annual rainfall is 3500 mm in the study area. All other physical characteristics are discussed in the underlying paragraphs.

Topographical maps are used for this study. Optical bands with standard false color combination (SFCC) of LANDSAT-7, Enhance Thematic Mapper Plus (ETM+) satellite images are used to determine the land use/land cover classes in the study area. All other details of the collateral data sets are given in the Table 1.

Table1. List of data used in the study

Sl. No.	Collateral data	Scale/ Resolution	Year of publication	Source
1	Topographical maps	1:250000	1960	National atlas of Papua New Guinea and topographical map
2		1:100000	1973 - 1980	
3	Landsat-7, ETM+	30 m	2001	University of Maryland
4	Soil map	1:500000	1975	USDA
5	Rainfall	Station: point data	1972-2002	weather-forecast.com report

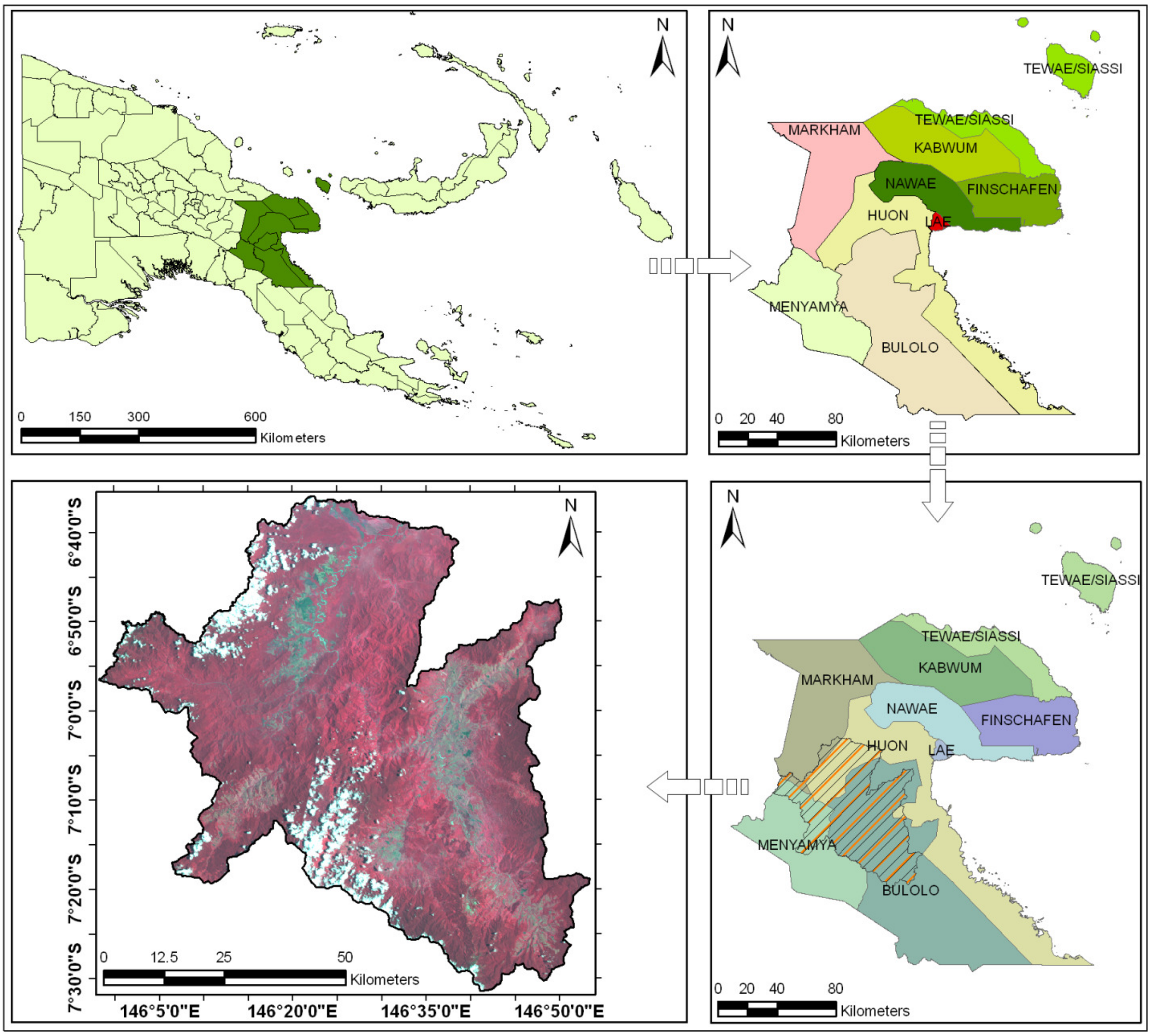

Figure 1. Location map of the Watut watershed region

III. METHODOLOGY

ArcGIS 10.0 and Erdas Imagine software are used for the preparation of different digital data set using satellite image, topographical map and collateral information. Six morphometric analyses, namely absolute relief, relative relief, dissection index, average slope, drainage density and ruggedness index and two hydrological analyses viz. surface runoff and soil loss estimation are performed using different algorithms in the model maker.

3.1. Preparation of drainage, land use/land cover and soil data set

A drainage map is prepared using the National atlas of Papua New Guinea, topographical map and satellite image for delineation of watershed along with the contour information. The drainage network of the entire Watut watershed is subdivided into individual lengths of channel and arranged according to the magnitude of orders as proposed by Strahler (1952). Using the magnitude of order attributes, stream order map is prepared (Figure 2a). The flow direction of the prepared drainage map of Watut watershed is from south-east to north-east. Bulolo river from left and Snake river from right hand side meet each other at 146° 35' 29.23" E and 7° 03' 20.32" S. Finally the flow, Watut river meets with Markham River, in the Huon district. Total length of the river is 224.45 km. Other tributaries of this river are Waime, Wafi river, Banir river, Isimp river, Mumena river and Laloona river. The maximum stream order of this drainage network is five which appear in lower part of the basin.

3.1.1 Land use/ land cover

Land use/land cover is one principal tool for runoff and soil loss estimation. The land use /land cover data sets are generated from the digital image classification of LANDSAT, ETM+ satellite images. This classification is performed taking nine classes within the entire study area, namely water body, dense forest, low dense forest, agriculture, shrub land, barren land, plantation, mangrove and settlement (Figure 2b). 80% of the study area comprises forests. In the lower catchment area some agricultural lands are found, albeit of a tiny proportion featuring only about 2% of the study catchment. Detailed land use and land cover statistics are given in Table 2. Overall accuracy achieved is 89%, after carrying out an accuracy assessment using ground truth (reference sample points) data sets.

3.1.2 Soil characteristics

Soil texture and hydrologic soil group are very important parameters for estimation of runoff, soil loss, transport capacity and net detachment. Soil texture is the principal factor affecting soil erodibility factor. Seven types of soil texture i.e. sandy clay, silty clay loam, silty clay, loam, sandy loam, silty loam and sandy clay loam are found in the study area (Figure 2c). The hydrologic soil groups indicate the infiltration potential (vertical flow) of the soil after prolonged wetting. The SCS model has classified all soils into four hydrologic groups. These are (i) "Group A" soils which have low run off potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sands or gravels while loamy sands or sandy loams are sometimes included in this group where the 'saturated infiltration rate' is greater than 0.76 cm/hr when thoroughly wet. (ii) "Group B" soils that have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately well to well-drained soils with moderately fine to moderately coarse textures. Silt loams or loamy soils embrace this group when the saturated infiltration rate is 0.38 to 0.76 cm/hr. (iii) "Group C" soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and also soils with moderately fine to fine texture. Sandy clay loams feature in this group and the saturated infiltration rate is 0.13 to 0.38 cm/hr. (iv) "Group D" soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist mainly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface and shallow soils over a nearly impervious material. Clay loams, silt clay loams, sandy clays and silty clays or clays are covered in this group when saturated infiltration rate falls to 0 - 0.13 cm/hr. All four types of hydrologic soil group are found in this watershed region (Figure 2d and table 2).

Table 2. Land use/land cover and hydrological soil group statistics of the study area.

Land use/Land cover	Area (sq km)	Area (%)	Hydrological soil group	Area (sq km)	Area (%)
Dense forest	2848.91	52.7	Group-A	127.52	2.4
Shrub	47.51	0.9			
Low dense forest	1707.89	31.6	Group-B	239.41	4.4
Mangrove	109.25	2.0			
Settlement	1.89	0.0	Group-C	1419.17	26.2
Barren land	638.51	11.8			
Plantation	2.18	0.0	Group-D	3624.64	67.0
Agriculture	14.81	0.3			
Water	39.80	0.7	Total	5410.74	100.0
Total	5410.74	100.0			

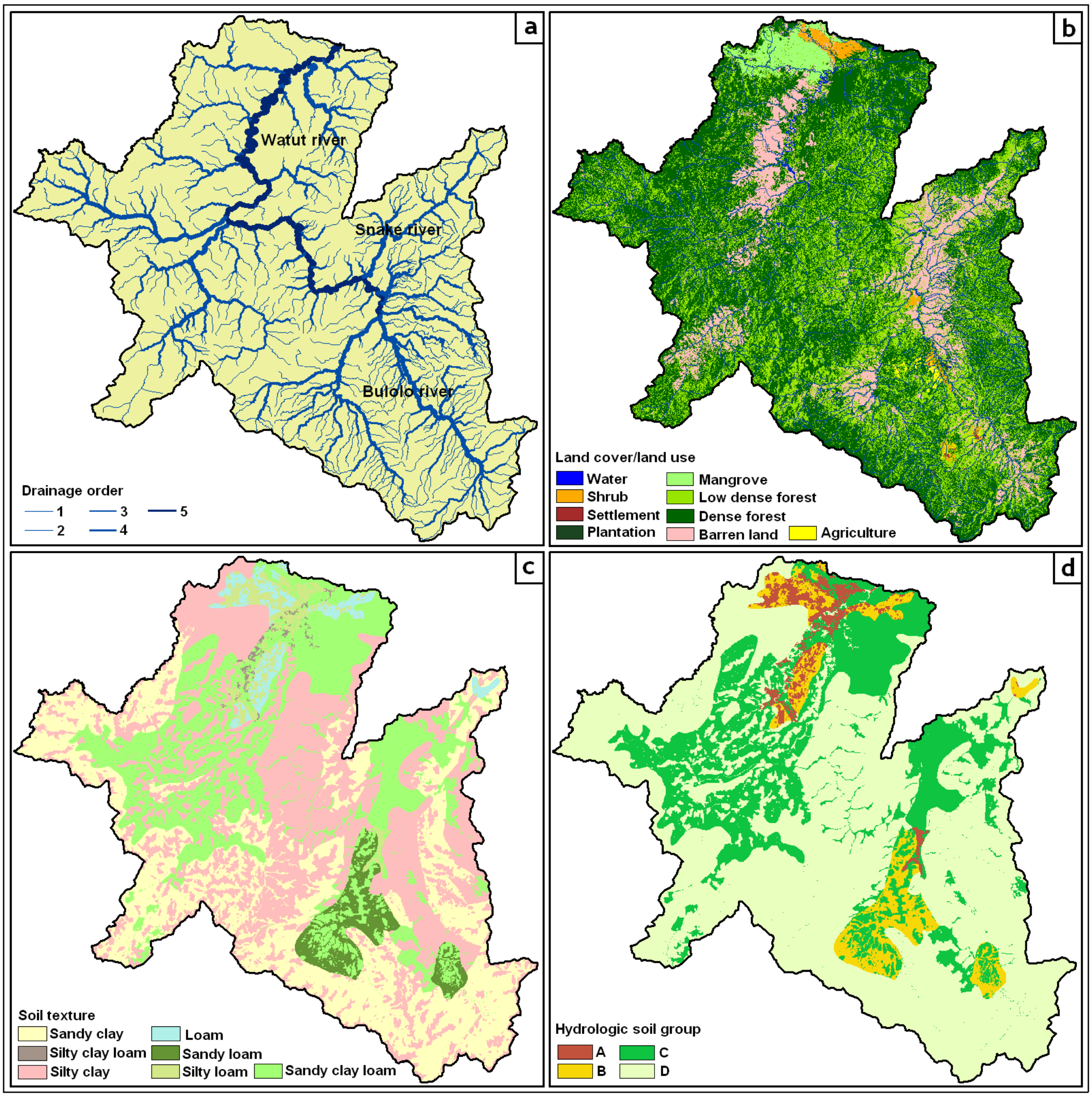

Figure 2. Drainage order (2a), land use/land cover (2b), soil texture (2c) and hydrologic soil group (2d) of Watut watershed, generated from satellite image and soil data.

3.2. Morphometric analysis of the watershed

Morphometry is the measurement and mathematical analysis of the configuration of the earth's surface, shape and dimension of its landforms (Agarwal, 1998; Obi Reddy et al., 2002). A major emphasis in geomorphology over the past several decades has been on the development of quantitative physiographic methods to describe the evolution and behavior of surface drainage networks (Horton, 1945; Leopold & Maddock, 1953; Abrahams, 1984). Different morphometric techniques, like absolute relief, relative relief, dissection index, average slope, drainage density and ruggedness index (Table 3) are considered for quantitative analysis of different attribute of the watershed. A point layer is generated in the ArcGIS s/w environment and the spot heights are collected according to the longitudinal and latitudinal value. Then spot height attribute for each sample location is introduced to the point layer. Arc coverage, which represents the contours, is used to build 3D surfacing in the ERDAS IMAGINE s/w environment. All point data are interpolated to the raster through krigging interpolation (Matheron, 1970) techniques in the ArcGIS s/w environment. Both interpolated and surfacing outputs are merged to create raster digital elevation model (DEM) for the Watut watershed and the absolute relief map is generated as shown in figure 3a.

Table 3. Different morphometric techniques used in the study

Sl. No.	Morphometric techniques	Key description	Data used	Software used
1	Absolute relief	Maximum height of relief	Spot-heights and contours with z values	Erdas Imagine (Surfacing)
2	Relative relief	Maximum – minimum relief	Digital Elevation Model	ArcGIS (Range)
3	Dissection index	Relative relief/Maximum height	Relative relief and Digital Elevation Model	Erdas Imagine (Model maker)
4	Drainage density	length of streams/area	Drainage map	ArcGIS (Line density)
5	Ruggedness index	(Drainage density x relative relief)/1000	Drainage density and relative relief	Erdas Imagine (Model maker)
6	Slope	(Rise/run) x 100	Digital Elevation Model	ArcGIS & Erdas Imagine (3D analysis)

The maximum altitude is 3316 m, demarcated in the southern part and the minimum elevation is closer to mean sea level (MSL) observed in the northern part of the watershed.

3.2.1 Relative relief

To show spatial variation from one place to another calculation of relative relief (Rao, 2011) is paramount. The value of relative relief is calculated from the contour and DEM data using range analysis in ArcGIS software. Figure 3b displays the relative relief characteristics, where maximum relative relief value is 631 m in the middle and eastern parts of the Watut watershed.

3.2.2 Dissection index

For better understanding of morphometry as well as physiographic attribute, dissection index analysis is performed (Schumm, 1956). Dissection index is defined as a ratio between actual dissection made by the rivers and potential dissection up to base levels. Relative relief and maximum altitude are used to compute the dissection index. Higher the value of dissection index, larger is the undulation and instability of the terrain. Maximum dissection index is calculated as 0.58 in the northern part of the watershed (Figure 3c).

3.2.3 Drainage density

The drainage density is the ratio of the total length of streams within a watershed to the total area of the watershed (Horton, 1932). A high value of the drainage density indicates a relatively high density of streams inducing a rapid storm response giving rise to a higher runoff yield. Using the ArcGIS kernel density function the drainage density map of the watershed is prepared (Figure 3d). Maximum drainage density is computed as 1.31 km per sq km in the south and south-east parts of the study area.

3.2.4 Ruggedness index

The topographic ruggedness index too indicates the extent of instability of land surface (Strahler, 1956). Ruggedness index map is generated using relative relief and drainage density data set. Here the values of ruggedness almost coincide with other morphometric values. Ruggedness index of the area varied from 0.01 to 0.45 (Figure 3e). The values of ruggedness index increase towards south and south-east in the watershed.

3.2.5 Average slope

The slope tool calculates the maximum rate of change between each cell and its neighbors. The lower slope value indicates the flatness of the terrain and higher slope value point to a steeper terrain. The output slope raster can be calculated as percent of slope or degree of slope. When the slope angle equals 45 degrees, the vertical rise is equal to the horizontal run and is expressed as 100 percent slope. As the slope approaches vertical (90 degrees), the percentage slope approaches infinity. Slope analysis is performed to prepare the slope data set of the area. Slope of the area is calculated in percent gradient using ArcGIS 3d analysis tool. The watershed region possesses a maximum slope of 153 percent in the north-west and middle part (Figure 3f).

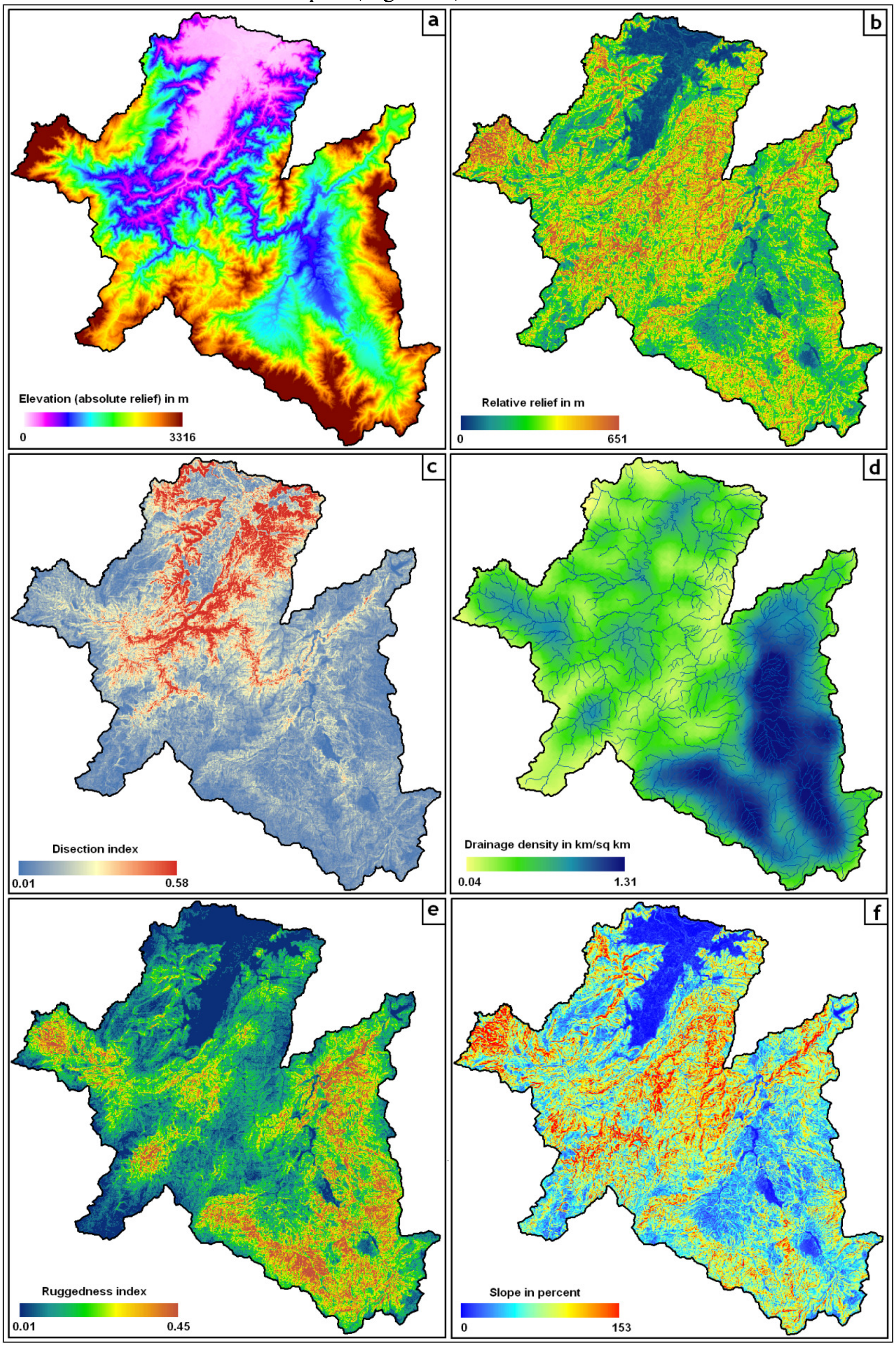

Figure 3. Absolute relief (3a), relative relief (3b), dissection index (3c), drainage density (3d), ruggedness index (3e) and average slope (3f) generated from satellite image and DEM

3.3. Spatial modeling of surface runoff

The SCS method has been used by many researchers because it gives consistently usable results (Rao et al., 1996; Sharma et al. 2001; Chandramohan and Durbude, 2001; Sharma and Kumar, 2002) for runoff estimation. The SCS model computes direct runoff through an empirical equation that required the rainfall and a watershed co-efficient as input. The watershed co-efficient is called the curve number (CN) which represents the runoff potential of the hydrologic soil cover complexes. The SCS model (SCS, 1972) involves relationships between land cover, hydrologic soil classes and curve number. The equation 1 is used to calculate the surface runoff of the Watut watershed.

$$Q = (P - Ia)^2 / (P - Ia + S) \text{ ----------------------- } (1)$$

Where,
Q is actual surface runoff in mm,
P is rainfall in mm,
Ia is 0.4S [Initial abstraction (mm) or losses of water before runoff begins by soil and vegetation (such as infiltration, or rainfall interception by vegetation)],
S is the potential maximum retention in mm and is calculated using the equation 2.

$$S = (25400 / CN) - 254 \text{ ----------------------------- } (2)$$

Where,
CN is curve number of hydrologic soil cover complex, which is a function of soil type, land cover and antecedent moisture condition (AMC), is shown in table 4.

Table 4. Curve numbers for different kinds of land use/land cover and soil (AMC II & Ia =0.4S)

Sl. No.	Land use/land cover	Hydrologic soil group	Curve number	Area in sq km
1	Water	A	100	6.41
		B	100	0.00
		C	100	12.29
		D	100	21.11
2	Dense forest	A	30	65.12
		B	55	106.28
		C	70	702.18
		D	77	1975.33
3	Low dense forest	A	45	15.09
		B	66	93.50
		C	77	401.25
		D	83	1198.07
4	Agriculture	A	62	0.00
		B	71	3.63
		C	78	3.63
		D	81	7.55
5	Shrub land	A	39	20.21
		B	61	3.55
		C	74	9.43
		D	80	14.33
6	Barren land	A	68	20.69
		B	79	32.45
		C	86	246.12
		D	89	339.23
7	Settlement	A	57	0.00
		B	72	0.00
		C	81	1.89
		D	86	0.00
8	Plantation	A	45	0.00
		B	66	0.00
		C	77	0.00
		D	83	2.18
9	Mangrove	A	0	0.00
		B	0	0.00
		C	70	42.38
		D	77	66.84
Total area in sq km				5410.74
Weighted curve number				77

3.4. Spatial modeling of soil loss

Hydrologic calculation of soil loss for Watut watershed is performed using simple equations. By using the revised universal soil loss equation (Renard, 1997), the total soil loss is measured for the Watut watershed. The revised universal soil loss equation (RUSLE) is-

$$A = R \times K \times LS \times C \times P \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where,

A is the potential long term average annual soil loss in tons per acre per year. This is the amount, which is compared to the "tolerable soil loss" limits.

R is the rainfall and runoff factor by geographic location, is calculated using the following equation.

$$R = 38.5 + 0.35 \times Pr \quad \ldots\ldots\ldots\ldots\ldots (4)$$

Where, Pr is average annual precipitation of the study area

K is the soil erodibility factor. K factor is calculated according to the soil texture type of the area (Robert, 2000), e.g. 0.24 for sandy clay, 0.32 for silty clay loam, 0.26 for silty clay, 0.20 for sandy clay loam, 0.30 for loam, 0.13 for sandy loam and 0.38 for silty loam.

LS is the slope length-gradient factor. The following equation (Robert, 2000) is used to calculate the slope length-gradient factor.

$$LS = [0.065 + 0.0456(slope) + 0.006541(slope)^2] \times (slope\ length \div const)^{NN} \quad \ldots\ldots\ldots\ldots\ldots (5)$$

Where, slope is the percent of steepness (%), slope length is length of slope (m), constant is 22.1 and - NN is 0.5 as slope is more than 1%.

C is the crop/vegetation and management factor, is obtained multiplying crop type factor and the tillage method factor, e.g. 0 for water, 0.002 for settlement, 0.004 for forest area, 0.050 for shrub land and grass cover land, 0.125 for agriculture and 0.5 for barren land.

P is the support practice factor, considered as according to the up and down Slope of the area, e.g. value 0.60 for 0-7% , 0.70 for 7-14% , 0.80 for 14-21% , 0.90 for 21-28% and 1.0 for more than 28% of slope.

IV. RESULT AND DISCUSSION

In upper watershed region number of stream is greater and steep slopes are found. Thus the overland flow velocity is also more, about 5.0 km per hour as measured in the upper watershed region. Relative relief, dissection index, average slope, ruggedness index, drainage density are more, indicating unstable topography and greater vulnerability for erosion and land slide. Lower reaches of the watershed region have gentle slope and fewer number of channel/streams. The dissection index and ruggedness index are also very low. Erosional materials are transported and deposited in this lower part of the Watut river, bereft of the required kinetic energy to carry forward. So the river thalwegs get continually escalated and water holding capacity goes down engendering frequent flash floods. The average bifurcation ratio is also measured at 1.74 for Watut watershed.

The runoff curve numbers for land cover delineation are used for determination of curve number for the watershed. The weighted curve number for AMC II is found 77 for the total watershed area. Similarly the weighted curve numbers for antecedent moisture conditions I & III are also calculated which are 61 and 89 respectively. Calculated curve numbers are used to model surface runoff of the area. The spatial distributions of calculated curve number (Figure 4a) are mapped for each pixel in the raster data format. Model maker tool of Erdas Imagine and spatial analysis tool of ArcGIS are used for this mapping purpose. The average slope-length gradient factor of the watershed is calculated as 20.30 from digital elevation model in the Erdas Imagine model maker. Slope-length gradient factor is mapped pixel-by-pixel for the area as shown in the figure 4b.

Land use/land cover, hydrologic soil characteristics, rainfall, curve number are used to estimate surface runoff by SCS model for Watut watershed. There is a big amount of storm rainfall recorded as 277 mm, in the month on March, 2011. The above rainfall (277 mm) is introduced as an input in the SCS model. As the model output (Figure 4c) the minimum range of surface runoff (125 to 150 mm) is found in the lower watershed area and maximum range (225 to 245 mm) in some parts of the upper watershed area. The calculated average surface runoff is 189 mm, almost 68 percent of the total storm rainfall.

Table 5. Estimation of runoff volume for Watut watershed

Month/date	Rainfall (mm)	AMC	CN	S	Runoff (mm)
15-20th September	171	II	77	75.87	91.37
January	275				186.74
February	260				172.62
March	277*				188.63*
April	262				174.50
May	195				112.71
June	153				75.78
July	144				68.15
August	117				46.20
September	113				43.09
October	158				80.07
November	179				98.42
December	255				167.94

** Spatial mapping is done using storm rainfall as shown in figure 4C (output: input → 1:1.47).*

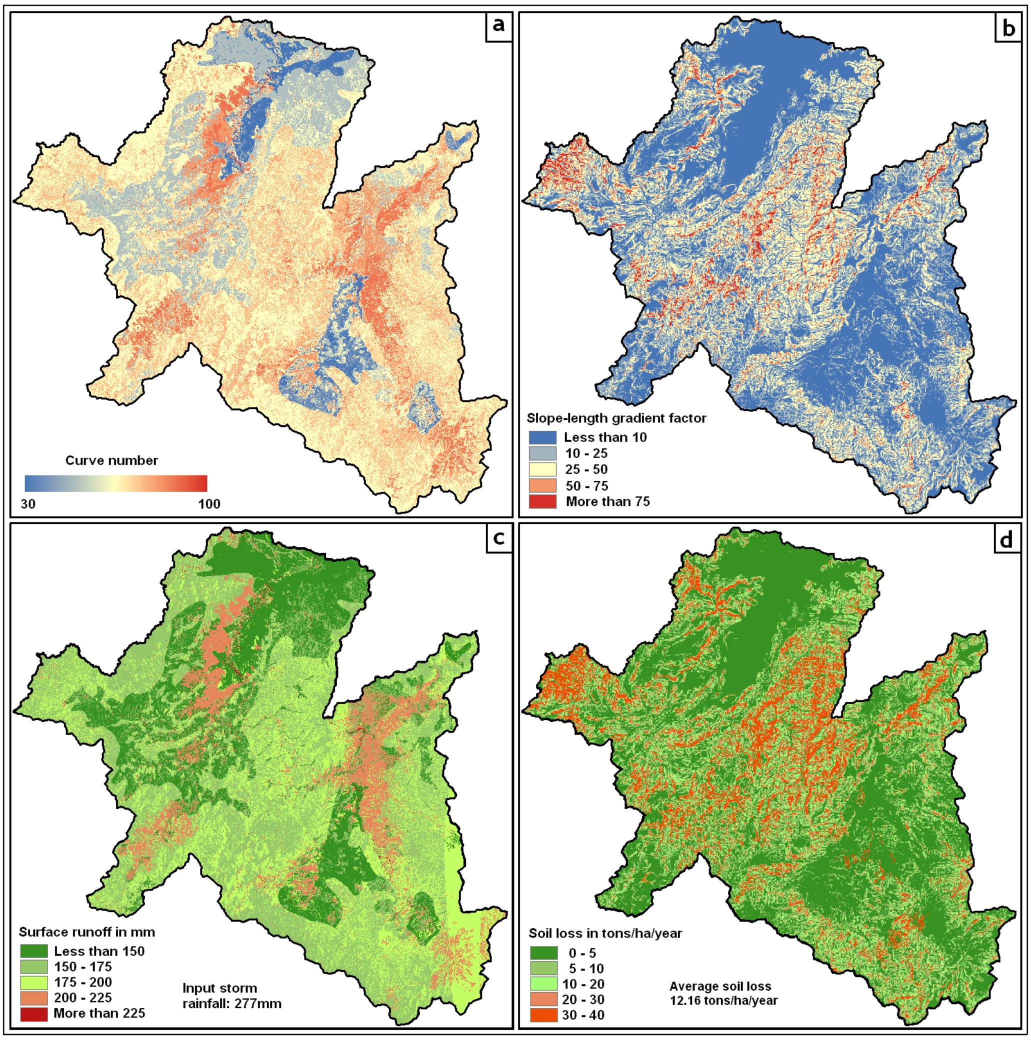

Figure 4. Calculated curve number from land use and hydrological soil group (4a), slope-length gradient factor from DEM (4b), estimated surface runoff (4c) and soil loss (4d) according to SCS and RUSLE model using Erdas Imagine and ArcGIS.

Rainfall and runoff factor, soil erodibility factor, slope length and steepness factor, crop management factor and conservation practice factor are used to calculate the soil erosion in the watershed area following USLE model. Monthly and annual rainfall data, soil map of the region, DEM, RS techniques (with use of normalized difference vegetation index) and land use/land cover map are used to obtain above parameters. Total soil loss is 6579914 tons/year calculated for the Watut watershed. Soil losses characteristics of the watershed area are shown in figure 4d. Red color pixels indicate high rate of soil erosion in the watershed area. The average soil loss of the area is calculated as 12.16 tons/ha/year.

V. CONCLUSIONS

Watershed is a basic unit for morphometric analysis. Remote sensing and GIS techniques are known for providing very high accuracy in mapping and measurement done in morphometric analysis. Absolute reliefs, relative relief, dissection index, ruggedness index, slope and drainage density are the most useful criteria for the morphometric classification of a watershed. These decisive factors are more in the upper part of the watershed and are instrumental in controlling the runoff pattern, sediment yield and other hydrological parameters of the watershed region. Surface runoff is calculated as very high (more than 200 mm, when the storm rainfall is 277 mm) in some parts of the watershed where land cover types are 'barren land' and / or 'open hills area'. The watershed region has considerably high rate of soil erosion (6579914 tons/year), because of high slope-length gradient factor. In this study, the methodology for determination of runoff, soil loss and spatial mapping are attempted for Watut watershed using RS, GIS, RUSLE and SCS model. This approach could be applied in other watersheds or river basin for planning of various conservation measures.

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