IJRSG
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International Journal of Remote Sensing & Geoscience (IJRSG)
www.ijrsg.com

GEOSPATIAL DATA FOR SURFACE RUNOFF AND TRANSPORT CAPACITY MODELING

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Abstract

Soil erosion, surface runoff, watershed analysis studies have largely been neglected in the past. Only studies connected to specific developments, mainly mining and hydropower, have been carried out. Some of these studies show very high intensities of erosion, indicating that certain areas of Papua New Guinea are among the most geomorphologically dynamic areas on the earth. The advance application of Remote Sensing (RS) and Geographic Information System (GIS) techniques helps to estimate watershed characteristics, surface runoff and soil loss based on different parameters. Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Global DEM data and Landsat satellite image are used for morphometric analysis of the Busu watershed (1311.32 sq km). Different mandatory inputs parameters to the model, namely the land use/land cover, hydrological soil characteristics, rainfall data, Potential Maximum Retention, Weighted Curve Number for SCS model; and rainfall and runoff , soil erodibility, slope length and steepness, crop management and conservation practice factor for RUSLE, have been derived either from remote sensing data or from conventional data collection systems. Finally transport capacity of Busu watershed is derived using estimated storm runoff, cover and slope factor. ArcGIS v10.1 software is used to store, manipulate, analysis, and modeling of soil loss, runoff calculation and watershed analysis. The average drainage density of this watershed is computed as 0.6 km/sq km with the average slope measuring about 51.72%, maximum relative relief of 496 m and a maximum ruggedness index of 0.29. The result also estimates an average of 80 % of total rainfall flowing out as surface runoff. The average soil loss of Busu watershed is calculated as 0.79 tons/hectare/year. Model predict a transport of 162 tons in 3-days storm rainfall of 229 mm with an average slope of 51.72 % of the study area. Pixel-by-pixel spatial mapping for the entire watershed is carried out using these results. The study underscores that the integrated approach of SCS, RSLUE and transport capacity model with RS and GIS technologies have great potential for modeling of different hydrological parameters and producing risk maps in any watershed of Papua New Guinea after gathering geospatial data.

Key words: 'Watershed', 'Morphometry', 'Surface Runoff', 'Soil Loss', 'Transport Capacity', 'Remote Sensing' and 'GIS'

Introduction

Lae is the capital city of Morobe province located in the east coast of Papua New Guinea (Mainland). The surroundings area of Lae is characterized with a tropical rainforest climate (high temperatures and high precipitation). Lae is one of the wettest places in Papua New Guinea with more than 4,500 millimeters of annual precipitation (Table 1). Daytime temperature is around 30 degrees Celsius all year round. Because of high temperatures in combination with high precipitation figures humidity figures are also high (Weatherbase, 2011).

The Busu River is the fastest flowing river in Papua New Guinea and the seventh fastest river in the world, located near Lae, in Morobe Province (Figure 1). Busu starts from elevation of 4090 m at 6° 19' 00'' S, 147°05' 11'' E and flows south for 75 km to empty into the Huon Gulf at 6°43' 44''S 147°03' 05''. The study area covers an area of about 1311.32 sq km (131132 hectares). This area is dominated by primary forest/vegetation, mountain ranges, high slope. Watershed is a natural laboratory of hydrology, can be defined as the area that drains the entire precipitation into a particular stream outlet.

Research of hydro-morphometry analysis on watersheds have been carried out in many parts of the world. Land cover, soil, topography and climate are the key determinants of running water ecosystems functioning at the basin scale (Lotspeich and Platts, 1982, Frissell et. 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). Watershed morphometric parameters can be used to describe the basin characteristics, namely basin size, drainage density, stream frequency and drainage intensity. The risk factor of inland flood in a watershed is indirectly related with the bifurcation ratio (Waugh 1996). Surface runoff is the water flow that occurs when soil is infiltrated to full capacity and excess water from rain, melt water, or other sources flows over the land. This is a major component of the hydrologic cycle. Infiltration excess overland flow occurs when the rate of rainfall on a surface exceeds the rate at which water can infiltrate the ground and any depression storage has already been filled. Soil erosion is a process by which productive surface soil is detached, transported and accumulated at a distant place culminating in dual predicament (Kandrika and Venkataratnam 2005).

Landslide, one of the major natural disasters is found by many studies on its susceptibility assessment. The initial concept was first introduced by Akguan et al., (2008), and Oh and Lee (2009) as the spatial distribution of factors related to the instability processes in order to determine zones of landslide prone areas without any temporal implication. It is widely recognized that geology, landform characteristics, soil type, land use, vegetation, slope and elevation, etc play a significant role in landslide occurrence. With remote sensing techniques one can attain information for a large area from time to time and by combining with GIS to demarked probable landslide areas (Akgun and Turk, 2010). In Papua New Guinea there are different types of floods are usually occurs, i.e. flash floods, rapid onset floods and slow onset floods. Flooding occurs when a watercourse is unable to convey the total storm runoff flowing down stream. Runoff is one of the most important hydrologic variables used in most of the water resources applications (Sherman, 1932). Reliable prediction of quantity and rate of runoff is needed in dealing in dealing with many watershed development and management problems (Kumar et al. 1991). Considerable hydrological and meteorological data are essential for prediction of river discharge through conventional models. Collection of these data is expensive, time consuming and a difficult process (Nayak, 2003). Soil erosion is a major problem throughout the world. Globally, 1964.4 M ha (1,903 M ha by water and 548.3 M ha by wind) of land is affected by human-induced degradation (UNEP 1997). The Revised Universal Soil Loss Equation (RUSLE) calculates the long term average annual rate of a watershed area based on average slope, rainfall pattern, soil type, drainage density topography, crop system and management practices. It only predicts the amount of soil loss that results from sheet or rill erosion on a single slope. 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, the surface water storage capacity by sedimentation and water quality.

The role of remote sensing in runoff calculation is generally to provide a source of input data for estimating equation coefficients and model parameters. The present study is carried out with preparing land use/land cover map of Busu watershed, which lead to the computation of the runoff volume by developing a suitable hydrological model and to estimate soil loss and transport capacity using remote sensing data.

Table 1. Climate data for Lae

Month	Average high Temperature (°C)	Precipitation (mm)
Jan	31	290
Feb	31	234
Mar	31	323
Apr	30	401
May	29	417
Jun	28	427
Jul	28	526
Aug	28	523
Sep	29	439
Oct	29	401
Nov	31	325
Dec	31	330
Year	29.7	4636

Source: Weatherbase, 2011

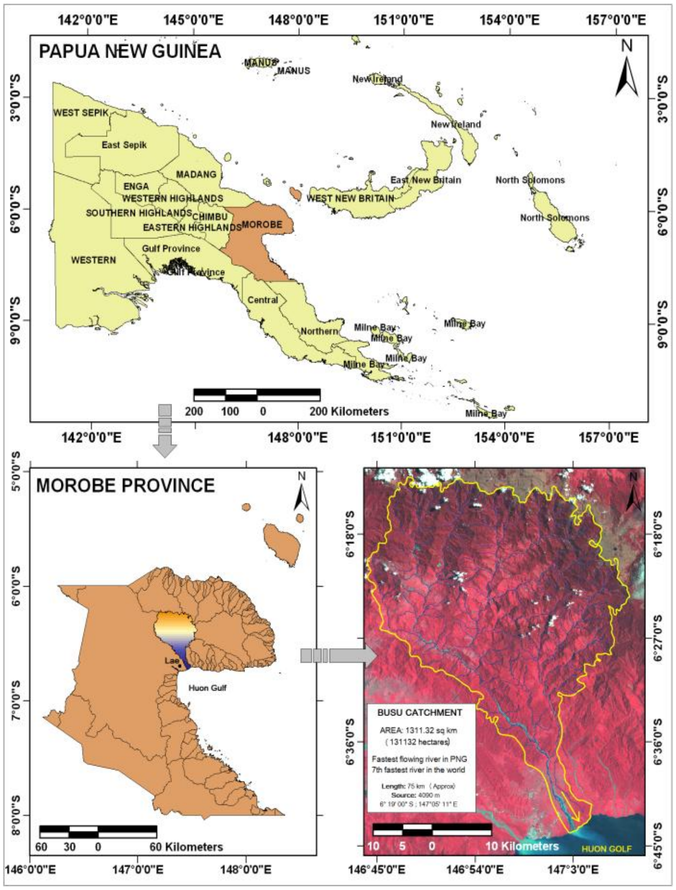

Figure 1. Location map of Busu catchment

Methodology

ArcGIS 10.1 and Erdas Imagine software are used for the preparation of different geospatial data set. Those data sets are used as mandatory input into the model. Few surface and geo-morphometric techniques are used to analyses the watershed characteristics, namely absolute relief, relative relief, dissection index, average slope, drainage density, drainage ordering and ruggedness index and three hydrological analyses , namely surface runoff, soil loss and transport capacity estimation are analyzed using different algorithms in the ArcGIS raster calculator environment.

A. Morphometric analysis

Morphometric analysis is a quantitative method to know configuration of the land surface (Agarwal 1998; Obi Reddy et al. 2002). Physiographic methods describe the evolution and behavior of surface drainage networks (Horton, 1945; Abrahams, 1984) in a watershed region.

Different techniques, like absolute relief, relative relief, dissection index, average slope, drainage density and ruggedness index are considered for quantitative analysis of various attributes of the Busu watershed (Table 2). A digital elevation model (DEM, or more correctly a land surface model - LSM) is one of the most useful sources of information for spatial modeling and monitoring (Samanta et al. 2012), with applications as diverse as catchment dynamics, prediction of soil properties, highway construction, wind turbine location optimization, land surface visualization and landscape simulation in computer games (Hengl and Evans 2007).

Table 2. Mophometric parameters of Busu watershed

Parameters	Maximum	Minimum	Average
Absolute relief	4090 m	0 m	1762.09 m
Relative relief	496 m	0 m	39.86 m
Dissection index	0.2	0.0012	0.03
Drainage density	0.96 km/sq km	0.056 km/sq km	0.60 km/sq km
Ruggedness index	0.29	0.001	0.024
Average slope (degree)	65 degree (Steep)	0 (Flat)	26.03 degree

Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) data sets are used as the digital elevation model (DEM). Absolute relief map of the Busu watershed is generated in the ArcGIS v-10 mapping platform with the maximum altitude of 4090 m, demarcated in the north-east part of the study area (Figure 2a). Spatial variation from one part to another within the Busu watershed represented through the calculation of relative relief with the input of elevation data using range analysis algorithm. Figure 2b displays the relative relief characteristics, where maximum relative relief value is 496 m in the northern parts of the watershed. Dissection index indicates the ratio between actual dissection made by the rivers and potential dissection up to base levels. For better understanding of physiographic attribute of a watershed region dissection index analysis is performed (Schumm 1956) using relative relief and maximum altitude. Maximum dissection index can be found as 0.2 in the southern part of the watershed (Figure 2c).

The drainage density is the ratio of the total length of rivers per sq km within a watershed (Horton 1932). A high value of the drainage density indicates a relatively high numbers of streams. It is the indication of higher runoff yield in a storm rainfall. Highest drainage density is computed as 0.97 km/sq km in the eastern parts of the study area (Figure 2d). The terrain ruggedness index indicates the extent of instability of land surface (Strahler 1956), is produced using relative relief and drainage density database. Ruggedness index of the area is varied from 0.0001 to 0.29 (Figure 2e). The values of ruggedness index increase towards east in the study area. Slope represented by raster data indicates change between each cell and its neighbors cell. The lower slope value indicates the flatness and higher slope value point to a steeper terrain. Slope of the area is calculated in percent gradient using 3D analysis tool. A maximum slope of 65 degree in the north-east part is prove the steepness of the region which is an important factor to be a seventh fastest river in the world (Figure 2f).

B. Spatial modeling of surface runoff

The SCS model gives useful output for runoff estimation in a particular watershed (Sharma and Kumar 2002). The SCS model computes runoff using equation 1 that required the rainfall, land use, hydrological soil as input parameters. The watershed co-efficient (curve number or CN) represents the runoff potential of the hydrologic soil cover complexes is calculated using land use/land cover and soil data base.

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

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

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

Where, CN is curve number of hydrologic soil

Land use/land cover, soil texture and hydrological soil data are mandatory inputs parameters into the SCS model to calculate storm runoff. Eight types of soil texture namely silty clay loam, sandy loam, sand, sandy clay, sandy clay loam, silty clay, loamy and peat found in the Busu watershed area (Figure 3a).

The hydrologic soil groups indicate the amount of vertical flow through the soil after prolonged wetting. The SCS model has classified all soil texture classes into four hydrologic category (Group A, B, C and D) as shown in figure 3b and table 3. Group A soils, like sands, loamy sands and sandy loams indicate deep, well drained (infiltration rate more than 0.76 cm/hr when thoroughly wet). Silt loams or loamy soils falls under Group B soils, with the saturated infiltration rate of 0.38 to 0.76 cm/hr. Group C soils (sandy clay loams) have low infiltration rates (0.13 to 0.38 cm/hr). Group D soils (Clay loams, silt clay loams, sandy clays and silty clays or clays) have high runoff potential and saturated infiltration rate falls between 0 - 0.13 cm/hr.

The land use /land cover derived from the digital image classification of LANDSAT 8, OLI (Optical Land Imager) satellite images. This classification is carried out taking seven classes for the study area, namely water, dense forest, low dense forest, shrub land, Grass cover/open fallow, barren land, and settlement (Figure 3c). Detailed land use and land cover statistics are given in table 3. Overall accuracy is achieved 90%, after carrying out an accuracy assessment using ground truth (50 reference sample points) data sets.

Curve number (CN) of hydrologic soil cover complex, which is a function of soil type, land cover and antecedent moisture condition (AMC), is derived through overlay analysis process in ArcGIS (v-10) for entire Busu watershed (Figure 3d and table 4).

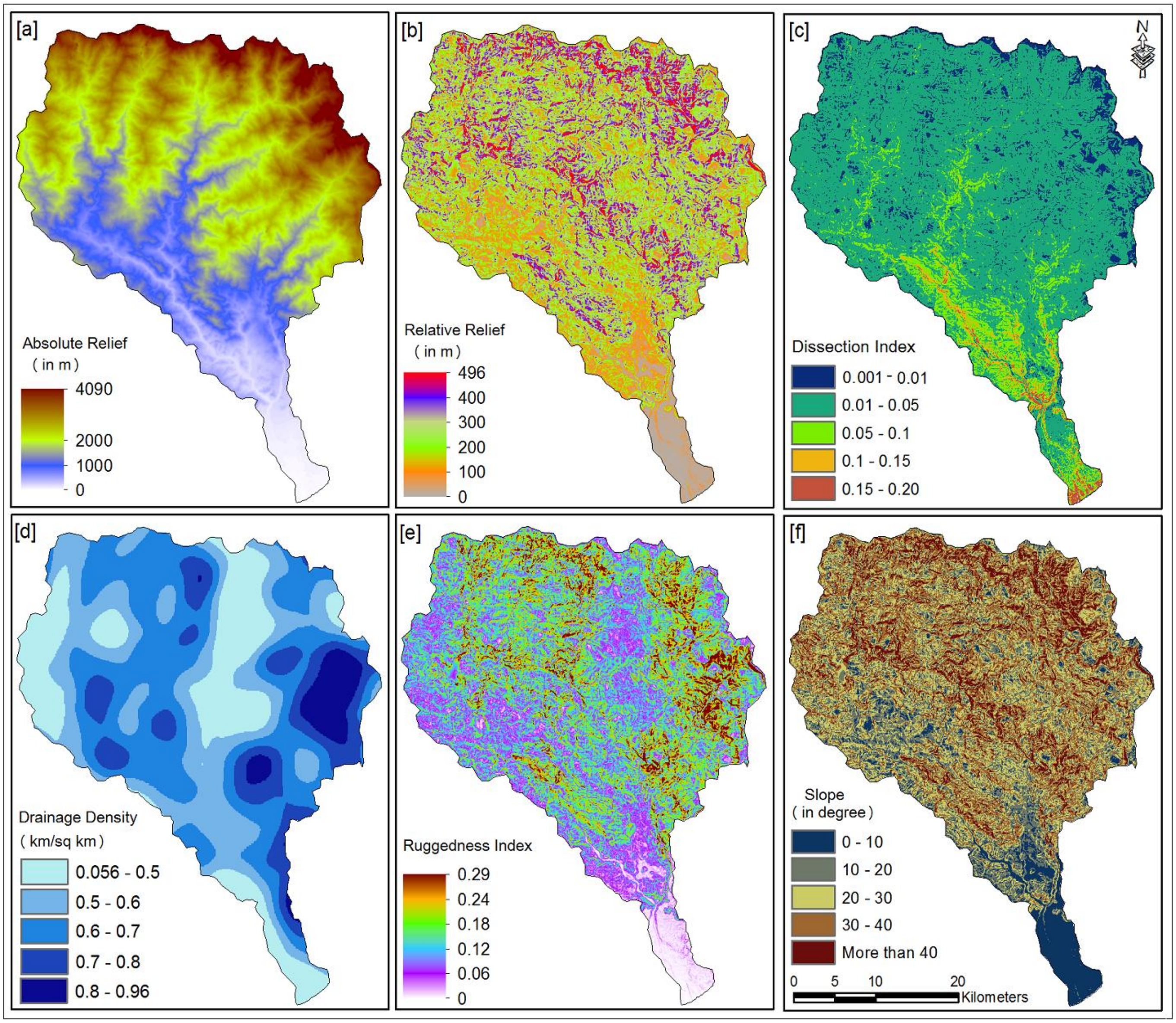

Figure 2: Absolute relief [a], relative relief [b], dissection index [c], drainage density [d], ruggedness index [e] and average slope [f] of Busu watershed generated from satellite image and DEM

Table 3. Land use/land cover and hydrological soil group of the Busu watershed

Land Use/Land Cover	Area (Acre)	Soil texture	Area (Acre)	Hydrological Soil
River Water	3985	Silty Clay Loam	58361.0	D
Dense Vegetation	130811	Sandy Loam	4611.4	A
Low Dense Vegetation	120184	Sand	967.4	A
Shrub land	42090	Sandy Clay	160674.2	D
Open Fallow/Grass Land	14489	Sandy Clay Loam	27555.5	C
Degraded land	12192	Silty Clay	33481.3	D
Sattlement	282	Peat	17768.0	D
Total	324033 Acres	Loamy	20614.4	B
		Total	324033 Acres	

Table 4. Watershed co-efficient (AMC II & Ia=0.4S) for Busu

Land use/ land cover	Hydrologic soil group	Curve number (CN)	Area (acre)
Water	A	100	1331.7
	B	100	28.02
	C	100	1986.87
	D	100	638.27
Dense forest	A	30	23.13
	B	55	13662.33
	C	70	68524.69
	D	77	48650.68
Low dense forest	A	45	717
	B	66	737.24
	C	77	78307.8
	D	83	40392.08
Shrub land	A	39	1066.82
	B	61	402.31
	C	74	28485.11
	D	80	12152.72
Grass cover/open fallow	A	49	2142.99
	B	69	298.68
	C	79	6979.61
	D	84	5079.03
Barren land	A	68	53.37
	B	79	5701.51
	C	86	3906.79
	D	89	2479.47
Settlement	A	57	64.94
	C	81	153.01
	D	86	67.83
	Total area (Acre)		324033

C. Spatial modeling of average soil loss

Hydrologic computation of soil loss for Busu watershed is achieved using revised universal soil loss equation (Renard, 1997). The revised universal soil loss equation (RUSLE) is described as equation 3.

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

Where, A is the potential average annual soil loss in tons per acre per year, R is the rainfall and runoff factor by geographic location, K is the soil erodibility factor, LS is the topographic factor, C is the cover management factor and P is the conservation support practice factor.

Spatial distribution of average annual rainfall data collected from PNG resource information centre. Entire area falls almost in a tropical climatic condition and there is much variation either in physiology or climate within its water divides. Rainfall and runoff factor (R), is calculated *(Nguyen Ma. Ha., 2011)* using equation 4 as follow (Figure 3e).

$$R = [(0.548257 * Pr) - 59.9] \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where, Pr is average annual precipitation in mm of the study area.

Soil strangeness represents the vulnerability of soil or surface material to erosion amount and rate of runoff given a particular rainfall input, as measured under a standard condition. K factor is calculated according to the soil texture type (table 5 and figure 3f) of the area (Robert 2000).

Table 5. K Factors for different soil texture in the study area

Sl No.	Soil texture	Area (Acre)	K Factor
1	Silty Clay Loam	58361.0	0.30
2	Sandy Loam	4611.4	0.12
3	Sand	967.4	0.02
4	Sandy Clay	160674.2	0.24
5	Sandy Clay Loam	27555.5	0.20
6	Silty Clay	33481.3	0.26
7	Peat	17768.0	0.01
8	Loamy	20614.4	0.30

Topographic factor (LS) is the combined effect of slope gradient (S) and slope length (L), expressed as LS factor in the equation 5.

$$LS = ([\text{Flow Accumulation}]*\text{Cell Size}/22.13)^{n} * (\sin([\text{Slope of DEM}]*0.01745)/0.0896)^{m}*1.4 \; \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Flow direction is derived from elevation model and uses as a mandatory input to generate flow accumulation data set for Busu watershed with the help of raster calculator in ArcGIS spatial analysis platform. The grids of flow accumulation correspond to the drainage in the catchment in a DEM. The values of n and m is 0.4 and 1.4 respectively used in the present study. Finally LS is calculated in ArcGIS raster calculator as shown in figure 3g and table 6.

Table 6. LS Factors of Busu Watershed

Sl No.	LS factor	Area (acre)
1	Less than 25	124843
2	25 - 50	78390
3	50 - 75	51323
4	75 - 100	27129
5	More than 100	42348

Vegetation cover protects the soil by dissipating the raindrop energy before reaching soil surface. The value of C depends on vegetation type, stage of growth and cover percentage (Gitas et. al., 2009). Higher values of C factor indicate no cover effect and soil loss comparable to that from a tilled bare fallow, while lower C means a very strong cover effect resulting in no erosion (Erencin, 2000). C factor is assigned for land use classes as shown in table 7 and figure 3h.

Table 7. C Factors for different LULC of Busu Watershed

Sl No.	Land Use/Land Cover	Area (acre)	C Factor
1	River Water	3985	0
2	Dense Vegetation	130811	0.004
3	Low Dense Vegetation	120184	0.004
4	Shrub land	42090	0.05
5	Open Fallow/Grass Land	14489	0.05
6	Permanent Fallow/Degreded land	12192	0.5
7	Sattlement	282	0.002

Conservation support practice factor is considered as according to the up and down Slope (Pal and Samanta 2011) of the area (Figure 3i and table 8). P factor for this watershed is verified with field-level investigations. In this area, no tillage practices are noticed. Therefore, these are not taken into account due to their very less spatial extent.

Table 8. P Factors for slope area of Busu Watershed

Sl No.	Slope (Percent)	Area (Acre)	support practice factor
1	0 - 7	9993	0.6
2	714	17932	0.7
3	14-21	19870	0.8
4	21 - 28	24253	0.9
5	More than 28	251985	1.0

D. Transport capacity of Busu watershed

All the detached sediment generally not been transported to the end of watershed outlet. It depends on the transport capacity of the flow (Yalin 1963). In the present a model equation (equation 6) used to explain the transport capacity of the flow (Kirkby 1985), as it accounts for surface cover variations.

$$Tc = Q^{d} * C * \sin(Sl) * U^{a} * 10^{-6} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Where, Tc *= Transport capacity of the flow in a storm rain,* Q *= Storm Runoff (mm),* C *is cover factor,* Sl *is Slope of the land element (%), and* U^{a} *= Unit area (*m^{2}*).*

Storm Runoff is calculated from spatial modeling of surface runoff using SCS model for a storm rainfall of 229 mm (21 to 23 October, 2012). Cover factor is considered as a mandatory input factor into equation 6. Slope (percent) of the land element calculated from DEM. Finally spatial variability of transport capacity for 229 mm storm rainfall is calculated for the Busu watershed.

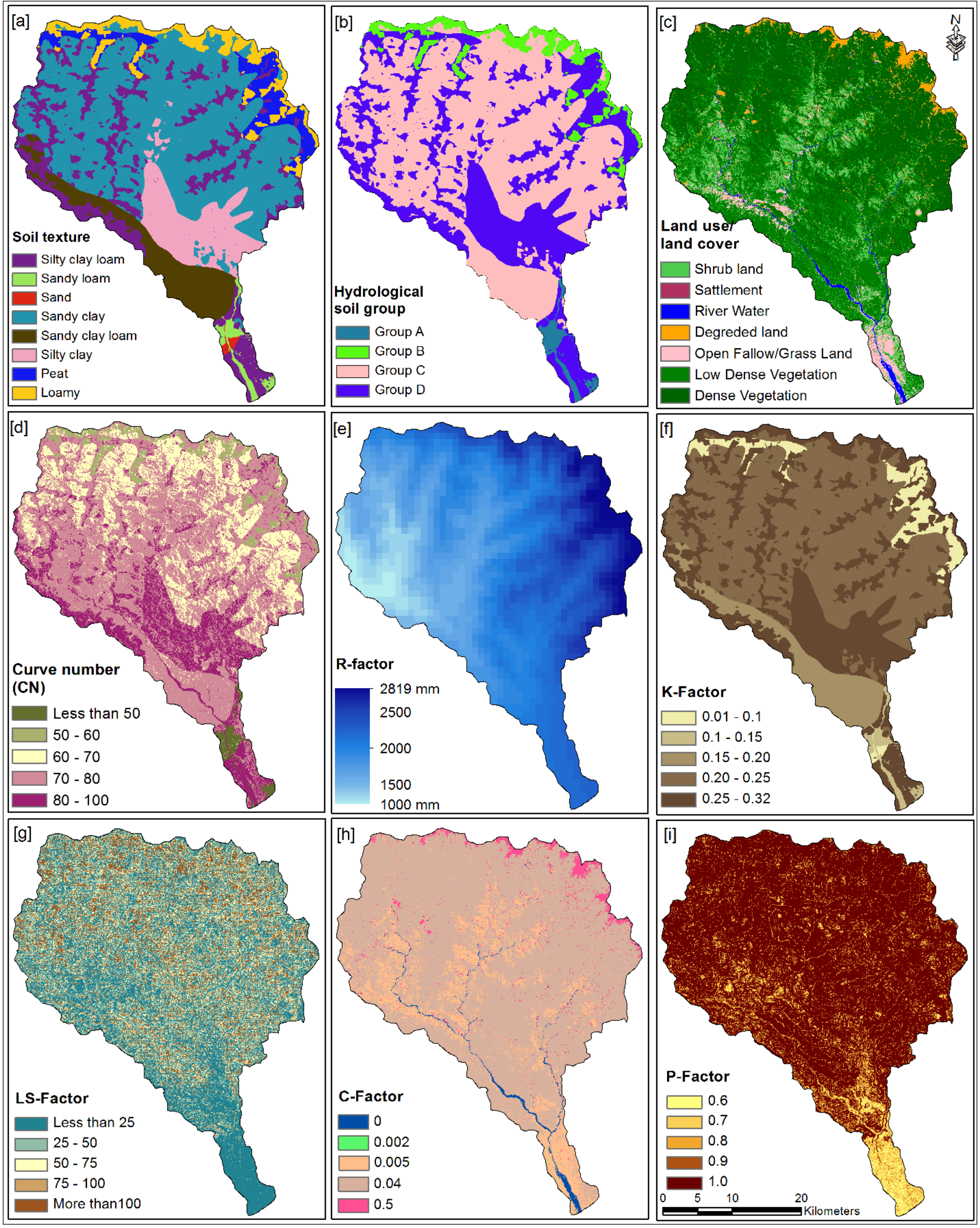

Figure 3. Soil texture [a], hydrological soil group [b], land use/ land cover [c], curve number [d], R-factor [e], K-factor [f], LS-factor [g], C-factor [h], and P-factor [i] generated from satellite image, soil and digital elevation model

Result and discussions

Busu river watershed is characterized as 5th order drainage lines with a dendritic drainage pattern (Figure 4a). In upper watershed region high number of streams are the indication of high drainage density (0.96 km/sq km). Steep slopes (30 degree and more) are also higher in this region and it leads the overland flow velocity. Relative relief (400 m and above) and ruggedness index (> 0.25) are higher, indicates unstable topography and greater vulnerability for erosion and land slide in the upper watershed region of Busu river. Lower watershed region of the watershed region have gentle slope (0 to 5 degree) and fewer number of channel/streams (5th order). The relative relief (<100 m), ruggedness index (<0.06), and drainage density are also very low. Only the dissection index is high which indicates actual dissection made by the rivers and potential dissection up to base levels. Erosion materials are transported and deposited in this lower part of the watershed and due to low slope, high water supply, large sediment load and less channel depth.

Land use/land cover, soil characteristics, storm rainfall are used to estimate surface runoff by SCS model for Watut watershed. There was a big amount of storm rainfall recorded as 229 mm, in the October 21 to 23, 2012. The above storm rainfall (229 mm) is introduced as an essential input in the SCS model. The model output (Figure 4b) indicates runoff range from 203 mm to 229 mm. The calculated average surface runoff is quite high, 214.21 mm for the Busu watershed, because of the distribution of hydrological soil group "C" and "D" in middle and lower watershed area. The average curve number for AMC II is found 75.39 for the Busu watershed area.

The mean LS factor of the watershed is calculated as 55.61 from digital elevation model, which is very high. Annual soil erosion rate of the watershed is found with the help of RUSLE together with the geospatial data sets and techniques. The average soil loss of the area is calculated as 0.79 ton/acre/year and total soil loss of 255986 tons/year for Busu watershed (Figure 4c). Soil losses characteristics of the watershed area are shown in figure 4d. Brown color pixels indicates high rate of soil erosion in the watershed area. High rate of soil erosion (more than 1/ton/acre/year) is found in the upper and middle watershed area where the average slope-length gradient factor (LS factor) and cover factor (C factor) is very high. Finally the transport capacity of Busu is analyzed in ArcGIS using equation 6 for a storm rainfall (229 mm). Resulted raster data shows (Figure 4d) few area of upper and middle watershed region having more than 0.10 ton of transport capacity in the above mentioned storm rainfall (Figure 4d), because of high runoff and high slope.

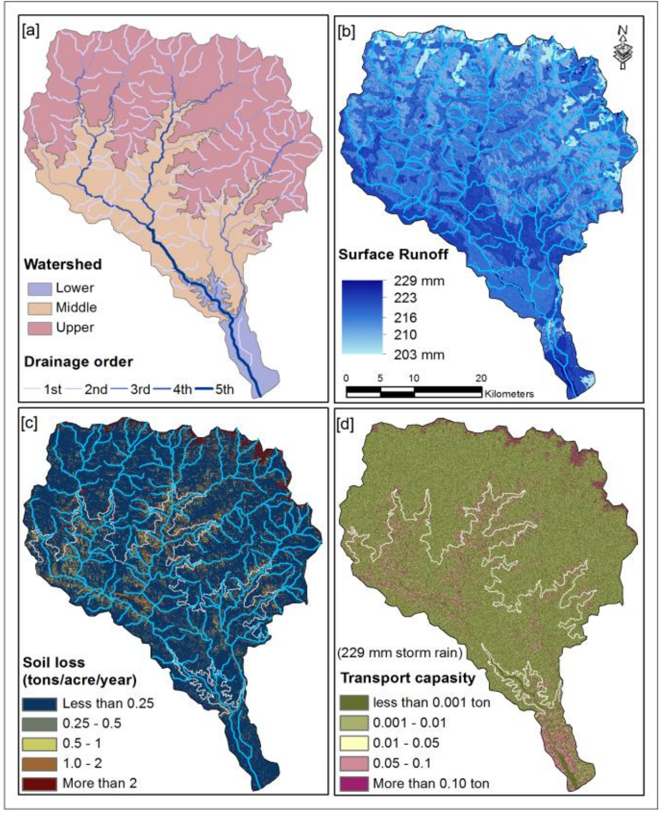

Figure 4. Watershed and drainage order (4a), estimated surface runoff (4b), calculated soil loss (4c) and transport capacity (4d) according to SCS and RUSLE model ArcGIS.

Conclusion

In Papua New Guinea, Soil erosion, surface runoff, watershed analysis studies have largely been neglected in the past. Only studies connected to specific developments, mainly mining and hydropower, have been carried out. Some of these studies show very high intensities of erosion, indicating that certain areas of Papua New Guinea are among the most geomorphologically dynamic areas on the earth. The aim of this paper was to contribute to better understanding the spatial differences in the estimates of surface runoff, soil loss and transport capacity. Soil erosion is a significant problem being reported from various parts of the world. There is less information available on the factors responsible for soil erosion vulnerability, which necessitates more area-specific studies. Geospatial tools, geospatial data and spatial analysis and modeling techniques used in this study greatly aided the delineation of erosion vulnerability of this Busu watershed. Rainfall and runoff factor (R), soil erodibility factor (K), slope length and steepness factor (LS), crop management factor/cover factor (C) and conservation practice factor (P) used for soil loss estimation using RUSLE model. Another factor for soils is called "T Value" which stands for "Tolerable Soil Loss". It is not directly used in RUSLE equation, but is often used along with RUSLE for conservation planning. Soil loss tolerance (T) is the maximum amount of soil loss in tons per acre per year, that can be tolerated and still permit a high level of crop productivity to be sustained economically and indefinitely.

Braiding channel pattern found in the final 8 km flow before it flows into Huon Gulf due to sudden decrease of slope in the lower catchment (Figure 5). High flow velocity and flowing pattern is the main causes of bank erosion and river course shifting also. The maximum continuous movement and excessive sedimentation of the river has been observed. The results also demonstrated that braiding channel is more than river sinuosity, designates the meandering commotion of the river increases, thus subsidising more sediment into the river. The findings of this study show that the reasons for the differences can be related to both the storm/average rainfall and other catchment characteristics. In this context the information from the hydrogeologic assessment proved to be extremely valuable in assessing the catchments overall runoff, soil loss and transport capacity behaviour. As the methodology implemented in this research is based on logical conditions and reasoning; however, it can be applied in other regions or watershed for delineating the susceptible soil erosion occurrence.

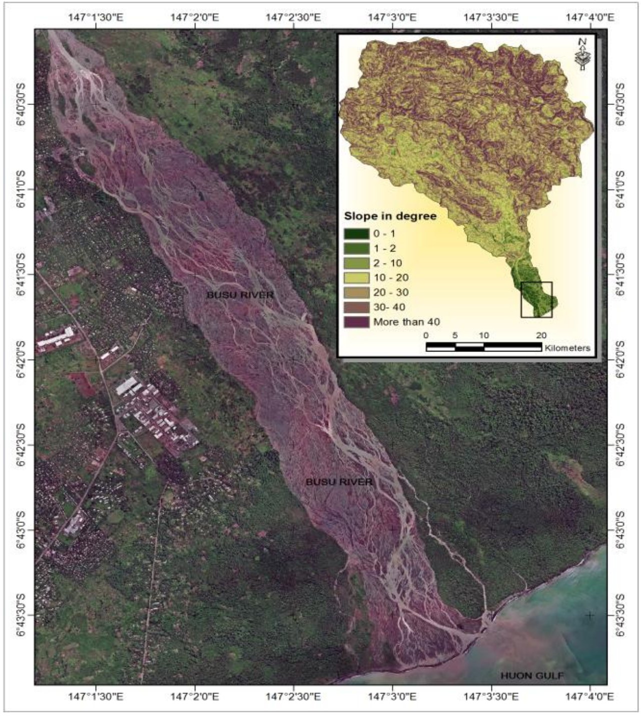

Figure 5. Braiding channel, sediment deposition, and bank erosion in the lower part of Busu Watershed; inset picture showing slope in degree of entire Busu watershed.

Acknowledgments

Author is thankful to the PNGUNITECH (Papua New Guinea University of Technology) and to the Department of Surveying and Land Studies for all the facilities made available and availed for the work as a researcher. Satellite digital data available from USGS Global Land Cover Facility and used in this study is also duly acknowledged. Author gratefully acknowledge the anonymous reviewers for providing their critical comments to improve the quality of this manuscript.

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