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Spatio-temporal Soil Loss Pattern Analysis of Markham River Basin Through Remote Sensing and GIS Techniques

[1] Cathy Koloa and [2] Sailesh Samanta

[1, 2] Department of Surveying and Land Studies, Papua New Guinea University of Technology, Private Mail Bag, Lae 411, Morobe Province, Papua New Guinea

[1] cmkoloa@gmail.com; [2] rsgis.sailesh@gmail.com

Abstract

Technological advancements in the application of Remote Sensing (RS) and Geographic Information System (GIS) techniques enable us to estimate river basin characteristics, and soil loss based on different independent parameters. The objectives of this study included spatial mapping of land use and land cover, slope pattern and temporal soil loss pattern of the Markham River basin. Soil loss due to soil erosion was estimated using predictive models such as Universal Soil Loss Equation (USLE) and Revised Universal Soil Loss Equation (RUSLE). Different mandatory input parameters, namely 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) that were used in RUSLE model, had been derived either from remote sensing data or from conventional data collection systems. Land use / land cover data for year 1992 and 2001 were derived from satellite images using supervised classification techniques to find C factors, which is one of the most important factors for spatio-temporal soil loss analysis. Spatial analysis tool of ArcGIS v-10.1 and model maker tool of ERDAS IMAGINE v-11 software were used to generate all input parameters and to estimate spatio-temporal soil loss. The Markham River basin encompassing an area of about 12765.91sq km was selected as the study area from which an average soil loss of 8.4 tons/acre/year was calculated. The study underscored that the approach of RUSLE model with RS and GIS technologies have great potential for the modeling of different hydrological parameters and the creation of risk maps for any watershed in Papua New Guinea .

Keywords: *Remote Sensing, Geographical Information System, Spatial analysis, RUSLE*

1. Introduction

Various in-depth studies have been conducted by WRI (World Resources Institute) in a number of key river basins around the world uncovering significant information about the unique conditions in certain critical river basins around the world. River basins are dynamic over space and time, and any single management intervention has implications for the system as a whole (WWF Global). Everything that we do affect our river basin – from washing clothes and growing food to mining, commercial farming, and building roads or dams. The opposite is also true: the river basin that we live in determines everything we do from what kinds of plants we can grow, the number and kinds of animals that live there, and how many people and livestock can be sustainably supported by the land (international rivers, 2013). The present study focuses on a temporal soil loss analysis of the Markham River Basin using Remote Sensing and GIS techniques. Altaf et al., (2013) defines morphometry as the measurement and mathematical analysis of the configuration of the earth's surface shape, and dimension of its land forms. In the higher slopes of the Markham river basin, there has been an increase in mining, agriculture, logging and other infrastructure and developments from the higher slopes, alongside the magnificent Markham River to the coast where the country's busiest port is currently undergoing expansion. According to field surveys/interviews were carried out at the Labu 1 community living alongside the port and near the mouth of Markham River, concerns of flooded gardens, decreasing soil fertility, eroding banks and widening of the river are expressed frequently. The Yasua and Lupu people of Wampar LLG living alongside Morobe's infamous Markham Bridge have similar concerns as that of the Labu people.

For a sustainably strong environment and economically active province, effective research and the utilization of current and updated technological methods such as GIS and Remote Sensing for hydrological and morphometric characteristics of the catchment studies are required to monitor the changing land use /land cover patterns and fluvial activities that may consequently lead to floods and other erosion problems. Biswas et al., (1999) stated that Remote Sensing and Geographic Information System (GIS) techniques are being effectively used in recent times as tools for determining the quantitative description of basin geometry i.e., morphometric analysis. Approaches such as these will surely result to better management and planning practices for concerned industries and developers who are or will be engaged in the Markham River Basin.

The research focuses on utilizing RS and GIS technology to analyze temporal soil loss pattern in order to understand its controlling factors for better management. Soil loss is a result of both sheet and rill erosion where soil is being washed away by wind or water and is one of the main threats to ecosystems in the tropics mainly instigated by erosion and its depositional power (Ramos & Martinez-Casanovas, 2006). The study however centers more on the water borne erosion which is prevalent in tropical humid climate. Apart from reduction in plant nutrients, soil loss also results in siltation and deposition in streams (Sthiannopkao et al., 2007). It usually occurs in the higher slopes where the soil has no plant cover or where men's activities have contributed to the high rate at which soil is lost than formed.

Some of the conventional and empirical methods employed in the soil loss estimation include the Water Erosion Prediction Project (WEPP) (Flanegan & Nearing, 1995), Limburg Soil Erosion model (LISEM) (De Roo, Wesseling, & Ritsema, 1996) , European Soil Erosion Model (EUROSEM) (Morgan *et al.*, 1998), and Revised Morgan, Morgan and Finney model (RMMF) (Morgan, 2001), and SLEMSA (Soil Loss Equation Model of Southern Africa), and Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) respectively. Recently the application of distributed USLE has been used widely (Beskow *et al.*, 2009), however one of the weaknesses of USLE is its inability to account for the impact of the upstream elements on soil loss (Jha & Paudel, 2010). It is also limited to yearly temporal time frame; thus it is unable to predict soil loss on daily, weekly and monthly basis, for instance. Therefore, the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.*, 1991) has been developed to overcome some of these weaknesses.

RUSLE was developed as an update to the USLE, with development work beginning in the late 1980s. The need for a USLE update became apparent as users demanded more flexibility in modeling erosion for new conditions, which clearly did not work well within the standard USLE (Wischmeier, 1978). In addition, new research and analysis provided scientists with the power to improve the USLE's performance for both new and old land management schemes (Renard et al., 1991). Suja et al., (2013) concurs that among numerous mathematical models used to estimate or simulate soil erosion, the RUSLE model is widely accepted and used. The extensive use of the USLE overseas and initial response to RUSLE indicates that RUSLE will also serve as a useful modeling tool internationally. These results indicate that RUSLE can be used almost without limit to model sheet-and-rill erosion on disturbed lands, that calculates the long term average annual rate of erosion on a field slope based on rainfall pattern, topography, crop system, and management practices through the following factors; Rainfall erosivity factor (R factor), Cover management (C Factor), K factor (Hydrological soil texture), Slope length (LS factor) and existing soil conversion measures factor (P factor).

2. Study Methodology

2.1 Study Location

Markham catchment in the eastern part of Papua New Guinea under Morobe province lies within the latitudinal and longitudinal extension of 5° 51' 19.41" S, 145° 58' 27.39" E and 7° 31' 21.93" S, 147° 02' 22.01" E. The Markham River starts from the Finisterre Range at 5° 51' 36.31" S and 146° 13' 22.40" E and flows southward and receives the Erap river, which courses south from the Saruwage Range, and the Watut River, which flows north from the Bulolo valley for 180 km to empty into the Huon Gulf at 6°44' 20"S 146°58' 05". The River Basin is demarcated by the Saruwage and Finisterre Ranges to the north and the Owen Stanley Ranges to the south that forms part of a major tectonic rift 20 km wide extending over 300 km and incorporating the Ramu Valley to the west and a large submarine canyon in the Huon Gulf east of Lae. The canyon extends out into the Solomon Sea, where it eventually joins the New Britain trench. The length of the Markham River is about 180 km and lies within the study area, the Markham Catchment have a surface area of 12766 sq km. The main activities that occur alongside the river include subsistence and market gardening along the banks of the river, on the plains and mountain slopes, large commercial farms and grazing land, human habitation within the catchment and some mining activities occurring at the higher slopes upstream.

2.2 Revised Universal Soil Loss Erosion (RUSLE)

Soil loss is a result of both sheet and rill erosion where soil is being washed away by wind or water and is one of the main threats to ecosystems in the tropics mainly instigated by erosion and its depositional power (Ramos & Martínez-Casasnovas, 2006). This study focuses on soil loss due to soil being eroded by the power of water. Apart from reduction in plant nutrients, soil loss also results in siltation and deposition in streams (Sthiannopkao *et al.*, 2007). It usually occurs in the higher slopes where the soil has no plant cover or where men's activities have contributed to the high rate at which soil is lost than formed. Table 1 shows the list of geospatial data that were used for soil loss calculation.

Table1. List of data used in the study

Collateral data	Scale/ cell size	Year	Source
Landsat-7, TM,ETM+	30 m	1992, 2001	University of Maryland
National soil atlas	1:2500000	1975	Commonwealth Scientific and Industrial Research Organization
Soil data	1:500000	1975	PNGRIS

Rainfall	Point data	1972-2002	weather-forecast.com report
DEM data	30m	2003	ftp://e0srp01u.ecs.nasa.gov

The model used to carry out the soil loss estimation for Markham basin was the RUSLE MODEL using the software Erdas Imagines model maker. The model equation is as following-

$$A = R * K * LS * C * P$$

Where, A= annual soil loss from sheet and rill erosion in tons/acre/year, R is rainfall runoff factor – obtained from rainfall data, K is soil erodibility factor – obtained from soil map, LS is slope length / steepness factor- obtained from topographic map, C is land cover and management factor – obtained from classification map, P is support practice factor - obtained using calculated up and down slope

2.3 Details description geospatial data for RUSLE model

For the study area, spatial distribution of annual rainfall data was available for the entire basin and falls almost in a tropical climatic condition with much variation either in physiology or climate within its water divides.

Rainfall and runoff factor (R) was calculated (Figure 1) using equation 1 as follows *(Samanta, 2015).*

$$R= [(0.548257 * Pr) – 59.9] \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

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

Soil erodibility factor (K) 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 was calculated according to the soil texture type (table 2 and figure 2) of the area (Robert, 2000).

Table 2. K Factors for different soil erodibility class

Code	Soil erodibility	K factor
1	Very low - soils with high to very high organic matter content and moderate to rapid permeability.	0.07
2	Low - except for sandy Entisols, these soils have moderate organic matter content and moderate permeability.	0.17
3	Moderate - Generally slowly permeable soils with moderate organic matter content; the alluvial Entisols have low to moderate organic matter content	0.27
4	High - Poorly structured top soils.	0.37

Topographic factor (LS) is the combined effect of slope gradient (S) and slope length (L), expressed as LS factor in the equation 2.

$$LS=([Flow Accumulation]*Cell Size/22.13)^{n} *(Sin([Slope of DEM]* 0.01745)/0.0896)^{m}*1.4\ldots(2)$$

Flow direction was derived from ASTER DEM with 30 m resolution and used as an input to develop flow accumulation data set for Markham watershed with the help of the raster calculator in ArcGIS spatial analysis platform. The grids of flow accumulation correspond to the drainage in the catchment in a DEM. The values n = 0.4 and m = 1.4 were used in the present study. Finally LS was calculated in ArcGIS raster calculator as shown in figure 3.

Vegetation cover (C) protects the soil by dissipating the raindrop energy before reaching soil surface. The C value 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). Temporal Land use / land cover data sets were derived from Landsat 7 ETM+ (Enhance Thematic Mapper Plus) image acquired on March 2001 for entire watershed region and Landsat 5 TM (Thematic Mapper) of September 1992 for sub basin number 11 and 14. Finally C factor value was assigned for all land use / land cover classes as shown in table 3 and figure 4.

Table 3. C Factors for different LULC of Markham

Sl No.	Land Use/Land Cover	C Factor
1	Water (Lake/River)	0
2	Dense Vegetation	0.004
3	Low Dense Vegetation	0.004
4	Shrub land	0.05
5	Out crop/Degraded land	0.5
6	Open Fallow/Grass Land	0.05
7	Agriculture field	0.125
8	Built up area	0.002

The *Conservation support practice factor* (P) was considered according to the up and down slope (Pal and Samanta, 2011) of the area (Figure 5 and table 4). P factor for this basin was verified with field-level investigations. In this area, no tillage practices were noticed. Therefore, these were not taken into account due to their very less spatial extent.

Table 4. P Factors for different slope of Markham

Sl No.	Slope (%)	Support practice factor
1	0 - 7	0.6
2	714	0.7
3	14-21	0.8
4	21 - 28	0.9
5	More than 28	1

In the next step all input factors that were used in the RUSLE model was used to calculate for 14 sub basin separately. All average value of R, K, LS, C and P factors for individual sub basin are shown in table 5.

Table 5. Average input factors according to individual sub basin

Sub basin	Area (Acre)	R	K	LS	C	P
1	254522.42	145.2	0.28	19.68	0.022	0.873
2	205607.51	186.5	0.35	29.26	0.006	0.958
3	164405.22	208.1	0.28	34.74	0.004	0.975
4	140497.61	138.5	0.30	17.53	0.019	0.83
5	98763.06	136.7	0.34	13.66	0.035	0.809
6	84766.47	135.7	0.30	12.89	0.042	0.845
7	296356.16	129.0	0.33	18.98	0.009	0.89
8	441960.49	116.1	0.30	18.19	0.010	0.873
9	219925.11	131.2	0.25	21.85	0.012	0.938
10	165560.89	140.3	0.28	18.23	0.011	0.913
11	206723.87	155.8	0.34	16.44	0.017	0.895
12	291711.01	159.9	0.30	23.15	0.018	0.937
13	137196.96	176.3	0.27	20.44	0.007	0.903
14	446516.04	147.4	0.21	5.50	0.042	0.696

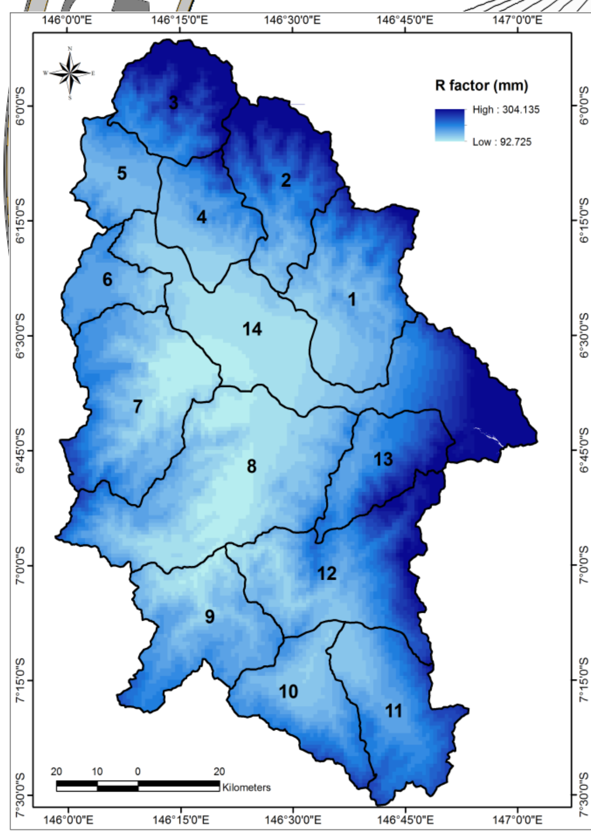


Fig 1. R-factor obtained from rainfall data

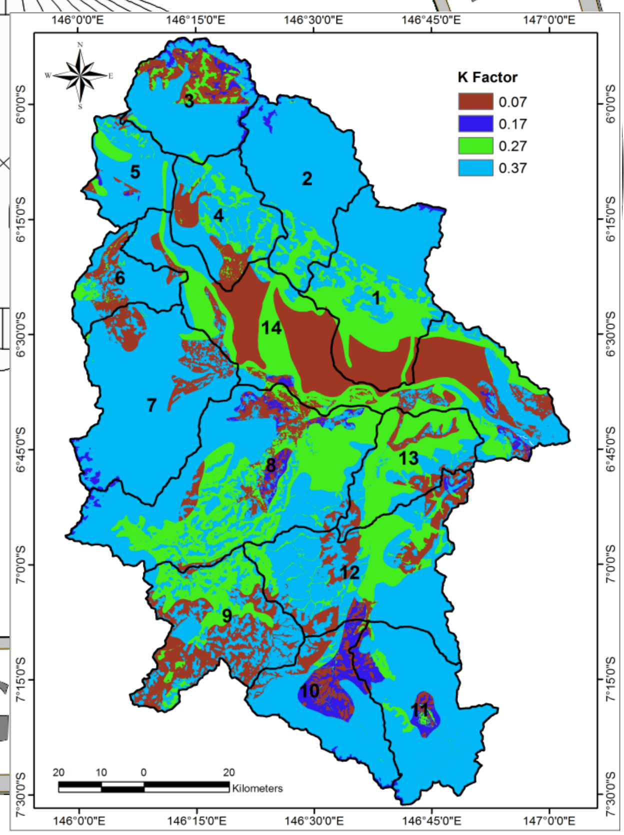
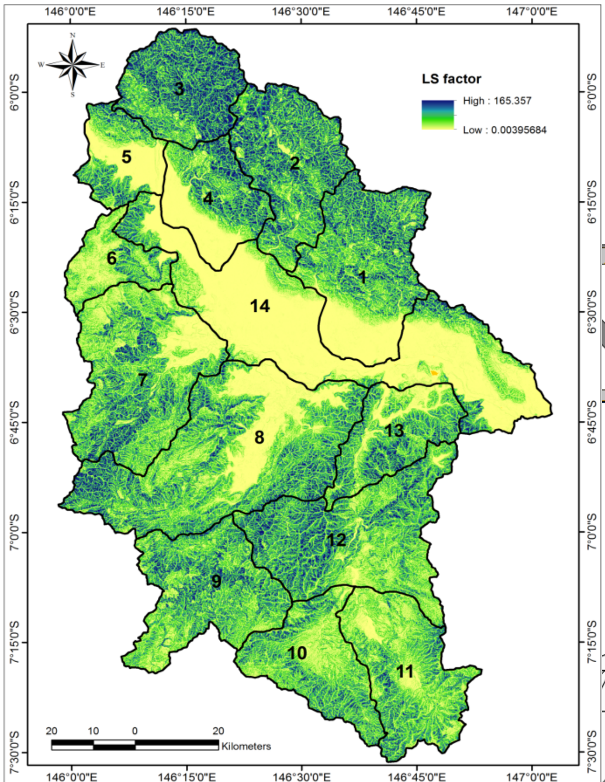


Fig 2. K-factor obtained from soil data base



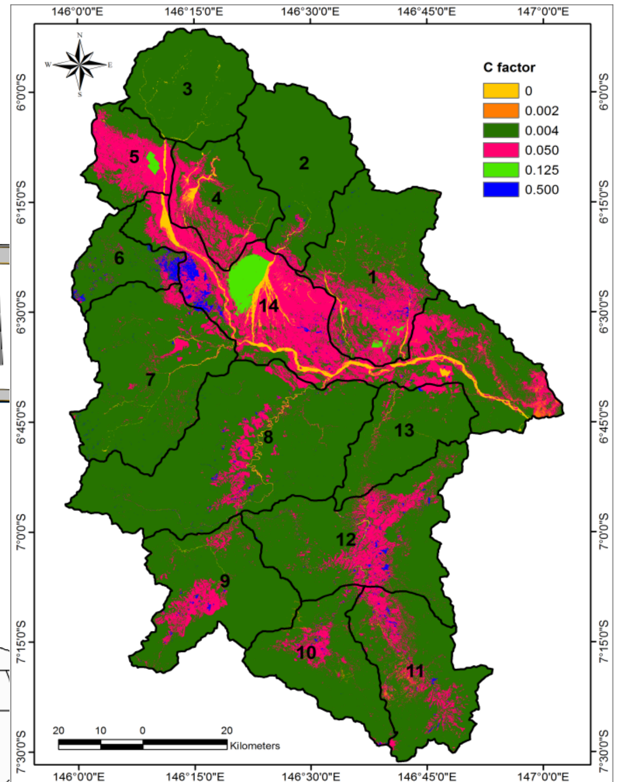


Fig 3. LS-factor generated from DEM

Fig 4. C- factor data set obtained satellite image

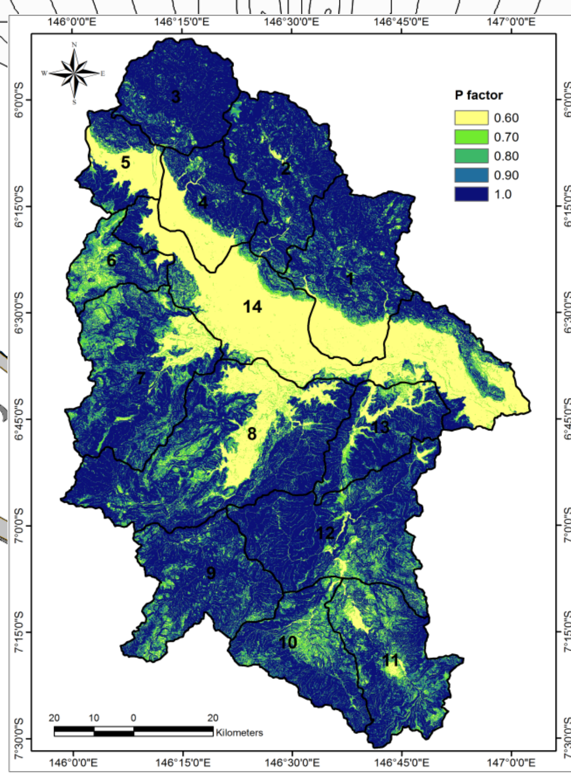


Fig 5. Support practice factor data set obtained after calculating up and down slope

3. Results and discussion

Different mandatory inputs parameters like 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 to estimate average soil loss, were derived either from remote sensing data or from conventional data collection systems. The mean LS factor of the study area was calculated as 18.55 from digital elevation model, which was high. Annual soil erosion rate of the watershed was found with the help of RUSLE together with the geospatial data sets and techniques. The average soil loss of the area was calculated as 8.4 ton/acre/year and total soil loss of 26494472 tons/year for Markham River basin (Table 6). Spatial soil loss characteristics of the watershed area are shown in figure 6. Red color pixels indicates high rate of soil erosion in the watershed area. High rate of soil erosion (more than 15/ton/acre/year) was found in the upper and middle watershed area where the average slope-length gradient factor (LS factor) and cover factor (C factor) was very high.

The whole basin was subdivided into 14 sub-basins (Figure 6) to represents sub-basin wise average soil loss (A) characteristics of the study area. Table 8.7 represents all average supported factors, average soil loss and total soil loss for individual sub basins of the study area. Sub-basin 3 represents highest average rainfall and runoff factor (208.1) and conservation practice factor (0.975), sub-basin 2 indicates maximum average soil erodibility factor (0.35) and slope length and steepness factor (29.26), sub-basin 6 and 14 shows high average crop management factor/cover factor (0.042). Maximum average soil loss was estimated about 26.24 tons/acre/year in sub basin number 6, where average P factor was 0.042 (Highest among 14 sub basins). Minimum average soil loss was calculates about 4.66 tons/acre/year in sub basin number 8. Maximum total average soil loss was calculated for sub-basin number 12, about 4296903.21 tons/year and minimum of 681868.89 tons/year for sub-basin number 13.

Table 6. Average supported factors, average soil loss and total soil loss for all Sub-basins

Sub basin	R	K	LS	C	P	Soil loss (Ton/acre/year)	Total soil loss (Tons/year)
1	145.2	0.28	19.68	0.022	0.873	10.82	2753932.57
2	186.5	0.35	29.26	0.006	0.958	9.62	1977944.21
3	208.1	0.28	34.74	0.004	0.975	7.86	1292225.01
4	138.5	0.30	17.53	0.019	0.83	7.19	1010177.79
5	136.7	0.34	13.66	0.035	0.809	11.42	1127874.20
6	135.7	0.30	12.89	0.042	0.845	26.24	2224272.16
7	129.0	0.33	18.98	0.009	0.89	5.68	1683302.99
8	116.1	0.30	18.19	0.010	0.873	4.66	2059535.90
9	131.2	0.25	21.85	0.012	0.938	7.23	1590058.56
10	140.3	0.28	18.23	0.011	0.913	5.28	874161.49
11	155.8	0.34	16.44	0.017	0.895	10.57	2185071.35
12	159.9	0.30	23.15	0.018	0.937	14.73	4296903.21
13	176.3	0.27	20.44	0.007	0.903	4.97	681868.89
14	147.4	0.21	5.50	0.042	0.696	6.13	2737143.32
Markham						**8.4**	**26494472**

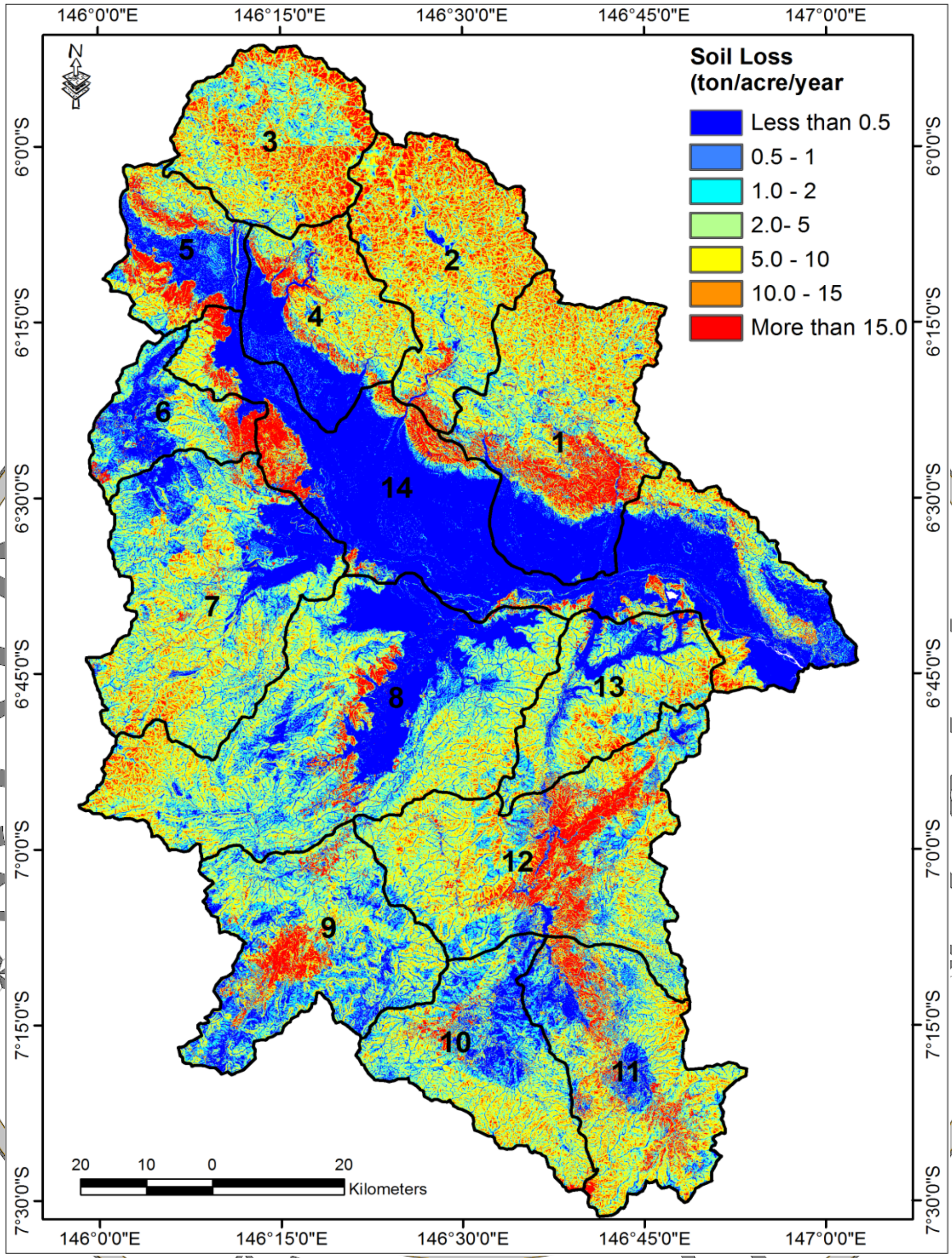


Fig 6. Spatial average soil loss characteristics of the study area

A comparative analysis of annual soil erosion rate of the watershed was ascertained for the years 1992 and 2001, respectively, with the help of RUSLE together with the geospatial techniques. Two sub basins were selected for this purpose, namely sub-basin 11 from upper Markham basin and sub-basin 14 from lower Markham basin. Land use / land cover was a leading factor for difference of annual soil loss according its seasonal and annual phonological changing pattern. All statistics related to land use / land cover change during 1992 to 2001 is tabulated in table 7. Land use / land cover map of sub-basin 11 (1992 and 2001) is shown in figure 7 (figure 7a and 7b) and sub-basin 14 in figure 8 (figure 8a and 8b).

Table 7. Land use land cover statistics (Area in Acre) of sub-basin 11 and 14, 1992 and 2001

Sl. No.	Land use/land cover	Sub-basin 11		Sub-basin 14	
		1992	2001	1992	2001
1	Dense Forest	97765	130106	107645	10569
2	Less Dense Forest	80737	35338	112200	157434
3	Shrubs/lowland	4885	8220	124978	116178
4	Outcrop/Degraded land	633	2154	1565	9609
5	Upland grassland	19381	29882	59767	94093
6	Settlement	0	700	1553	3442
7	Lake	0	0	812	1077
8	River	3322	323	37996	31248
9	Agriculture field	0	0	0	22866

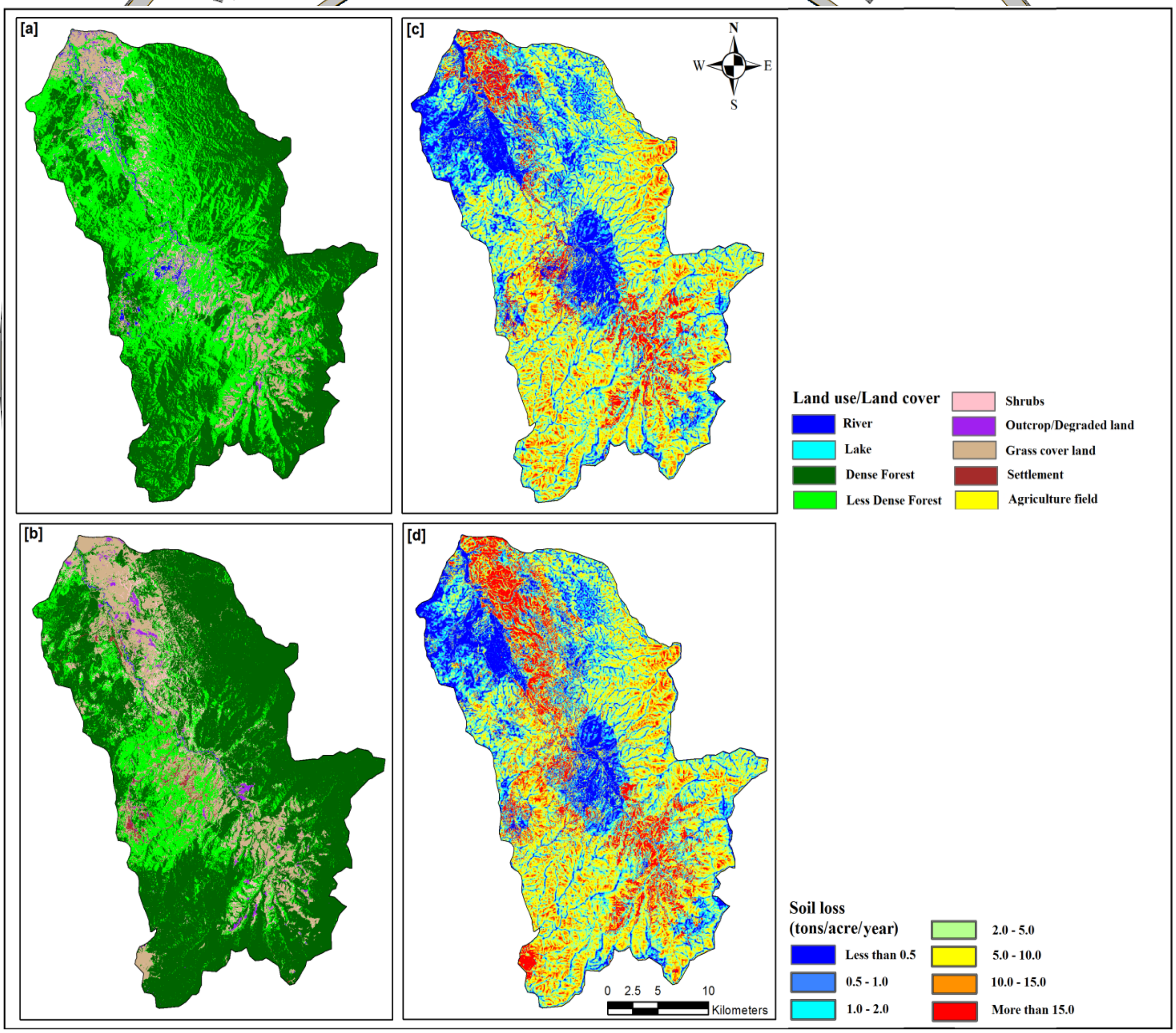


Fig 7. Land use /land cover of 1992 [a], 2001 [b] and annual soil loss of 1992 [c] and 2001 [d] for sub-basin 11

An extensive increase in the built-up area and agriculture land had been observed for the year 2001 when compared to that of 1992 in sub basin 14. Due to rapid agriculture activity (0.125 value of agriculture land in C factor) soil loss also increased dramatically as shown in figure 8. Average soil loss was calculated as 6.88 ton/acre/year in 1992 and 10.57 ton/acre/year in 2001 for sub-basin 11 (figure 7 and table 8) and 3.48 ton/acre/year in 1992 and 6.12 ton/acre/year in 2001 for sub-basin 14 (Figure 8 and table 8).

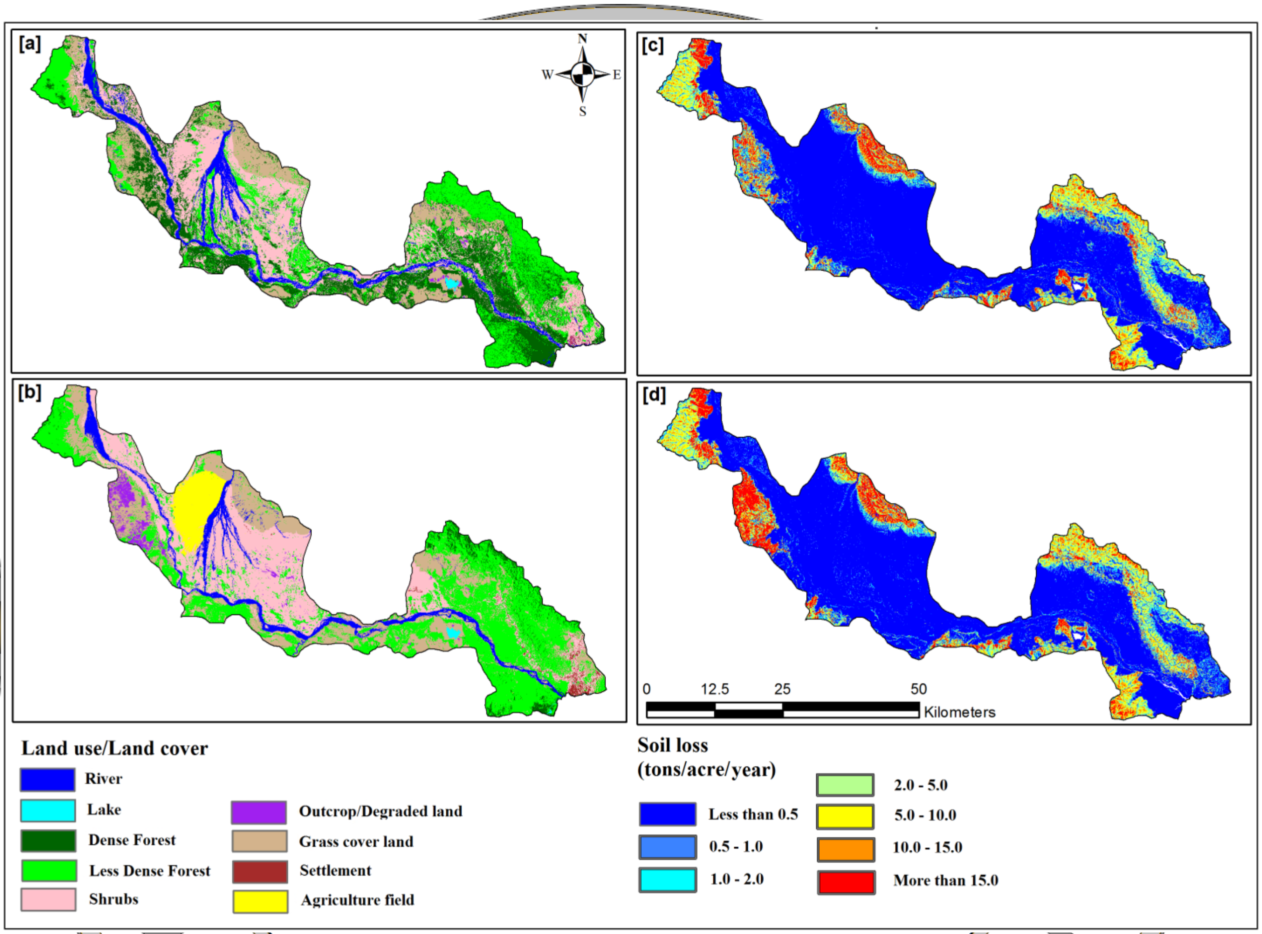


Fig 8. Land use /land cover of 1992 [a], 2001 [b] and annual soil loss of 1992 [c] and 2001 [d] for sub-basin 14

Table 8. Comparative analysis of annual soil erosion rate from 1992 to 2001

Sub-basin	Soil loss - 1992 (Ton/acre/year)	Soil loss - 2001 (Ton/acre/year)	Total annual soil loss 1992 (Ton/year)	Total annual soil loss 2001 (Ton/year)
11	6.88	10.57	1422260	2185071
14	3.48	6.12	1553876	2732678

4. Conclusions and recommendations

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 research 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 modelling techniques used in this study greatly aided the delineation of erosion vulnerability of this 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) were used for soil loss estimation using RUSLE model which was developed by the United States Department of Agriculture (USDA), Agricultural Research Service (Wischmeier and Smith, 1978). Since this study aimed to understand an important hydrological aspect of the watershed in terms of soil erosion vulnerability, EVUs (Erosion vulnerability units) were computed across the entire watershed. There were 7 EVU categories established for this watershed ranged over five severity classes, namely extremely low (<0.5 ton ac^{-1} yr^{-1}), very low (0.5 - 1.0 ton ac^{-1} yr^{-1}), low (1.0–2.0 ton ac^{-1} yr^{-1}), moderate (2.0–5.0 ton ac^{-1} yr^{-1}), high (5.0 - 10 ton ac^{-1} yr^{-1}) very high (10 - 15 ton ac^{-1} yr^{-1}) and extremely severe (>15 ton ac^{-1} yr^{-1}). Thus, EVUs were derived based on the soil erosion values obtained across various land use/ land cover classes of the basin. Soil loss was increased during last 10 years (1992 to 2001) due to changes of land use, like increase of agriculture land and fallow/barren land based on the satellite data of the years 1992 and 2001. Thus, the techniques adopted in this study have the potential to be extended to other watersheds as well to manage them sustainably with better planning and conservation approach. Tolerable Soil Loss (To) estimation was not directly used in RUSLE equation, but was potently 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.

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Author Biographies

First Author *(corresponding author)* is an PhD researcher at the PNG University of Technology. She received her B.Sc. degree in Geographic Information Science (GIS) in 2013 and M Phil degree in 2015 from the PNG University of Technology.

Second author (Dr. Sailesh Samanta) is Senior Lecturer and Section Head of GIS section under Department of Surveying and Land Studies at the The Papua New Guinea University of Technology, Papua New Guinea.