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ORIGINAL ARTICLE

Estimation of potential soil erosion rate using RUSLE and E_{30} model

Sailesh Samanta[1] · **Cathy Koloa**[2] · **Dilip Kumar Pal**[2] · **Babita Palsamanta**[3]

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Abstract This research established an empirical methodology to estimate potential soil erosion rate based on revised universal soil loss equation (RUSLE) and E_{30} model. The study was conducted on a highly precipitated, rugged, tropical forested with steep slope watershed during 1992 to 2009. The fourth (4th) largest river of Papua New Guinea, and its catchment area was considered for this research. Lots of commercial mining and logging activities are the ongoing processes in the upper catchment area without proper conservation measures. Digital elevation model (DEM), landsat satellite images, average annual rainfall, soil texture data base were used to derived mandatory input factors into the RUSLE and E_{30} model. Raster calculator of ArcGIS spatial analyst was used to generate all input factors and final pixel-by-pixel based computation of soil loss pattern. The average potential soil erosion rate were calculated in the range of 20.34 mm/year to 23.70 mm/year through RSULE model and in the other hand the rate varies from 21.07 mm/year to 26.78 mm/year through E_{30} model during 1992 to 2009 respectively. The erosion rate through both model indicates extremely severe rate of erosion in the upper catchment area are required immediate attention of soil conservation practices.

Keywords RUSLE model · E_{30} model · NDVI · Watershed · Remote sensing · GIS

✉ Sailesh Samanta
rsgis.sailesh@gmail.com

Cathy Koloa
cmkoloa@gmail.com

Dilip Kumar Pal
dkpal200090@gmail.com

Babita Palsamanta
mundey2@gmail.com

[1] GIS Section, Department of Surveying and Land Studies, The PNG University of Technology, Private Mail Bag, Lae, Morobe, Papua New Guinea

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

[3] The PNG University of Technology Campus, Private Mail Bag, Lae, Morobe, Papua New Guinea

Introduction

Soil is one of the most valuable natural resource (Kouli et al. 2009) in any agriculture based developing nation. Soil erosion is a critical lively processed and serious environmental problem caused by many natural and human activities. Quantitative data on rates soil erosion in the national scale are very much essential to develop soil conservation and management plans and to asses environmental implications (Alexakis et al. 2013). Different onsite effects of soil erosion (Pimentel 2006) like loss of top soil, change of soil structure, loss of soil organic matter content which leads to reduction of productivity and on the other hand offsite events (Sinha and Joshi 2012) like reduction of channel depth, water holding, water discharge and transport capacity of a stream (Zhou and Wu 2008) caused increase of flood intensity and frequency. In a hilly and steep sloppy region soil erosion may initiate landslide (Michael and Samanta 2016) as a short term and degradation of soil quality as long term effects. The erosion in upper catchment area depends on amount of rainfall, vegetation cover, soil characteristics, slope (Pal et al. 2012) and accelerated by human activity like mining, agriculture and deforestation. In last two decades several studies and empirical models were developed by many researches (Morgan et al. 1998; Kim and Julien 2006; Darbral et al. 2008; Melesse et al. 2011) to estimate soil erosion in different region around the globe. The use of remote sensing and GIS techniques is very useful in estimation of total soil loss (Prasannakumar et al. 2011; Koloa and Samanta 2013) and soil erosion rate spatially and temporally with minimum costs and better accuracy in larger areas (Rahman et al. 2009). Revised universal soil loss equation (RUSLE) is one of the most familiar soil loss estimation process based on ground based observation and remote sensing and GIS technology (Pandey et al. 2007; Sharma 2010; Pal and Samanta 2011). Other empirical model is named as E_{30} to calculate the rate of soil erosion in any region (Honda et al. 1996; Hazarika and Honda 2001; Bagyaraj et al. 2014) where hydrological, meteorological, geographical and river morphological data are limited (Udayakumara et al. 2010). It is best to measure soil erosion rate in a catchment area. Preparation of digital data base is first essential task to generate factors/parameters (Samanta et al. 2012) which are mandatory to be incorporated into RUSLE or E_{30} model. The study was aimed to assess the applicability of GIS based RUSLE and E_{30} model for determination of soil erosion risk zone in Markham catchment, which is mostly comes under Morobe province of Papua New Guinea. The main objective of this research was to estimate soil loss through RUSLE and E_{30} model and to comparative analysis of soil erosion results obtained from both model in the Markham catchment.

Study location and materials used

This research work was attempted in the fourth (4th) largest catchment of Papua New Guinea. The Markham catchment is located in the eastern part of main island. Most of the area falls under Morobe province and small portion in the north and north-east of the study area comes under Madang and Eastern highland province, respectively (Fig. 1). The study area includes a geographical area extending from 145°58′27.39″E to 147°02′22.01″E and 5°51′19.41″ S to 7°31′21.93″S. Markham river is originated from Finisterre range (5°51′36.31″S and 146°13′22.40″E) in the north and gets emptied into Huon Gulf (6°44′20″S 146°58′05″) in the east after 180 km of chequered path (Fig. 1). Erap and Watut are two major tributary rivers of Markham. Upper catchment area of Markham is dominated by dense forests, rugged topography and steep slopes. Lack of proper soil conservation and management measure are exacerbated by commercial logging, mining and small scale mining on the river for alluvial gold extraction. The study area is characterised with tropical hot and humid climate with an average rainfall of 4200 mm. Markham carries flows from the 12,450 km^2 catchment with huge mobile bed load ranging from fine silt to cobbles (Tilley et al. 2006).

For this research three different satellite images during 1992 to 2009 were collected from earth explorer (http://www.earthexplorer.usgs.gov) to generate normalised differential vegetation index (NDVI) data base for different year (1992, 2001 and 2009). Digital elevation model (DEM) in 30 m spatial resolution was collected from Advanced Space Thermal Emission Radiometer (ASTER) mission to produce slope map of the study area. All other collateral information that were used in this study are given in Table 1. For RUSLE model different factors like rainfall erosivity factor (R), vegetation cover factor (C), soil erodibility factor (K), slope length & steepness factor (LS) and existing soil conversion measures factor (P) were used as a mandatory input parameters, which were developed using ArcGIS spatial analyst tool from rainfall, elevation and soil data base. On the other hand rate minimum and maximum of erosion in 30 degree slope area, NDVI, and slope data base were used to calculate rate of soil erosion through E_{30} model.

Methodology

Multi-temporal (1992 to 2009) satellite images of Landsat thematic mapper (TM) and enhancement thematic mapper plus (ETM+) were used in this study. Four satellite images (path/row: 96/64, 96/65, 97/64 and 97/65) were collected to cover entire study area. All satellite images were geo-referenced carefully using universal transverse mercator (UTM) projection system, second order polynomial transformation and nearest neighbour resample method. The range of root mean square error of the transformation varies from 0.09 to 0.15 which is much lower than the pixel size (30 m) of the satellite data. All satellite images and digital elevation data were cropped with the Markham catchment boundary and the entire catchment was marked with of 14 sub-catchments based on elevation, contour, drainage pattern and drainage order (Fig. 1). Maximum slope (more than 80 degree) is found in the sub-catchment number 3.

E_{30} and RUSLE model were used to estimate the rate of soil erosion in the Markham catchment. To execute E_{30} model Normalised differential vegetation index (NDVI) and the slope gradient were used as two major parameter. Aster DEM data was used to develop slope data base (Paz and Collischonn, 2007; Warren et al. 2004) for the study area. NDVI was calculated using a simple band rationing technique (NDVI = B4 − B3/B4 + B3) using band 4 (Near-infrared) and Band 3 (Red) of landsat satellite image (Lillesand et al. 2007). NDVI value (ranged from +1 to −1) is the measure of vegetation coverage of an area

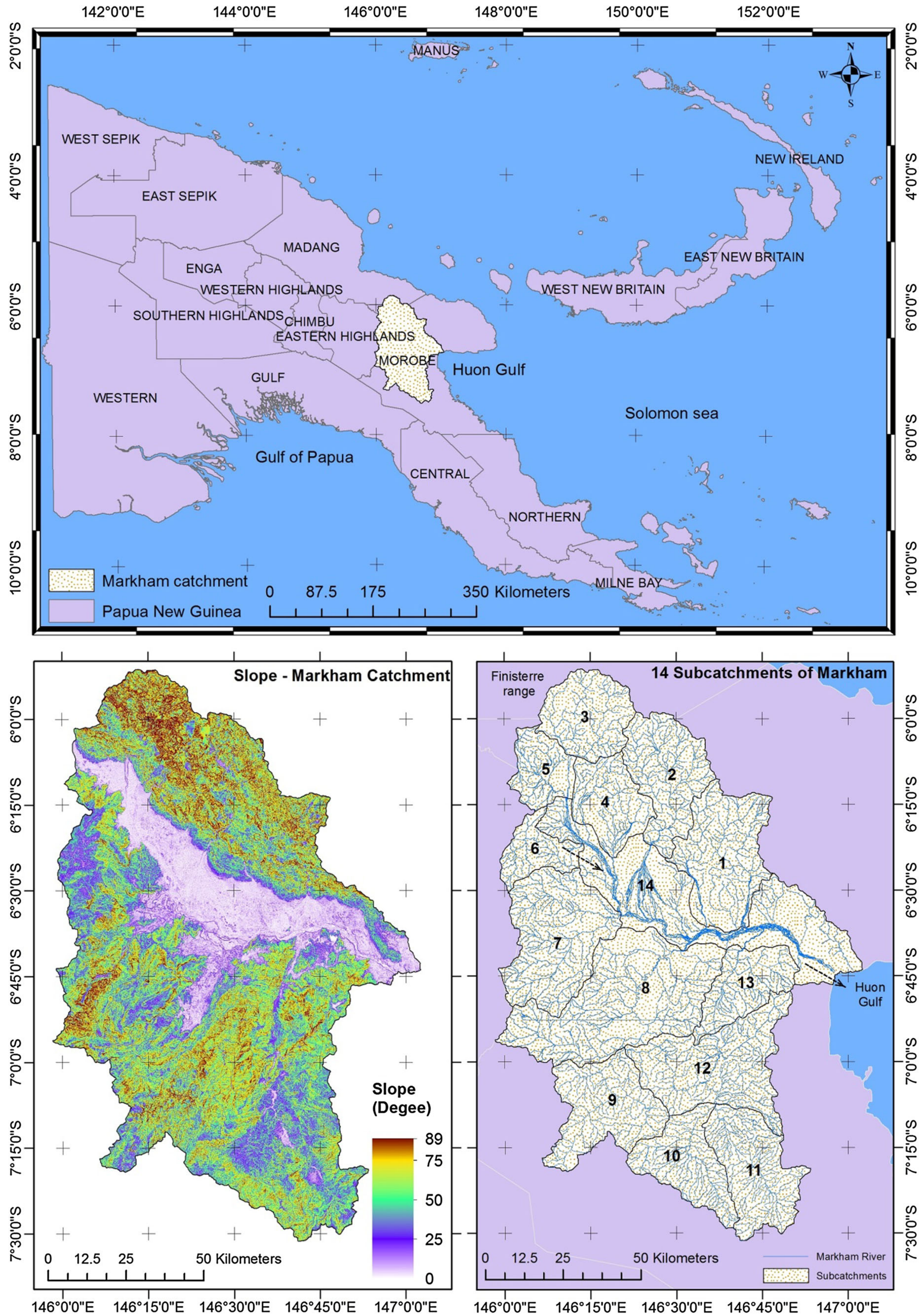

Fig. 1 Location map with details of slope and sub catchments of the study area

Table 1 List of data used in the study

Materials	Scale/cell size	Year	Source
Landsat TM	30 m	1992, 2009	http://www.earthexplorer.usgs.gov
Landsat ETM+	30 m	2001	
National soil atlas	1:250,000	2009	Geobook
Administrative boundary, drainage	1:250,000	2009	PNGRIS
Rainfall	1:250,000	1972–2009	Geobook
ASTER DEM data	30 m	2003	ftp://e0srp01u.ecs.nasa.gov

(Zhou et al. 2008). E_{30} model is expressed in the Eq. (1) based on the previous researches (Hazarika and Honda 2001; Gunawan et al. 2013).

$$E = E_{30} \times (S/S_{30})^{0.9} \quad (1)$$

where, E is the rate of soil erosion (mm/year), S represents the slope gradient of the area in degree and S_{30} refers to tan 30° and E_{30} refers to the soil erosion at 30° slope within the study area which was calculated based on Eq. (2) (Hazarika and Honda 2001).

$$E_{30} = Exp[(\{\log E_{\max} - \log E_{\min})/(NDVI_{\max} - NDVI_{\min}\}) \times (NDVI_{\max} - NDVI_{\min}) + \log E_{\max}] \quad (2)$$

where, $NDVI_{max}$ and $NDVI_{min}$ are the maximum and the minimum NDVI values, E_{min} and E_{max} are the minimum and the maximum rate of soil erosion at 30° slope. Maximum and minimum rate soil erosion at 30° slope in the study area were 14.8 and 1.5 mm/year.

Computation of soil loss was achieved using revised universal soil loss equation (Koloa and Samanta 2013) is described as Eq. (3).

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

where, A stands for the average annual soil loss at a cell (t ha/year), R represents the rainfall and runoff erosivity factor at a geographic location (MJ mm ha/h/year), K refers the soil erodibility factor, LS is slope steepness and length factor for a cell, C is the cover management factor and P is the conservation support practice factor at a cell.

Rainfall was obtained from national database (Geobook 2009) of Papua New Guinea and used to calculate R factor using Eq. (4) (Parveen and Kumar 2012).

$$R = 79 + 0.363R_N \quad (4)$$

where, R_N is the average annual rainfall in mm

Soil erodibility factor (K factor) was calculated based the soil texture type as presented in the Table 2. *Topographic factor* (LS) was derived using Eq. (5) in bellow (Tirkey et al. 2013).

$$LS = ([Flow\,accumulation] \times cell\,size/22.13)^n \times (Sin([slope] \times 0.01745)/0.0896)^m \times 1.4 \quad (5)$$

where, flow direction was derived from ASTER DEM, The flow accumulation correspond to the drainage in the catchment, value of n is 0.4 and m is 1.4.

The C factor database were generated from NDVI result for each year. The C factor values vary between 0 and 1 based on types of land covers excluding water area (Karaburun 2010). Many other researchers also used regression analysis to estimate C factor values for land cover classes in erosion assessment (Van der Knijff 2000; Symeonakis and Drake 2004; Lin et al. 2006). The regression equation was expresses as bellow Eq. (6).

$$C = 1.02 - 1.21 * NDVI \quad (6)$$

The P factor was considered according to the up and down slope (Pal and Samanta 2011) of the area which was verified with field-level investigations (Table 3). In this area, no tillage practices are noticed. Therefore, these are not taken into account due to their very less spatial extent.

Table 2 K factors for different soil erodibility class

Code	Soil erodibility	Description	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

Table 3 P factors for different slope of Markham

Sl no.	Slope (percent)	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	1.0

Raster calculator tool in ArcGIS 10.0 spatial analyst extension was used to incorporated all input parameters and raster based out puts were generated.

RUSLE output of average total soil loss (ton ha/year) was converted into rate of soil erosion (mm/year) based on Schertz 1983. Soil conservation programs consider soil-loss tolerance values (T) values to be 5–12 tons/ha/year (30), equivalent to 0.4–1 mm/year of erosion (Montgomery 2007), assuming a soil bulk density of 1200 kg/m^3.

Result and discussion

The modelled output on rates of soil erosion based on E_{30} and RUSLE model were classified into seven (7) categories. They were 0–5 (extremely low), 5–10 (very low), 10–15 (low), 15–20 (medium), 20–25 (high), 25–30 (very high) and more than 30 mm/year (extremely high) respectively (Figs. 2, 3). Class wise statistics (histogram, area in hectare and percentage) were generated after conversion of total histogram for each categories of erosion rate (Table 4). According to the E_{30} model most of the area were marked with the erosion rate of more than 20 mm/year in 1992 and 2001, whereas more than 25 mm/year in 2009 (Fig. 2). The RUSLE model predicted erosion rate in most of the area comes under less than 5 mm/year followed by more than 30 mm/year for each year of study (Fig. 3). The result showed that the erosion rate increases with the increase of slope. The calculated erosion rate through both models was found to be exceeded 20 mm/year in the upper catchment area due to the steep slope. In 2009 based on E_{30} model average rate of erosion was calculated as 2.5 mm/year in the 0°–5° slope and 37.5 mm/year in the 30°–40° slope respectively. The increase rate of soil erosion, 15 times due to change of slope from 0°–5° to 30°–40° is the indication of extreme rate of soil erosion in the hilly region with steep slope. NDVI refers an index of vegetation depending on the intensity of red and near-infrared band. High density vegetation refers higher NDVI value. Calculated maximum NDVI values were decreased from 0.75 in 1992 to 0.65 in 2009. In RUSLE model NDVI is only one parameter which was differed from 1 year to another which was used to calculate c-factor. With the decreased of NDVI values average rate of erosion was increased by 3.36 mm/year in 2009 than year 1992. On the other hand based on E_{30} model, the rate of erosion was increased by 5.71 mm/year in 2009 as NDVI was incorporated to calculate the soil erosion at 30° slope.

According to E_{30} model average rate of soil erosion was calculated as 21.07 mm/year in 1992, 21.80 mm/year in 2001 and 26.78 mm/year in 2009, respectively (Fig. 2). On the other hand the average soil erosion was estimated at the rate of 20.34 mm/year in 1992, 21.24 mm/year in 2001 and 23.70 mm/year in 2009, respectively through RUSLE model (Fig. 3). The correlation (r) between two model estimation was calculated 0.9897 (Fig. 4). Within the catchment area maximum average soil erosion rate, 54.83 mm/year was found in sub-catchment number three (3), followed by sub-catchment 2, 52.68 mm/year and minimum of 6.64 mm/year in sub-catchment 14 based on RUSLE model in 2009 (Table 5; Fig. 5). The average soil erosion rate of 45.07, 41.07 and 9.97 mm/year were yield by E_{30} model in the sub-catchment number 3, 2 and 14, respectively (Table 5; Fig. 5). The correlation (r) of estimated average soil erosion rate for 14 sub-catchments through both models was calculated as 0.90, which indicates a good relationship of the estimations (Fig. 6). The average slope of was calculated as 30.07° in sub-catchment number 2, 25.39° in sub-catchment number 3 and 6.57° in sub-catchment number 14 (Table 5). Result suggested that the slope is the major factor for both model in the estimation of soil erosion rate. The comparative analysis was carried out to find out correlation (r) between slope and average estimated soil erosion rate in 14 sub-catchments area by both models in 2009. The correlations with slope and RUSLE model was calculated as 0.89 and for E_{30} model as 0.99 (Fig. 7).

Conclusion

Slope of the land, NDVI, soil erosion in 30° slope were considered as mandatory inputs into E_{30} model, where as rainfall and runoff erosivity (R factor), soil erodibility (K factor), slope steepness and length (LS factor), cover management (C factor) and conservation support practice (P factors) were used into the RUSLE model. Expectedly, some difference in the estimation were likely to crop up in

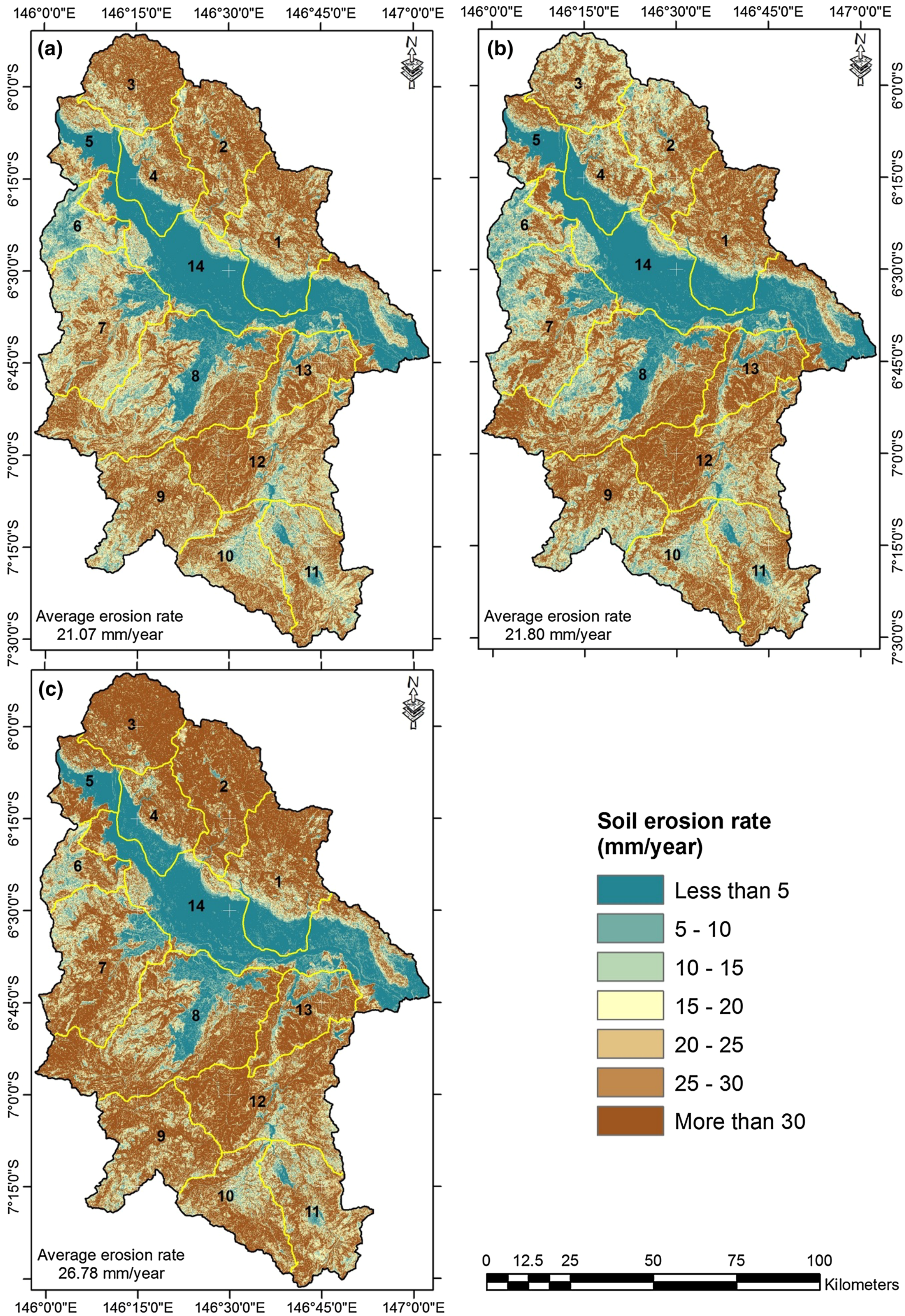

Fig. 2 Soil erosion rate base on E_{30} model for year 1992 (**a**), 2001 (**b**) and 2009 (**c**)

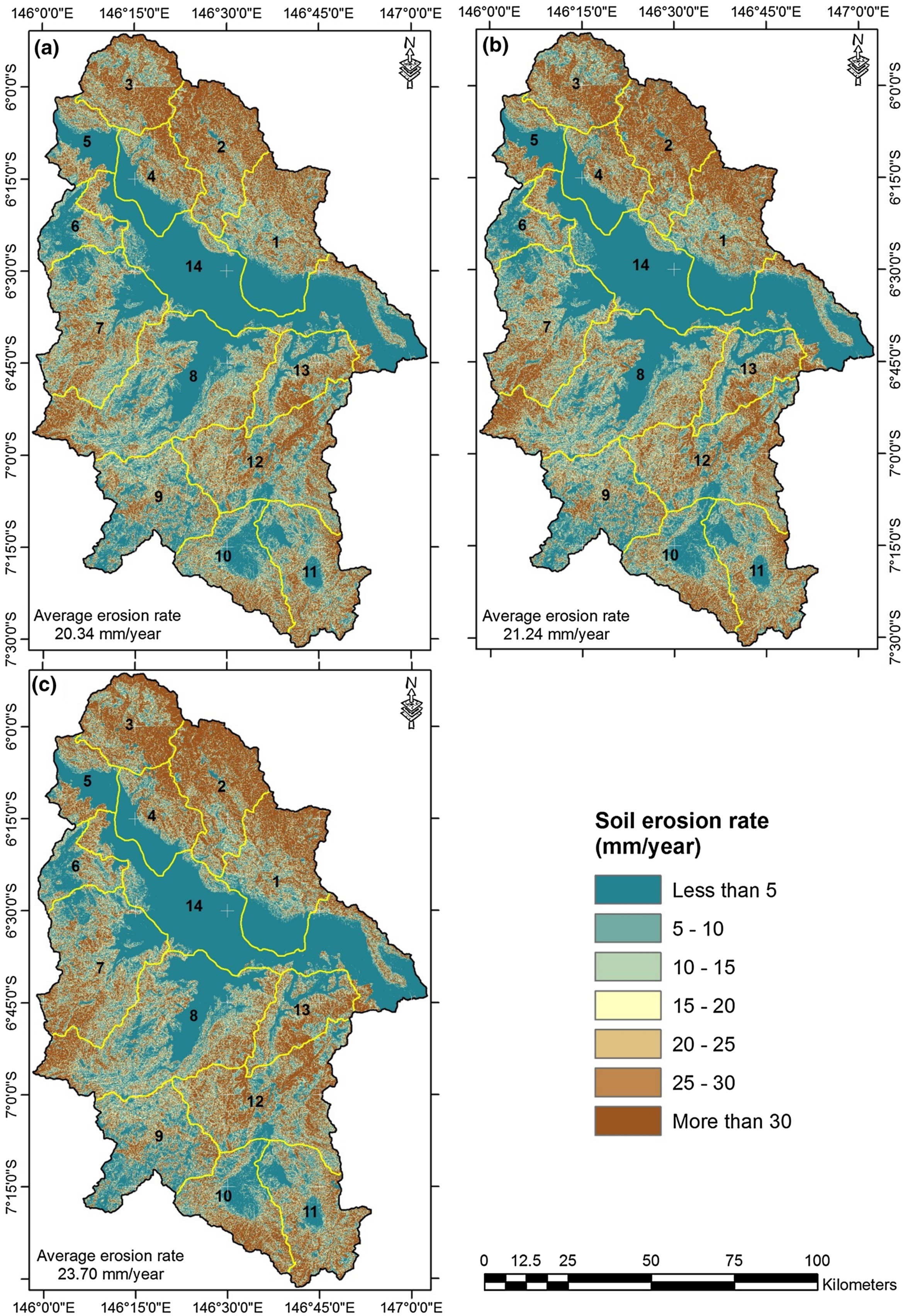

Fig. 3 Soil erosion rate base on RUSLE model for year 1992 (**a**), 2001 (**b**) and 2009 (**c**)

Table 4 Categories of rates of soil erosion and detail statistics

Soil loss (mm/year)	E_{30} 1992	E_{30} 2001	E_{30} 2009	RUSLE 1992	RUSLE 2001	RUSLE 2009
Histogram						
Less than 5	2,491,469	2,466,920	2,182,377	4,883,663	4,936,960	4,858,489
5–10	1,138,158	1,301,121	937,249	1,851,917	1,747,898	1,686,835
10–15	1,402,554	1,465,952	980,955	1,455,151	1,387,182	1,341,014
15–20	1,629,029	1,622,235	1,234,056	1,161,807	1,117,144	1,084,196
20–25	1,865,332	1,604,092	1,419,134	946,812	904,461	879,423
25–30	1,781,757	1,493,067	1,460,046	755,824	725,253	710,424
More than 30	3,858,371	4,213,283	5,952,853	3,111,496	3,347,772	3,606,289
Total	14,166,670	14,166,670	14,166,670	14,166,670	14,166,670	14,166,670
Area in hectare						
Less than 5	2242.32	2220.23	1964.14	4395.30	4443.26	4372.64
5–10	1024.34	1171.01	843.52	1666.73	1573.11	1518.15
10–15	1262.30	1319.36	882.86	1309.64	1248.46	1206.91
15–20	1466.13	1460.01	1110.65	1045.63	1005.43	975.78
20–25	1678.80	1443.68	1277.22	852.13	814.01	791.48
25–30	1603.58	1343.76	1314.04	680.24	652.73	639.38
More than 30	3472.53	3791.95	5357.57	2800.35	3012.99	3245.66
Total	12,750.00	12,750.00	12,750.00	12,750.00	12,750.00	12,750.00
Area in percentages						
Less than 5	17.59	17.41	15.41	34.47	34.85	34.30
5–10	8.03	9.18	6.62	13.07	12.34	11.91
10–15	9.90	10.35	6.92	10.27	9.79	9.47
15–20	11.50	11.45	8.71	8.20	7.89	7.65
20–25	13.17	11.32	10.02	6.68	6.38	6.21
25–30	12.58	10.54	10.31	5.34	5.12	5.01
More than 30	27.24	29.74	42.02	21.96	23.63	25.46
Total	100.00	100.00	100.00	100.00	100.00	100.00

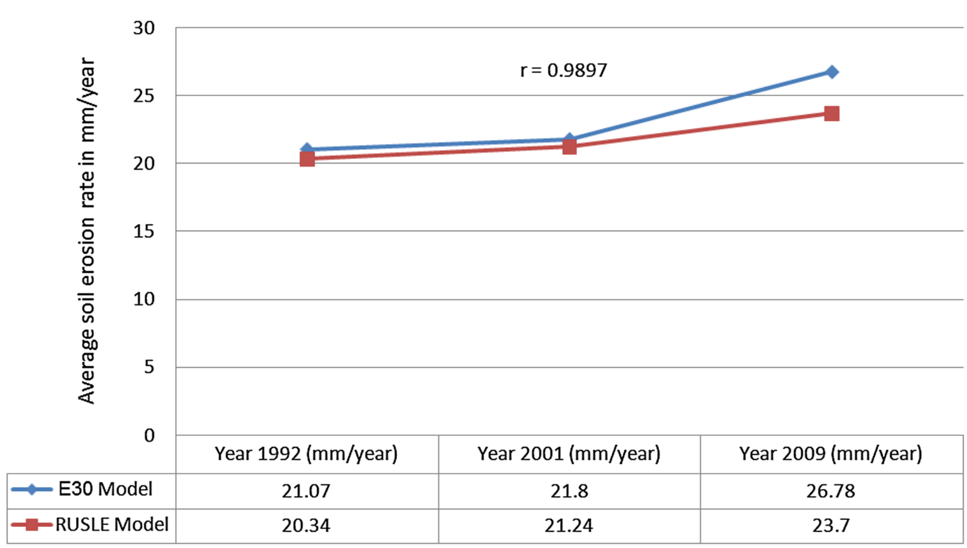

Fig. 4 Comparison of erosion rate of E_{30} and RUSLE model for year 1992, 2001 and 2009

Table 5 Rates of soil erosion for all sub-catchments of Markham from 1992 to 2009

Sub-catchment	Average soil erosion rate (mm/year)						Slope in degree
	E_{30} 1992	E_{30} 2001	E_{30} 2009	RUSLE 1992	RUSLE 2001	RUSLE 2009	
1	22.64	24.46	27.00	22.89	27.87	28.64	18.57
2	29.86	33.78	41.07	42.89	47.93	52.68	25.39
3	31.17	35.21	45.07	43.19	47.75	54.83	30.07
4	17.92	16.71	23.29	20.26	20.11	22.96	16.63
5	14.45	17.26	21.58	13.73	16.54	17.15	13.93
6	13.65	15.79	22.37	10.03	12.45	12.76	14.23
7	18.91	20.61	27.20	17.76	19.52	20.66	18.18
8	21.43	23.60	26.74	15.86	16.55	17.56	17.63
9	26.56	26.21	31.17	15.51	15.78	16.57	21.50
10	23.91	23.78	28.48	17.81	19.69	22.39	18.66
11	22.00	23.71	25.10	21.79	22.47	23.46	17.14
12	26.58	29.01	31.64	26.30	25.78	30.05	21.21
13	24.77	27.74	30.18	23.47	22.85	27.77	19.18
14	8.40	8.91	9.97	6.28	6.33	6.64	6.57
Total	21.07	21.80	26.78	20.34	21.24	23.70	17.78

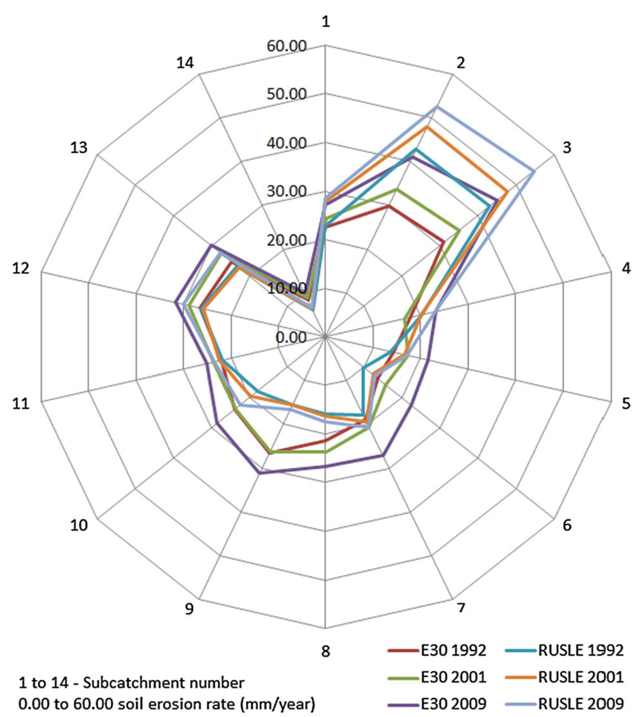

Fig. 5 Average erosion rate for sub-catchments of Markham for year 1992, 2001 and 2009

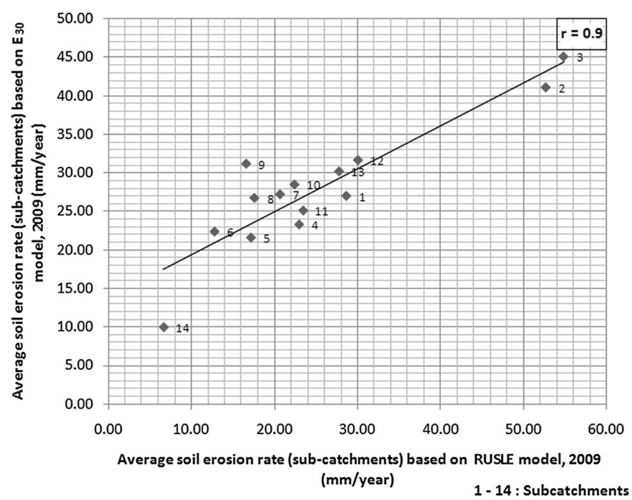

Fig. 6 Correlation of estimated average erosion rate for sub-catchments through E_{30} and RUSLE model

this research work. A closed relationship was calculated ($r = 0.9897$) between the estimation of soil erosion rate through E_{30} and RUSLE model. An increase rate of soil erosion rate was recorded almost in all sub-catchments area because of continuous loss of forest or vegetation cover caused by increased logging, agriculture and mining activity which resulted decrease of NDVI value year after year. The erosion rate through E_{30} and RUSLE model indicates extremely severe rate of erosion in the upper catchment area having rugged terrain and steep slope. These area are required immediate attention of soil conservation practices. This kind of research can be conducted in any other watershed region of Papua New Guinea to determine potential spatio-temporal soil loss pattern where

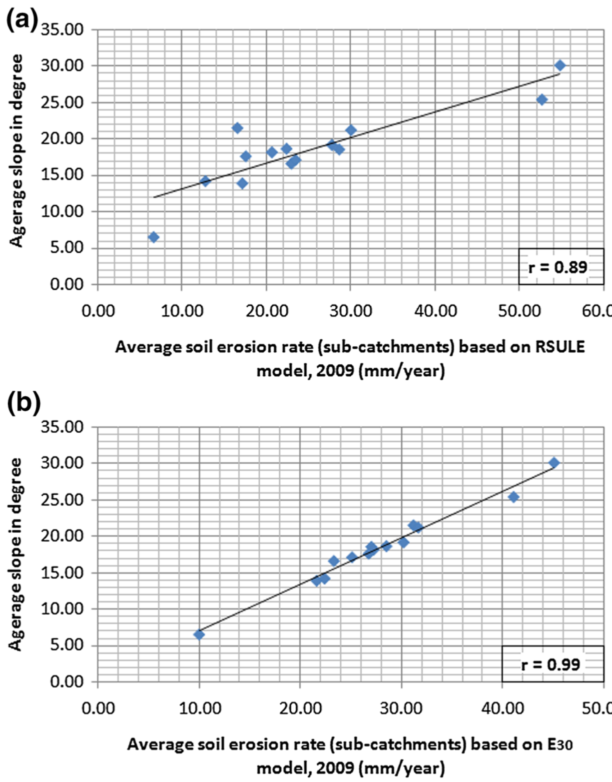

Fig. 7 Relationship between slope and estimated average erosion rate for sub-catchments through RUSLE (**a**) and E_{30} (**b**) model

there are no proper ground observation on the soil erosion measures.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest for the publication of this article.

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