Land use and erosion risk in small forest catchments on the Coral Coast of Fiji: baseline estimates of sediment inputs to coastal lagoons.

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Key Points
- Poor land use practices in catchments along the Coral Coast of Fiji have increased sediment runoff to adjacent coastal lagoons
- Such catchments can only be identified and managed once baseline sediment runoff values are obtained
- Despite its shortcomings, the USLE model (combined with GIS) produced potential soil erosion values in good agreement with the sediment load obtained using field data
- The USLE model is a useful tool to assist in catchment management in Pacific Island Countries (PICs) where data is scarce and hard to obtain

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Abstract

In Fiji, coastal hinterlands are often characterized by small steep watersheds which have a low retention capacity for eroded sediments. Adjacent coral reefs and lagoons may therefore suffer degradation when exposed to periodic inputs of high sediment loads. The 'Coral Coast' of southern Viti Levu is Fiji's longest continuous fringing reef, but faces threats from land use change in coastal catchments. Efforts to manage sediment sources are hindered by a lack of sufficient data on erosion risk and suspended sediment transport. The present study investigates the reliability of using the Universal Soil Loss Equation (USLE) model in predicting soil erosion risk for Fiji's catchments. The USLE was combined with data from Geographical Information Systems (GIS) to identify areas of potential soil erosion risk in the Votua Creek catchment, a steep naturally forested watershed on the Coral Coast. The modeled values were compared with estimates of sediment loads calculated using turbidity and rainfall data obtained for the catchment over a period of 8 months from October 2009 to June 2010. There is good agreement between modeled results and estimates from field data hence supporting the proposition that the USLE model can be a useful tool to assist in targeting watershed management efforts of a resource poor developing Pacific island country like Fiji.

Keywords

Coral Coast, Votua catchment, USLE model, turbidity, rainfall, erosion, suspended sediment

Introduction

A recent study done on Fiji's watersheds by Atherton *et al.* (2005) found that one of the major threats to the country's watershed condition is potential soil erosion due to the impact of anthropogenic development. Land use practices such as overgrazing, deforestation, commercial forestry, ginger, dalo, cassava and sugar cane cultivation on steep slopes are causing increased catchment erosion thus increased sediment delivery to waterways (Cochrane, 1969; Barbour and Terry, 1998; Mahadevan, 2008). Logging in smaller coastal watersheds is likely one of the major contributors to degradation of coastal marine ecosystems and fisheries in Fiji, since such watersheds have low retention capacity for sediments relative to larger watersheds (Atherton *et al.*, 2005). Reefs adjacent to smaller coastal watersheds, unlike those near larger rivers, are not adapted to periodic exposure to high sediment loads, resulting in long-term degradation of reef ecosystems (Atherton *et al.*, 2005). Several studies done throughout the world (e.g. Allan *et al.*, 1997; Sliva and Williams, 2001; Tong and Chen, 2002; Fabricius, 2005; Mora, 2008), reveal that coastal water quality issues need to be addressed at a watershed scale since watershed health is inextricably linked with the well-being of coastal systems. However, lack of sufficient data on suspended sediment transport from smaller, local watersheds is one of the major factors hindering watershed restoration efforts in Fiji (IAS, 2008). Hydrological monitoring is only limited to a few larger watersheds in Fiji due to limited financial resources allocated to responsible authorities by local government, and lack of expertise considering the multidisciplinary nature of catchment studies (SOPAC, 2007; IAS, 2008).

Recently, an increasing amount of coastal pollution has been reported in the Coral Coast area. Mosley and Aalbersberg (2003), observed high levels of algal growth (e.g. *Sargassum sp*.) along the Coral Coast area. Terry *et al.* (2006) proposed

Ram, A. R. & Terry, J. P. (2014). Land use and erosion risk in small forest catchments on the Coral Coast of Fiji: baseline estimates of sediment inputs to coastal lagoons, in Vietz, G; Rutherfurd, I.D, and Hughes, R. (editors), Proceedings of the 7th Australian Stream Management Conference. Townsville, Queensland, Pages 436-444.

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practices such as burning and grazing in adjacent steep catchments are causing large quantities of terrigenous sediments being discharged during high stream flow in a channel along the Coral Coast. The effect of land use practices on stream water quality can be studied through measurement of turbidity and the suspended sediment concentration in similar watersheds with different land use. However real time monitoring of suspended sediment in catchment to measure sediment load using field data is not a viable option for many developing Pacific Island Countries who have limited funding, resources and expertise to carry out such studies. This study aims to investigate temporal sediment dynamics in relation to rainfall parameters in a steep, naturally forested coastal watershed in the Coral Coast of Fiji, to provide a benchmark against which comparisons can be made for adjacent areas of more intense land use. This study also aims to predict potential soil runoff from the study area using the USLE model to see if it gives reliable potential soil erosion risk values for the catchment when compared to values obtained from field data. The USLE model was developed by Wischmeier and Smith in 1978 and predicts the annual rate of erosion on a field slope based on five parameters: rainfall pattern, soil type, topography, land use, and management practices. If successful, the model can be used for management of other similar basins with different land use using limited data and resources available locally which is outside the scope to this study.

Study area and methods

Study area description

Fiji has a mass tourism industry focused on beach resorts along the Coral Coast where beach tourism, nature tourism and Fijian culture are the main tourist attractions. Off the coast, large coral reefs are a treasure sensitive to erosion that is why it is so important to analyze and to manage the catchments of this area. The study area chosen for this project is the Votua catchment, one of the few watersheds where most of the natural vegetation remains intact in the Coral Coast, hence making it a good catchment to measure baseline soil erosion (Figure 1). It is a small, steep coastal catchment with an area of 9.3 km^2 and an average slope of 17.54°. The elevation ranges from 0 m at the outlet to 440 m on peaks while the average height is 191 m. The geology of the Votua watershed is composed of extrusive and intrusive igneous rocks ranging from mafic to silicic in composition and small areas of metamorphic rock in contact zones. The stream has a dendritic drainage pattern showing that the underlying igneous rocks have uniform resistance to erosion. The stream is of the fourth order which is typical of medium size streams. The mean annual precipitation at the closest rainfall station located 30 km away at the Nacocolevu Research Station is 1,753.6 mm and the mean annual temperature is 20.4°C. In terms of landcover, the majority of the watershed has natural rainforest cover (93.1%), with small areas of grasslands (4.7%), patches of bare or burnt land (1.7%) and minor infrastructure e.g. roads, settlements (0.6%) (Figure 2). Human activities where present, are restricted to the lower watershed close to the main highway and the coast where the Votua village and the Votua housing are situated. Close to these habitations are few, less than a hectare, subsistence based farms that are mostly located in the floodplain areas and comprise of dalo, cassava, banana, plantain and pawpaw plantations.
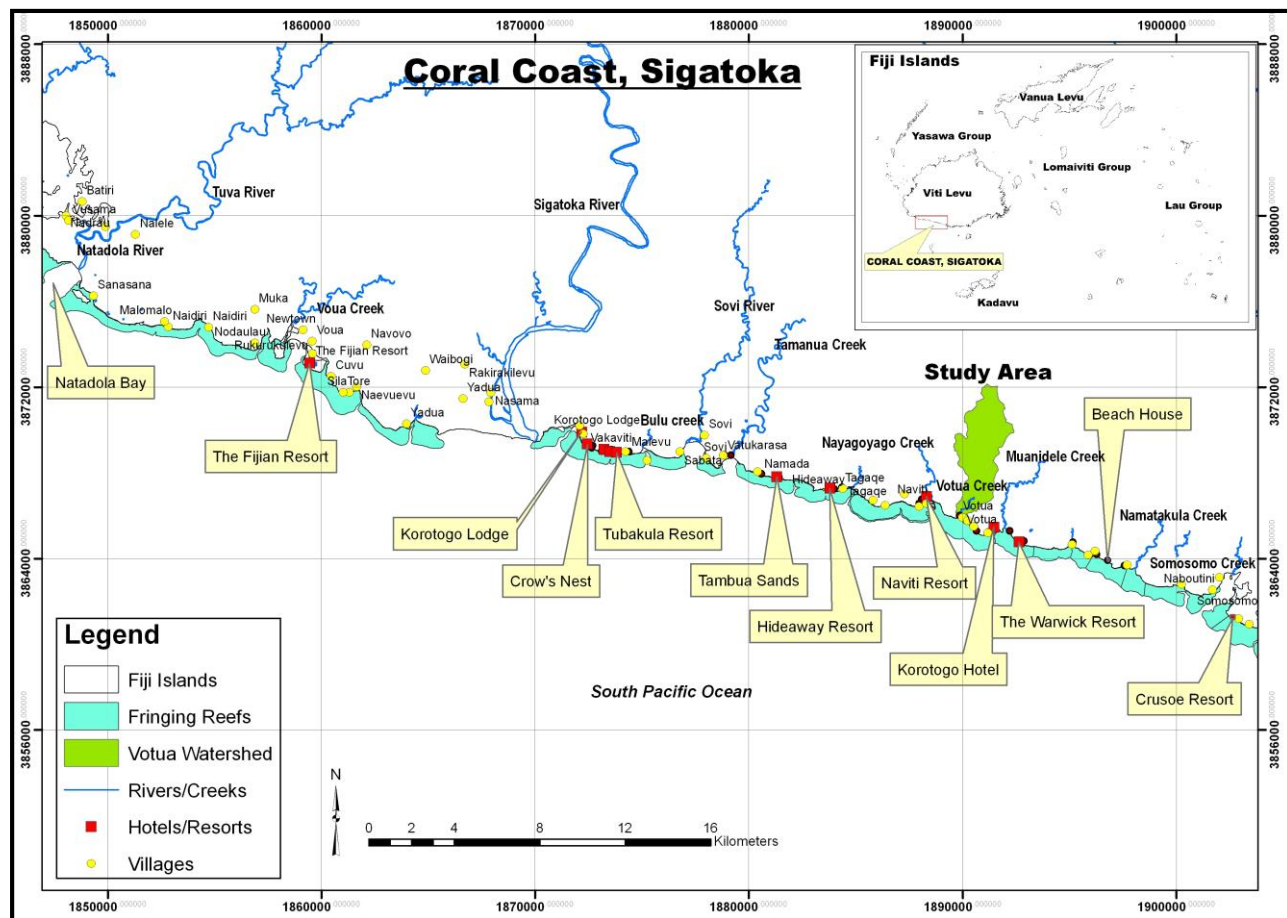
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Figure 1. Map showing location of study area (Votua watershed) along Coral Coast, Fiji
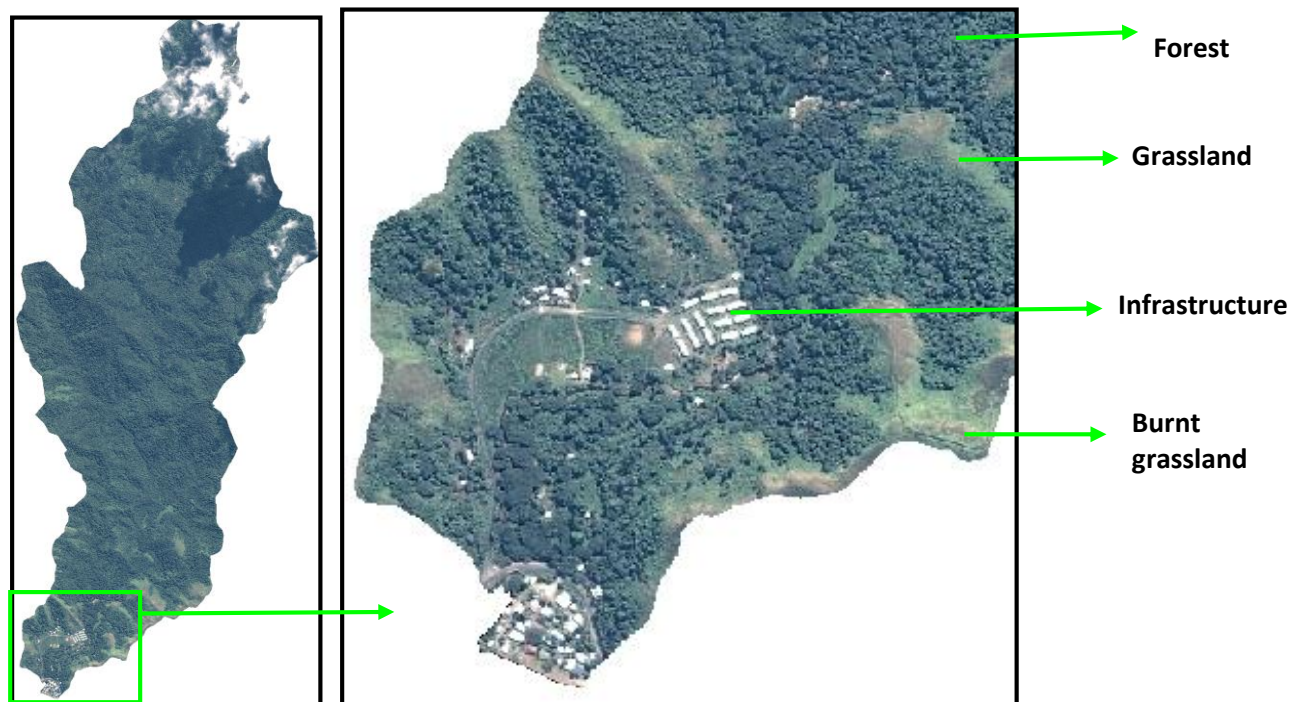
Figure 2. 2006 Quickbird Aerial Image of the Votua watershed showing different land use/land cover areas

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Catchment modelling

The USLE predicts potential erosion and is widely used in the world (Printemps, 2008).   The equation is:

A = R x K x LS x C x P

Where:

A = average potential annual erosion (t/ha/yr),

R = rainfall-runoff factor (erosivity) (MJ.mm/ha.h.yr),

K = soil erodibility factor (t.ha.hr/ha.MJ.mm),

LS = topographic factor (L-slope length, S-slope gradient),

C = land cover management factor,

P = soil conservation practice factor.

The data source(s) used to obtain the layer of each factor for modeling potential soil erosion risk using USLE in Votua catchment is summarized in Table 1. Details on processing of these data to obtain layers on each factors to input in the USLE model is given in Ram (2013). After analyzing each factor of the model, the values of each factor were then integrated to quantify soil loss. The overlay was done by multiplication of values for the four factors: R, K, LS, and C in the Raster Calculator under ArcGIS. Before the overlay was done, it was ensured that all the layers were of the same pixel size 25 m by 25 m i.e. layers with larger or smaller pixel size were downsized or upsized respectively so that overlay could done successfully. The result of this multiplication was a raster giving the amount of potential soil loss in t/ha/yr over the study area.

Table 1: Summary of sources used to obtain relevant data for the USLE modeling

Factor	Data	Scale	Geographical Extent	Source
Rainfall (R)	Word Climate Rainfall Data (raster) *(www.worldclim.org)*	1km pixel resolution	World	Hijmans *et al.* (2005) from University of California
Soil Erodibility (K)	Geographical Shapefiles (Watershed area, soil type)	1:50,000	Study Area	USP GIS lab (data originally from FLIS)
Topographic (LS)	i. Geographical Shapefiles (Watershed area, contours) ii. AML script obtained from:*http://www.onlinegeographer.com/slope/slope.html*	1:50,000	Study Area	i. USP GIS lab (data originally from FLIS) ii. Van Remortel *et al.* (2003)
Cover Management (C)	Satellite image	0.61m pixel resolution	Study Area	2006 Quickbird Image (obtained from IAS)
Watershed Area Delineation and General Information.	Geographical Shapefiles (Watershed area, streams, contours, roads, soils, geology, reefs, towns, villages etc.)	1:50,000	Study Area	USP GIS lab (data originally from FLIS)

Catchment monitoring

An estimation of annual soil runoff from field data was obtained using limited time, resources and funding available for the study. The rainfall, turbidity and total suspended sampling data was collected for the Votua catchment over a period of 8 months from October 2009 to June 2010. The rainfall measurement within the watershed was done using a Data Logging Rain Gauge (7852M) which integrates a HOBO® Pendant™ Event Data Logger (WD1501) into a tipping-bucket rain gauge where time and date stamp is stored for each 0.2 mm tip event for detailed analysis. Considering the size of the watershed exceeded a few square kilometers, it was noted that rainfall amount and rainfall intensities might vary within the watershed. Therefore rain gauges were deployed at two spots within the watershed; the lower and the upper watershed at elevations 16 m and 440 m, respectively and a middle rain gauge was also installed for data backup

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purposes (Figure 3). The turbidity and depth of the Votua stream was continuously monitored during the study period using the YSI6600 V2-4 Sonde. The 3-point calibration of turbidity probe using appropriate standards and methods was carried out per instructions in the YSI6600 V2-4 Sonde manual. The Sonde was set-up for unattended sampling and the sampling interval was set to 10 minutes considering the catchment was small and steep thus the fast response of the stream to rainfall. The Sonde was deployed on the old Votua bridge just next to the Votua village located on the bank of the Votua stream outlet (Figure 3). Grab samples were also taken near the Votua creek outlet (about 20m downstream of Sonde) during rainfall events for Total Suspended Solids (TSS) analysis. The relationship between turbidity and TSS was used to calculate the average TSS values from the average turbidity for each of the rainfall events producing significant runoff response in the Votua stream. The total sediment load of each rainfall-runoff event was calculated by multiplying this value with total runoff estimation of each event obtained by using the rainfall data through the Modified Rational Method (MRM) as described by Marek (2011). It must be noted that the period of the data collection fell within an El Niño period in Fiji and significantly lower amounts rainfall took place compared to the expected.
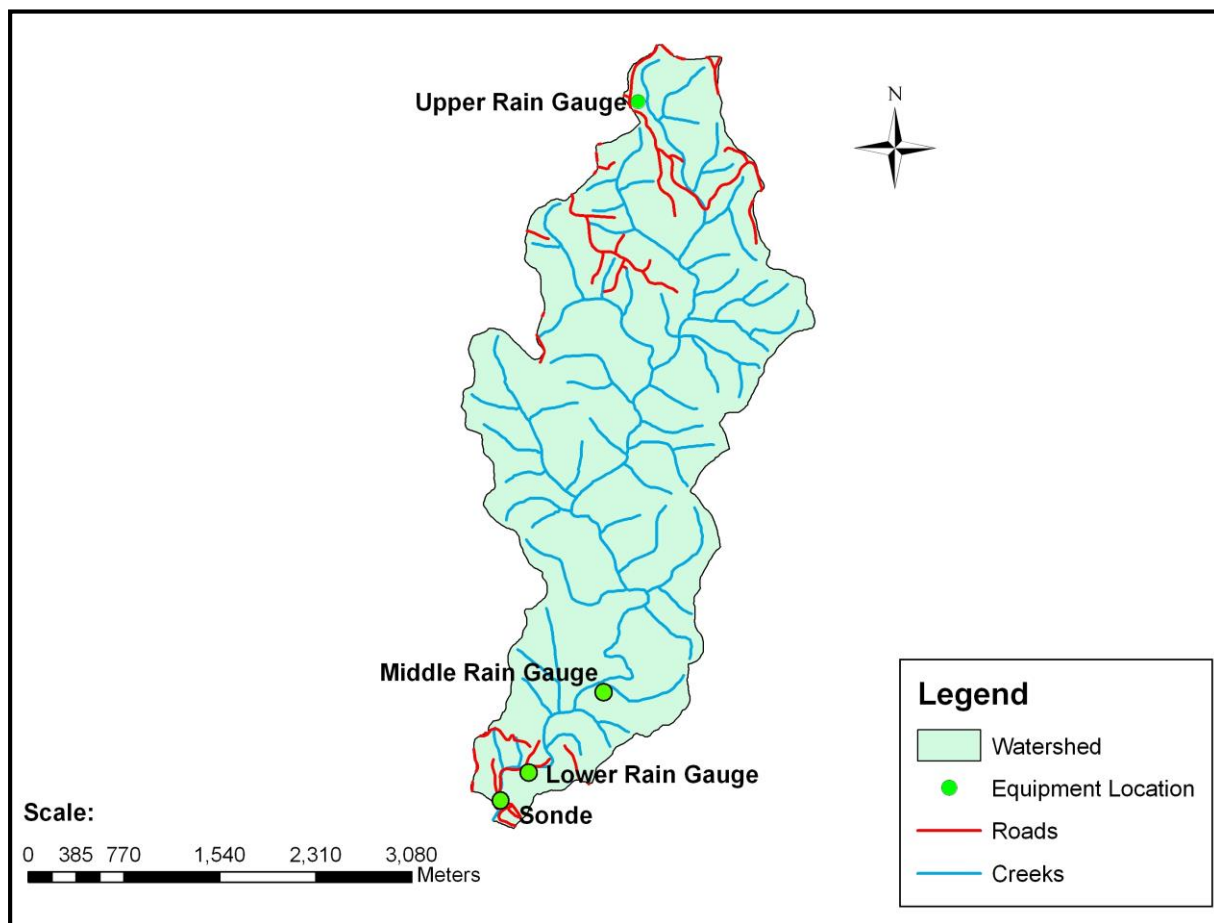

Figure 3. Map of Votua watershed showing location of equipment used for the study

Results and discussion

Estimated annual load from catchment modelling

The output of the USLE model after multiplication of all the factors R, K, LS and C is depicted in Figure 4. The values of the potential erosion on the study area range from 0 to 907.3 t/ha/yr. The average of the values obtained on the area is 6.4 t/ha/yr. The computed soil losses using the USLE are frequently related to soil-loss tolerances, or T-values, which are defined as the maximum annual soil losses that can be sustained without adversely affecting the productivity of the soil (Batie, 1983). The T-value for tropical soils has been suggested to be 13.5 t/ha/yr by Hudson (1971). About 4 % of the study area has a potential erosion rate greater than 13.5 t/ha/yr, which correspond mainly to areas where infrastructure

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and bare land are located. Nearly 96% of the study area has potential soil erosion values less than 13.5 t/ha/yr, mainly corresponding to areas covered by dense vegetation (forest). Nevertheless, the values obtained for this study are compatible with results of a similar study done by Printemps (2008) for northern Viti Levu, where potential soil erosion values obtained ranged from 0 to 1,984 t/ha/yr. The average value obtained by Printemps (2008) for the modeled northern Viti Levu area was 7.77 t/ha/yr which is very close to the values obtained for the study area. A similar study conducted by Printemps et al. (2007) in a mining impacted area in New Caledonia found much higher values ranging from 0 to 15,690 t/ha/yr, with an average of 137 t/ha/yr. The results were also compatible with estimations of Morrison (1981) who found soil loss rates to be around 36.7 t/ha/yr under sugar cane near Nadi, Fiji; and Liedke (1984), who found soil loss rate between 16.6 and 80 t/ha/yr near Lautoka, Fiji. Nelson (1987) found soil loss rates of 10 and 170 t/ha/yr on Rewa and Ba watersheds in Fiji. Therefore, the USLE model does seem to give a potentially reliable soil erosion prediction despite its limitations.
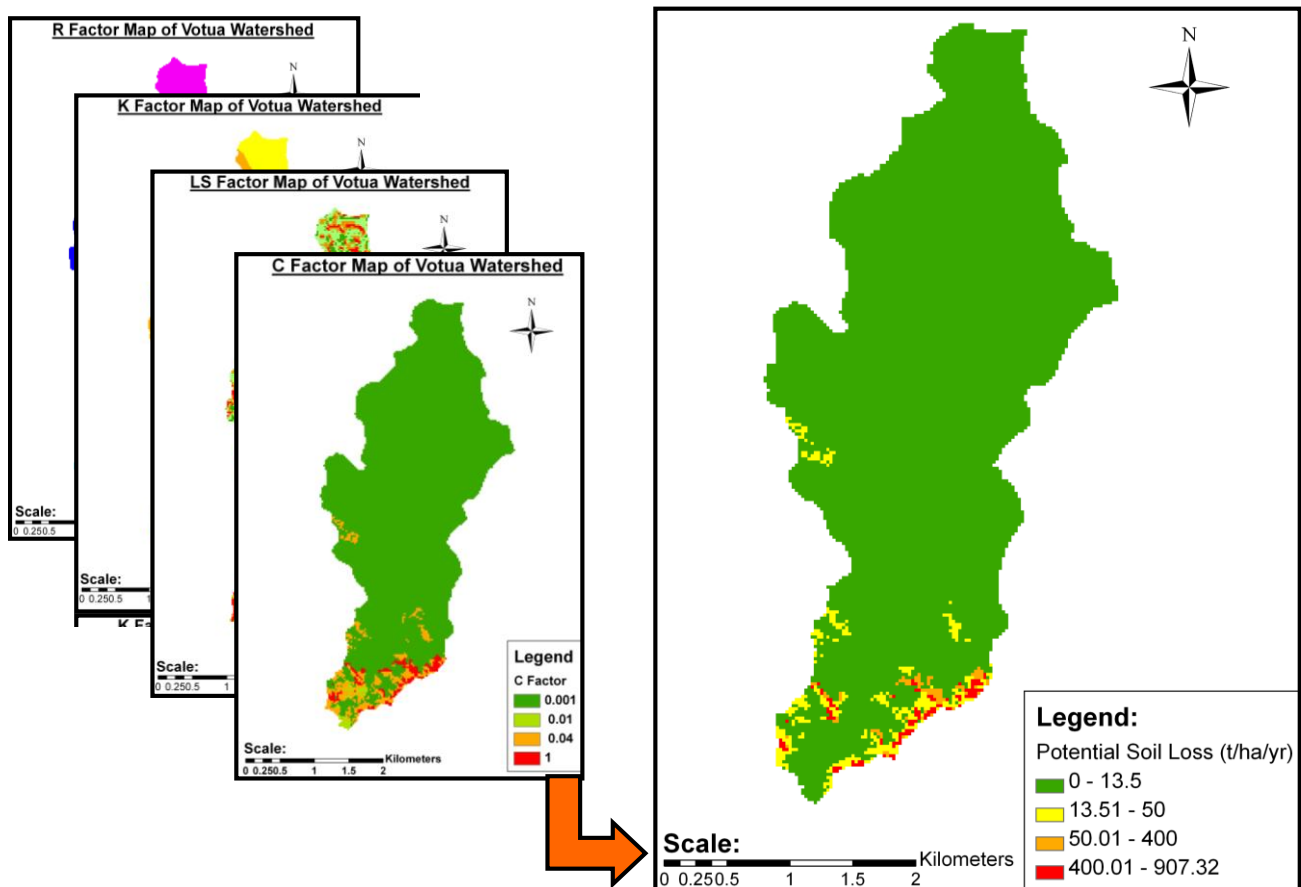

Figure 4. USLE model output showing potential soil loss map of the Votua watershed

Estimated annual load from catchment monitoring

The details on how the linear regression model was obtained for turbidity and TSS in Votua creek is discussed in Ram (2013). The simple linear regression model was used to obtain the average TSS in mg/L in the runoff of the analyzed hydrological response events using their average turbidity values. This multiplied by total runoff measured for the individual hydrological response events can give approximate TSS load of the events.

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Table 2: Calculated values of total runoff volume (V) and total TSS load of the analyzed events

Rainfall Event Details			MRM Output Values		Regression Model Output	MRM Output X RM Output [V(L) x TSS(mg/L)]		
Event # (>10 mm)	Rainfall Start Date and Time	Type of Rainfall Event	V (m³)	V (L)	TSS* (mg/L)	Total TSS (mg)	Total TSS (t)	% of Total TSS
1	10/12/09 10:20	Small	90070.69	90070686	36.8	3.3E+09	3.3	0.8
2	10/13/09 8:40	Small	116220.2	1.16E+08	147.6	1.7E+10	17.2	4.1
3	12/14/09 1:10	Large	916202.9	9.16E+08	273.6	2.5E+11	250.7	60.5
4	1/26/10 3:50	Medium	299999.2	3E+08	50.4	1.5E+10	15.1	3.6
5	2/4/10 11:30	Medium	205802.9	2.06E+08	84.2	1.7E+10	17.3	4.2
6	2/15/10 9:10	Medium	338060.6	3.38E+08	167.3	5.7E+10	56.6	13.6
7	3/15/10 0:00	Small	162708.3	1.63E+08	40.3	6.6E+09	6.6	1.6
8	3/21/10 4:10	Medium	200052.9	2E+08	53.2	1.1E+10	10.6	2.6
9	3/31/10 8:00	Low	38496.05	38496048	42.4	1.6E+09	1.6	0.4
10	4/25/10 20:40	High	278166	2.78E+08	127.8	3.6E+10	35.6	8.6
Total							414.6	100.0

The calculated output values of each of the models are summarized in Table 2. The final outcome of multiplied model outputs is also summarized in Table 2, which expresses the approximate TSS load transported by each event in tonnes (t). The total amount of TSS load transported from the Votua catchment by all of the analyzed rainfall-runoff events in this study is 414.6 t. About two thirds (60.5%) of this approximated total TSS load transported is seen to be transported by the Cyclone Mick (Event # 3) alone, which transported a total of 250.7 t of total TSS load. The total TSS load of 414.6 t was obtained from 6 complete months of rainfall and turbidity data from the study area. Therefore, if the total TSS load transported by all the significant rainfall-runoff events is to be estimated for a whole year then this value has to be doubled to be extrapolated to 12 months i.e. 414.6 t x 2. Hence, in a typical El Niño year, the total amount of TSS load from the Votua catchment can be estimated to be 829.3 t from an area of 9.3 km^2 or 0.9 t/ha/yr.

Comparison between modelled and measured annual sediment load

The aforementioned estimated TSS load of the Votua catchment obtained using field data 0.9 t/ha/yr is nearly sevenfold lower than average potential soil erosion value obtained from the study area using the USLE model, which is 6.4 t/ha/yr. This could be due to that fact that TSS load value was calculated using only 6 months of real time data collected during an El Niño year that noticeably produced much lower rainfall compared to long-term values used in the USLE model. In addition, one must take note of the fact that the P factor of was 1 used in the USLE model causing the output to produce slightly higher values of soil erosion potential. One must also consider the limitations and assumptions of the MRM and the disadvantages of using the USLE discussed in Ram (2013). Keeping all these factors in mind, the TSS load estimated with the assistance of the MRM can be considered to correspond well with potential soil erosion values obtained from the USLE model.

Conclusions

Despite the limitations associated with the use of the USLE at catchment level, the model can still provide a better knowledge of the distribution of erosion hazard in Fiji's catchments. Many tropical countries face more soil erosion problems than the temperate climate countries because of logging pressures and the more intense rainfall characteristics. Since most developing tropical countries do not have the necessary resources to develop their own soil loss prediction models, the USLE is the first step towards obtaining an estimation of terrigenous inputs delivered to coral reef environments. This is valuable for the developing PICs where limited resources and expertise constantly hinder implementation of soil conservation and watershed management efforts. The spatial representation at the watershed scale of the USLE model can be a useful tool for sustainable soil conservation planning. The results of this research, by

providing baseline conditions of potential soil erosion risk associated with a catchment with minimal impact by human activities and limited land use change, can give some directions for future management of similar small watersheds with different land use practices in the Coral Coast region and elsewhere in the Fiji Islands.

The regression model derived from the TSS and turbidity data when combined with total runoff estimated from the Modified Rational Method predicted overall TSS released from the Votua watershed to be 0.9 t/ha/yr. The value could be considered reasonably close to the long-term estimate of 6.4 t/ha/yr obtained using the USLE, taking into account the fact that data was obtained in a drier than usual El Niño year. It is recommended that future studies if conducted in the Votua catchment should focus on obtaining accurate annual sediment yield to ground-truth the results of potential soil erosion risk obtained through the USLE, so that parameters of the model can be better calibrated to give more precise values. A proper gauging station should be installed in the catchment where discharge measurements can be done simultaneously with depth and turbidity measurement. The establishment of a stage-discharge curve for the catchment through this station will allow calculation of more accurate runoff values for rainfall-runoff events, which in turn can be used to better approximate TSS load of each event.

Acknowledgments

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