A GIS-Based Estimation of Soil Loss in the Densu Basin in Ghana

G. Owusu
Department of Geography and Resource Development, University of Ghana, P. O. Box LG 59, Accra, Ghana
Email: owusugeorge@ug.edu.gh

Abstract
Distributed erosion simulation models are useful in evaluation of different strategies for land-use and soil management improvement in watersheds. The increased soil erosion in Densu basin of Ghana has led to siltation of the river channel that is causing flooding in some parts of Accra, Ghana. The most urbanized basin in Ghana, Densu, supplies water to 600,000 people, with agriculture employing about 40% of the active population. A PCRaster GIS soil loss risk maps have been developed for Densu basin using models of Universal Soil Equation (USLE) and Revised Universal Soil Equation (RUSLE). Soil loss factors such as rainfall erosivity, soil erodibilty, slope and slope length were also mapped for the basin. The model predicted average, minimum and maximum annual soil loss rates of 2.2, 0, and 63 t ha^{-1} y^{-1} , respectively, indicating that some areas in the basin are above tolerance level of 5.0 t ha^{-1} yr^{-1}. The total soil loss was 756,507 tonnes per hectare per year. Among the soil types Lixisols experienced the highest soil loss of 402,080 t ha^{-1} yr^{-1} with Plinthosols experiencing the lowest soil loss of 64 t ha^{-1} yr^{-1}. Among the administrative districts in the basin Suhum, Kraboa and Coaltar experienced the highest absolute soil loss of 216,957 t ha^{-1} yr^{-1} while Fanteakwa experienced the highest average soil loss of 4.5 t ha^{-1} yr^{-1}. The results can serve as data and information to water resources managers and soil conservationists.

Introduction

Soil loss is one of the main threats to ecosystem in the tropics. It is mainly instigated by erosion and its depositional power (Ramos & Martínez-Casasnovas, 2006). Apart from reduction in plant nutrients, soil loss also results in siltation and deposition in streams (Sthiannopkao *et al.,* 2007). In addition to supplying water from its Weija reservoir to the over 400,000 people living in the western parts of Accra, Densu basin is a major source of water supply to other urban settlements such as Koforidua, Suhum, and Nsawam, with a combined population of about 140,000 (Abrahams & Ampomah, 2010). The basin is at high erosion risk because the main economic activity, agriculture, employs about 40% of the economically active population (Commission, 2011) . A good soil loss management is, therefore, needed to reduce land degradation and low water quality due to siltation and sedimentation. In this study a Geographic Information System (GIS) soil loss model was developed to enable soil managers evaluate factors influencing soil degradation.

Soil loss is normally estimated with empirically and physically-based models (Jha & Paudel, 2010). The well known physically-based models include 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). Empirically based models include SLEMSA (Soil Loss Equation Model of Southern

Africa), and Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978). Universal Soil Loss Equation (USLE) has been successfully applied in the tropics in Kenya (Burrough & McDonnell, 1998). In its original form USLE was applied to a plot of land (Wischmeier & Smith, 1978) and, in recent years, the application of distributed USLE is wide spread (Beskow *et al.,* 2009). USLE estimates soil loss based on the product of erosivity of rainfall (R), erodibility of the soil (K), slope length in metres (L), slope in per cent (S), cultivation parameter (C), and protection parameter (P).

One of the weaknesses of USLE is its inability to account for impact of the upstream elements on soil loss (Jha & Paudel, 2010). USLE is also limited to yearly temporal time frame; it is unable to predict soil loss on daily, weekly and monthly bases, for instance. A new version of USLE called Revised Universal Soil Loss Erosion (RUSLE) (Renard, Foster, Weesies, & Porter, 1991) has been developed to overcome some of these weaknesses. The analysis of slope length in USLE helps workers to determine erosion and deposition areas on a hill slope (Mitasova, Hofierka, M. Zlocha, & Iverson, 1996). By default slope length ends where deposition begins: Slope length is defined as the distance from the point of origin of overland flow to the point where either the slope gradient decreases enough that deposition begins, or runoff water enters a well-defined channel (Rodríguez & Suárez, 2010). In recent years GIS has been used to estimate erosion and deposition areas worldwide (Jha & Paudel, 2010; Mitasova, Mitas, Brown, & Johnston, 1998), but using distributed GIS to model erosion is very rare in Ghana.

The main objective of the study is to use GIS to estimate annual soil loss in the Densu basin of Ghana using USLE and RUSLE models. Second, an attempt is made to quantify factors influencing soil loss. Third, an attempt is made to develop erosion risk maps of the basin. Fourth, an attempt is made to classify soil loss based on 12 administrative districts in the basin, and spatial soil erosion vulnerability map of the basin is created.

Materials and methods

The study area

The Densu basin is one of the coastal watersheds in Ghana (Fig. 1), and it has an area of 2,490 km^2. The basin, which spans latitude 5^0 30' N to 6^0 20' N and longitude $0^0$10' W to $0^0$35' W, shares three administrative regions – Eastern, Western and Greater Accra – of Ghana. The basin is a home to 10 administrative districts, with most of them in the Eastern Region of Ghana. It has a population density of about 387 persons/km^2, higher than the national density of 77 persons/km^2. The main river, Densu, takes its source from the northern mountains and enters the sea near Accra, where there is a threatened wetland site. Excess flow from the Weija reservoir on the basin discharges into the Densu delta (Sakumo) lagoon and salt pans complex, which constitutes one of Ghana's internationally recognized protected areas. The river supplies Accra half of its water through its water supply, Weija Reservoir (Abrahams & Ampomah, 2010).

The main soil types in the basins include Acrisols, Fluvisols, Luvisols, Lixisols, Leptosols and Plinthosols. The northwestern

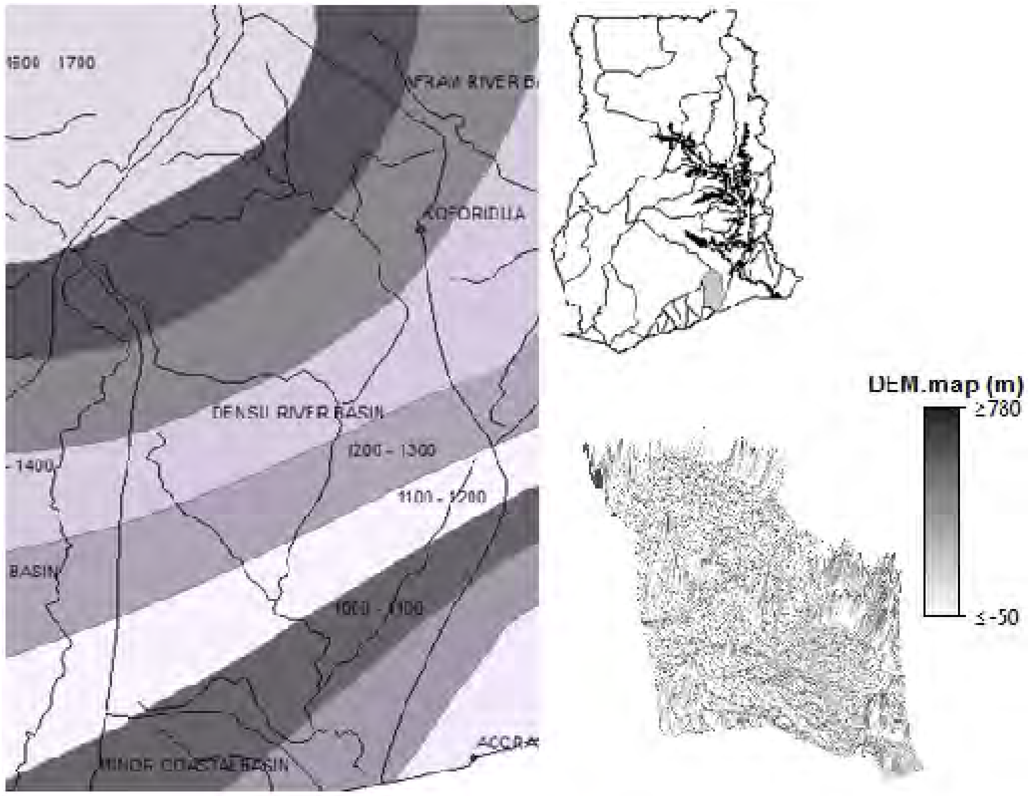

Fig. 1. Annual rainfall distribution (mm) and DEM map of the study area

part of the basin is underlain by Birimian Vocalnonics of metamorphosed Lava, Pyrocassic Rock, Hypabyssal Basic Intrusive, phyllite and Greywacke. The southeastern part is underlain by Togo Series of Quartzite, Sandstones, Shale, Phyllite, Schist and Sillicified limestonds. The greater part of the basin lies within Dahomeyan granotoid undifferentiated rocks.

The basin climate is dominated by its rainfall; there are about eight rainfall zones in the watershed. Rainfall ranges from 900 mm in the coastal dry south to 1700 mm in the mountainous north (Fig. 1). While mountains dominate the northern part of the catchment, the south lowland flatly slopes to join the sea. The area slopes from the north, as high as 850 m above sea level, to the south, as low as 42 m below sea level. The rainfall amount in the mountainous north is twice the amount in the coastal south; therefore, the north mostly dictates the supply of water to the catchment.

Model input and processing

The conceptual model (Fig. 2) shows that input data include soil, rainfall, and digital elevation model (DEM) and its derivative slope map. Land use map is also needed to derive the cultivation and the protection

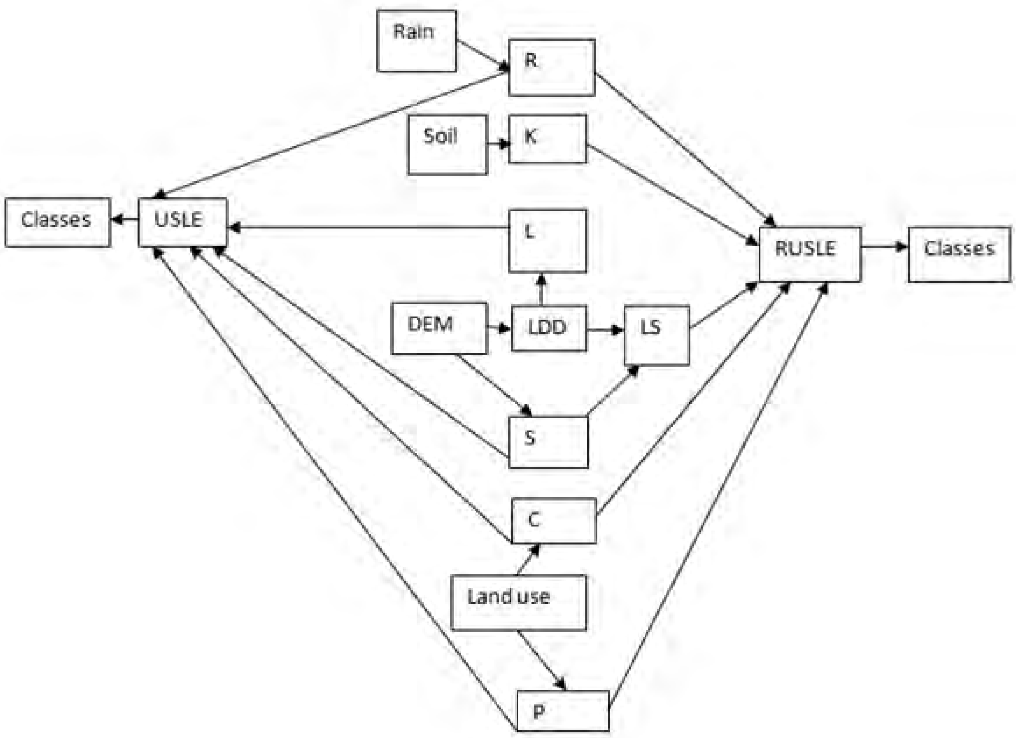

Fig. 2. Conceptual model and flow chart of USLE and RUSLE models

parameters. The difference between USLE and RUSLE model in the conceptual model is the approach L and S are computed. While USLE computes L and S separately, using DEM through Local Drain Direction (LDD), RUSLE computes LS together, accounting for upstream overland flow (Burrough & McDonnell, 1998).

A prototype geographic information system, PCRaster (Karssenberg, 1996, 2002; Van Deursen, 1995), was used to estimate soil loss with the two models: Universal Soil Loss Equation (USLE) and Revised Universal Soil Loss Equation (RUSLE). The USLE and RUSLE predict soil loss (A) in tonnes per hectare per year by using empirical equations (Burrough & McDonnell, 1998):

$$A = R * K * L * S * C * P \quad (1)$$

where A is the annual soil loss in tonnes/hectare, R is the erosivity of rainfall, K is the erodibility of the soil, L is the slope length in metres, S is the slope in per cent, C is the cultivation.

The R, L, and S in equation (1) and Fig. 2 are sub models that were estimated from empirical equations; while K, C, and P were derived from soil and land use maps.

Estimation of rainfall factor (R)

The power of rainfall to erode a soil is called erosivity (R); it depends on rainfall intensity and amount. High rainfall intensity will easily splash or remove top soil, and it can also cause mass movement. In USLE erosivity, (R) is empirically estimated as (Burrough & McDonnell, 1998):

$$R = 0.11abc + 66 \quad (2)$$

where *a* is the average annual precipitation in cm, *b* is the maximum day-precipitation occurring once in 2 years in cm, and *c* is the maximum total precipitation of shower of one year occurring once in 2 years in cm. In the tropics the best estimates of *a, b* and *c* are (Wielemaker & Boxen, 1982): 175.5 ± 20 cm, 5.41 ± 1.1 cm, 2.25 ± 0.5 cm, respectively.

In this study *a* (average annual precipitation) in equation (2) was estimated from annual rainfall values as shown on Fig. 1. It can be seen that average annual rainfall increases linearly from the coast to the northern mountainous part of the basin. Therefore, one dimension linear equation trend with y-coordinates of the map was fitted to estimate the rainfall values in GIS as:

$$a.map = 108.6 + 0.00843 * y\,\text{coordinate} \quad (3)$$

Parameters *b* and *c* in equation (2) were estimated as b = 5.41 cm, c = 2.25 cm for the mountainous northern part of the basin. In the rest of the study the parameters *a* and *b* were estimated by normalizing them to the northern parameters as:

$$\text{b. map} = \frac{\text{a}}{\text{mapmaximum (a.map)}} \times 5.41 \quad (4)$$

$$\text{c. map} = \frac{\text{a}}{\text{mapmaximum (a.map)}} \times 2.25 \quad (5)$$

where "mapmaximum(*a*.map)" is a PCRaster GIS operation computing maximum rainfall value from annual rainfall (a.map). Equations 4 and 5 produce "bs" (b.map) and "cs" (c.map) that linearly increase from the coast to reach the maximums at the mountainous part of the basin in the north.

By using equation (2) R factor was, therefore, estimated in PCRaster GIS as:

$$R.map = (0.11 * a.map * b.map * c.map) + 66 \quad (6)$$

Erosivity (*R* factor) map values therefore range from 100 cm in the south to 286 cm in the north (Fig. 3a).

Estimation of soil erodibility factor (K)

Soil erodibilty depends on soil and, or geological characteristics, such as parent material, texture, structure, organic matter content, porosity, catena and many more (Schwab, Fangmeier, Elliot, & Frevert, 1993). Erodibility factor must be estimated from field measurement or experiments, or through calibration or with Monte Carlo Simulation (Burrough & McDonnell, 1998). For less erodible soil K value of 0.1 ± 0.05 is acceptable and in GIS it can be considered a lumped parameter such as K = 0.1 or it can be estimated base on soil or geological groups (Table 1). In this study a look up Table 1 was used with soil groups of the basin to produce erodibilty (K) maps (Fig. 3b).

TABLE 1

K values for soils with different textures (Dion, 2002)

Sandy, fine sand, loamy sand	0.10
Loamy sand, loamy fine sand, sandy loam, loamy, silty loam	0.15
Loamy, silty loam, sandy clay loam, fine sandy loam	0.24
Silty clay loam, silty clay, clay, clay loam, loamy	0.28

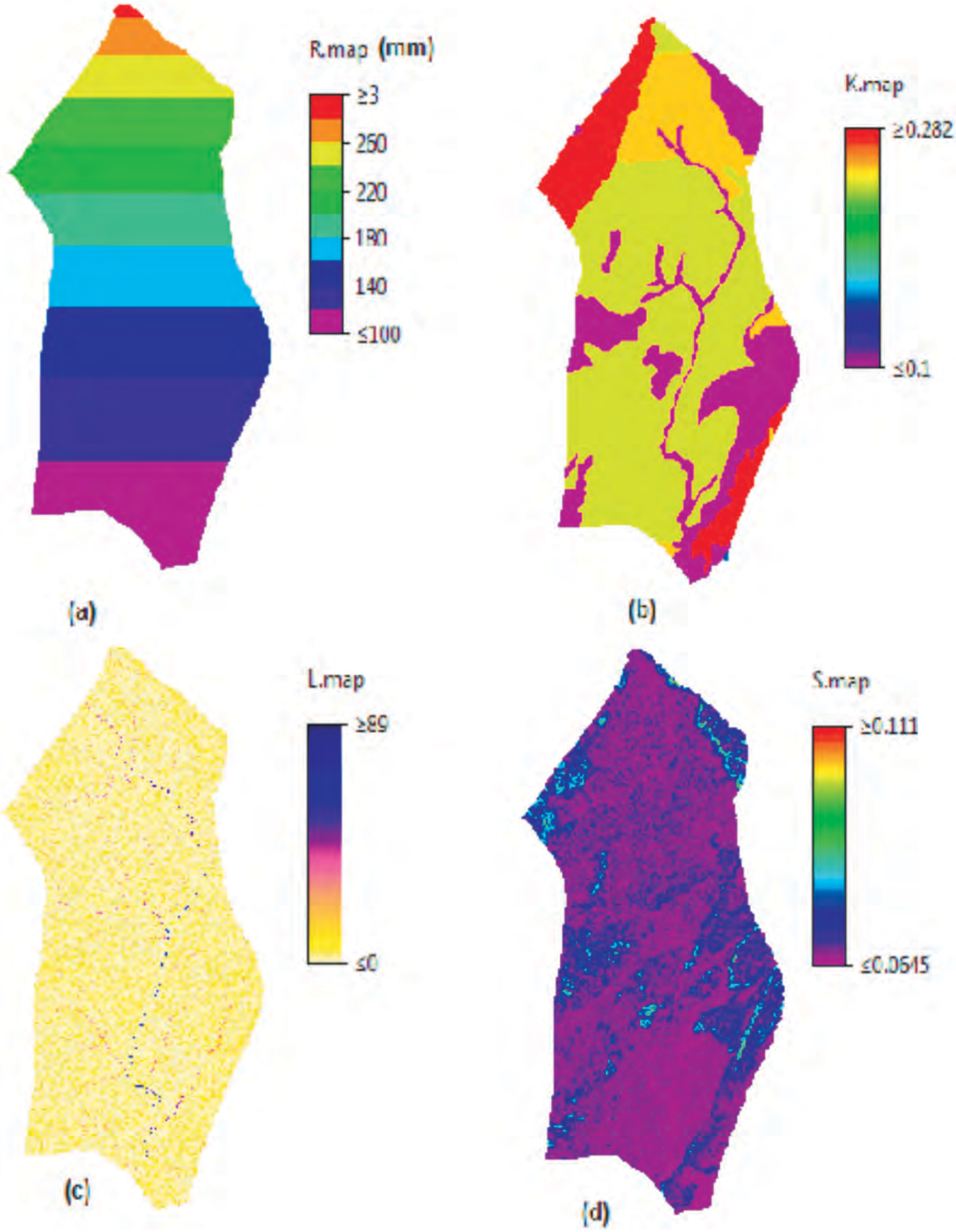

Fig. 3 Maps of estimated parameters of USLE (a) Erosivity, (b) Erodibilty, (c) Slope length and, (d) Slope Factor.

Slope length factor (L)

Slope length is the linear distance of a slope measured along its surface from a higher to a lower point elevation. In USLE, the L factor was estimated as (Burrough & McDonnell, 1998):

$$L = (l/22.1)^{0.5} \quad (7)$$

where l is the slope length in metres. The *L*.map (Fig. 3b) was calculated through three steps: (1) creation of DEM (Fig. 1); (2) creation of LDD and (3) creation of *L*.map, respectively. Local drain direction (*ldd*.map) of the basin was computed from *DEM* map using "lddcreate()" function in PCRaster as:

ldd.map - lddcreate (dem.map, 1E35, 1E35, 1E35, 1E35) (8)

The "1E35,1E35,1E35,1E35" is used to remove pits or sink holes in the DEM (Karssenberg, 1996). The function uses D8 (deterministic) algorithm to approximate the flow direction by the direction of steepest downhill slope within a 3 × 3 window of cells (Burrough and McDonnell, 1998). In GIS modeling L factor map was estimated along Local Drain Direction as:

$$\text{L. map} = \left(\frac{\text{slopelength(ldd,map,1}}{22.1} \right) *05 \quad (9)$$

The "Slopelength(ldd.map,1)" calculates slope length from the cells with no local drain direction to those areas with nominal value of 1. Local drain direction map was estimated according to the principle explained by Van Deursen (1995): "The current generation of geomorphologic landscape and catchment analysis tools for raster grids are all based on the concepts of the local drain direction (LDD). This concept analyses each cell in the DEM, and determines the slope in each of the eight directions connecting the cell to its neighbours.

For each grid cell the steepest downward direction defines the direction in which (potential) surface water from that cell would flow. This direction is called the local drain direction. The actual availability of surface water is not essential, the local drain direction is defined purely based on the slopes and slope directions in the Digital Elevation Model. The analysis is performed by placing a 3 × 3 window over the raster map, and by analysing this 3 × 3 window, the local drain direction for the centre cell can be found. If the local drain direction of the current cell is found, the 3 × 3 window is moved to the next cell."

Slope (S) factor

In USLE slope factor (S) is estimated as (*Burrough* and *McDonnell, 1998)*:

$$S = 0.0065s2 + 0.065 \quad (10)$$

where s is the slope in per cent.

In PCRaster GIS slope in per cent (slope.map) was estimated from DEM as (Fig. 3d):

S.map = 0.0065*slope.map**2+ 0.0454* slope.map+0.065 (11)

where slope.map is a map in per cent.

LS factor

RUSLE, as shown on Fig. 2, uses combination of L and S to estimate soil loss. The LS was estimated (Burrough & McDonnell, 1998) with sediment transport index () as:

$$\tau = [A_s / 22.13]^{0.6} * [\sin\beta / 0.0896]^{1.3} \quad (12)$$

where A_s is the contribution catchment area in m^2 (number of upstream elements multiply by the area of each grid cell) and is the slope measured in degrees.

In GIS, unlike USLE, RUSLE calculates LS in four steps that include estimations of DEM map, LDD map, upstream map and LS map (Fig. 2). Upstream map was estimated as:

upstream.map=acculux(ldd.map,1) (13)

The "accuflux" function in PCRaster sums the cell values of upstream cell(s), which is along the local drain direction map (ldd.map). PCRaster GIS command equivalent of equation (12) is:

LS.map=upstream.map*cellarea()/22.13)**0.6) * (sin(atan(slope.map))/0.0896)**1.3 (14)

The log distribution of LS.map clearly shows the path of the main river (Fig. 4c)

Crop management (C) factor

Crop management plays an important role in erosion control; different crops have different cover factors. In the tropics most farming practices are seasonal, this also affects crop cover in a year, and in some periods there is no crop cover where the land may be bare or weedy. The crop cover coefficient for maize is estimated at 0.63 ± 0.15 (Burrough & McDonnel, 1998). If there are different types of crops on a landscape the C factor can take different values. In this study C was considered as a parameter equaling the maize value of 0.63.

The protection (P) factor

The P factor is a management soil erosion control. It helps protect the top soil from erosion. It is intentional initiatives of the farmers to control erosion. The P factor can range from 0.01 in case there is almost maximum cover to 1, where there is no cover. The application of contour ploughing, for instance, can reduce P factor value to 0.1. In GIS P factor is estimated like C factor, either with a parameter or with distributed lookup table. In this study P factor value of 0.5 was used.

Results and discussion

USLE soil loss estimates

The total soil loss, estimated through USLE, for the study area is 756,507 t ha^{-1} yr^{-1}. The results of USLE on Fig. 4a and Table 2 show that soil loss in the basin is positively skewed, with minimum, maximum and average values of 0, 62, and 2.2 t $ha^{-1}yr^{-1}$, respectively. The R, S and L factors in equation (1) strongly influence spatial variability of USLE soil loss (Table 2).

The average soil loss of 2.2 t ha^{-1} yr^{-}1, relatively conforms well to other studies. In a similar study done in the tropics in Kissii area in Kenya, Burrough & McDonnell (1998) estimated soil loss of 23 t ha^{-1} yr^{-1} with R = 297 cm, K = 0.1, L = 2.13, S = 1.169, C = 0.63 and *P* = 0.5. In that study the estimated K, L, C and P factors correspond well with the average of this study of 2.9, 0.18, 0.63 and 0.5, respectively. However, their estimates of S and R are relatively higher than Densu basin's 0.06 and 178 cm, respectively. The most striking difference between their soil loss estimates of 23 t ha^{-1} yr^{-1} and this study's average of 2.2 t ha^{-1} yr^{-1} is the S factor. Substituting Densu basin's S factor into Kissii USLE model produced soil loss of 1.2 t ha^{-1} yr^{-1}. Kissii area in Kenya Mountains, with slope of about 11%, being steeper than Densu basin's 7% slope, registered a higher soil loss.

The reclassification USLE soil loss map (Fig. 4a) produces a detailed spatial variability of soil loss risk map of the basin (Fig. 4b). A very low risk soil loss is found in the southern part of the basin, and a very high

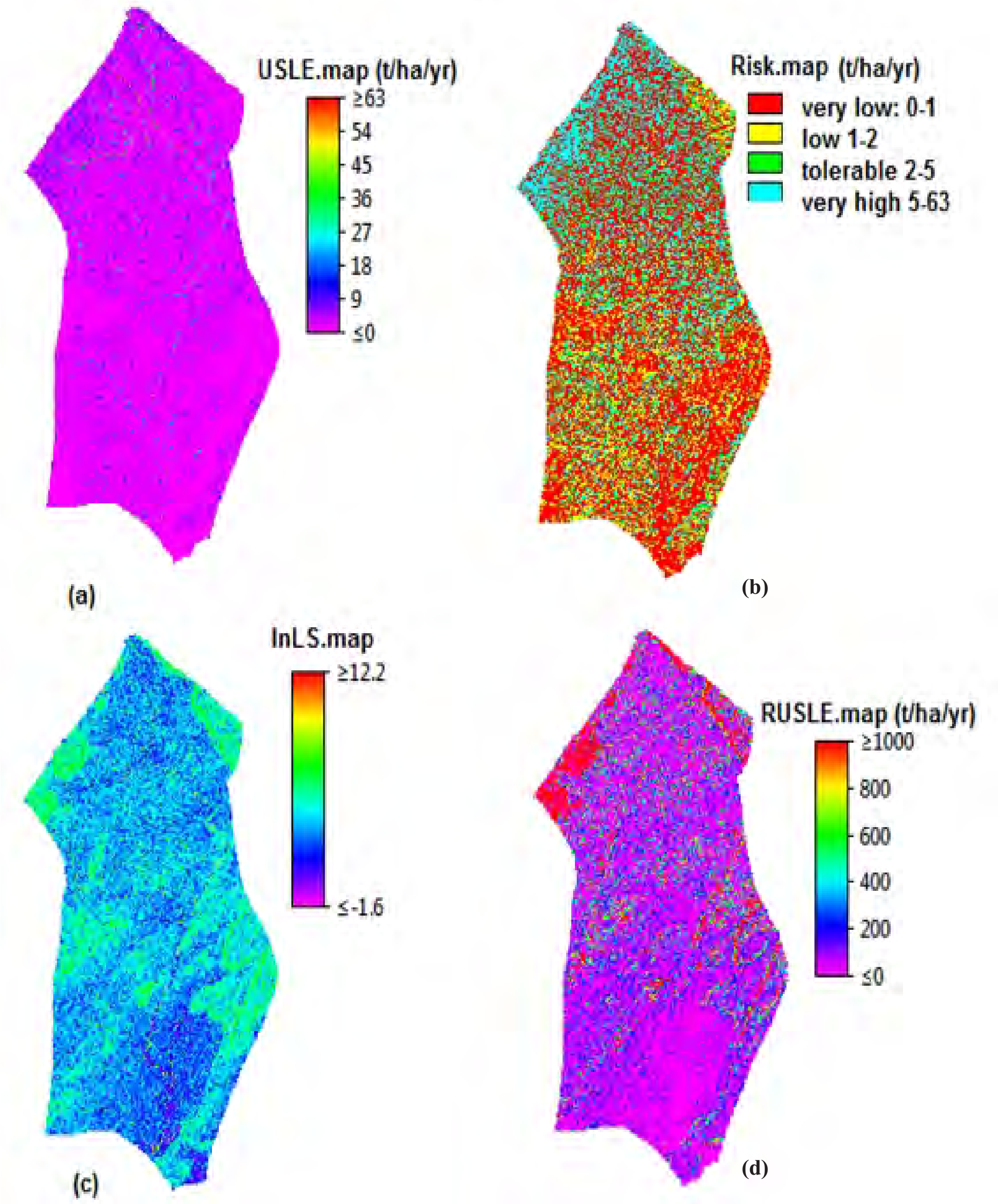

Fig. 4(a). Estimated USLE soil loss, (b) the USLE classified soil loss risk map, (c) the computed LS factor for RUSLE, (d) the estimated RUSLE soil loss of the basin

TABLE 2

Statistics of USLE soil loss estimation of the basin

Map	*USLE*	*R (cm)*	*K*	*L*	*S*	*C*	*P*
Minimum	0	100.4	0.1	0	0.06	0.63	0.5
Maximum	62.6	287	0.28	88.15	0.11	0.63	0.5
Average	2.19657	178	0.18	2.9	0.06	0.63	0.5
Total	756507	58990000	1.47	1002530	23539.4	0.63	0.5

soil loss risk is predominately in the northern mountainous areas, which registered soil loss more than 5 t ha^{-1} yr^{-1} tolerance level (Schertz, 1983). No area of the basin was masked because there was no area of the basin having slope higher than 30% (Renschler, Mannaerts, & Diekkrüger, 1999).

Soil conservationists are more interested in the erodibliblity of soil types; of the average soil loss of 2.2 t ha^{-1} yr^{-1} in the study area, Acrisols, Fluvisols and Luvisols were above the mean while Lixisols, Leptosols and Plinthosols were below it (Fig. 3b). In absolute terms, Lixisols and Plinthosols registered highest and lowest soil losses in the basin, respectively.

The government agencies such as district assemblies (Fig. 3) and municipal assemblies (Fig. 4) are more concerned about the rate of soil erosion in their region. Fig. 4 shows that Suhum, Kraboa and Coaltar district registered the highest rate of soil loss of 216,957 t ha^{-1} yr^{-1}. However, on areal average, Fantekwa in the mountainous northern part of the basin has the highest soil loss rate of 4.5 t ha^{-1} yr^{-1}. East Akim, Ga and Akim south also registered high annual soil loss rates of 166,059; 75,535; and 117,528 t ha^{-1} yr^{-1}, respectively. Other northern mountainous districts, such as East Akim and Kwaebibirem, registered high areal average soil loss of 3.6 and 2.4 t ha^{-1} yr^{-1}, respectively.

TABLE 3

USLE soil loss (t/ha/yr) per soil types of Densu basin

Soil	*USLE Total*	*USLE average*	*Average S*	*Average L*	*LS*
Lixisols	402080	2.1	0.067	2.62	0.18
Acrisols	123879	3.2	0.069	2.73	0.19
Leptosols	58411.7	0.96	0.071	2.76	0.2
Fluvisols	36616.8	2.47	0.067	7.5	0.5
Luvisols	133764	3.48	0.067	2.9	0.19
Plinthosols	64.3647	0.97	0.065	3.01	0.2
Solonotz	1684	0.63	0.067	2.88	0.2
No data	0	0	0.065	3.01	0.2

Forms of erosion

USLE results show various forms of erosion, and, in terms of process and forms, in the Densu basin, Rill or Sheet wash erosion occur on upstream gentle slopes with soil loss less than 1 t ha^{-1} yr^{-1} (Fig. 4a). Most of the rills in upstream of the study area on the map come together to form gully erosion that produced up to 30 t ha^{-1} yr^{-1} (Fig. 4a). The main Densu river induces channel erosion that produces about 50 t ha^{-1} yr^{-1} on the map (Fig. 4a).

TABLE 4

USLE soil loss (t/ha/yr) per district of Densu basin

District	*Total*	*Arial average soil loss*
Fantekwa	21810.1	4.5
East Akim	166059	3.6
Kwaebibirem	58.4	2.4
Yilo Krobo	9788.37	1.4
New Juabeng	68573.8	2.9
Suhum/Kraboa/Coaltar	216957	2.3
Akim North	27377.7	2.4
West Akim	18207.2	1.8
Akim South	75534.7	1.7
Tema Municipal Area	1909	1.7
Ga	117528	1.5
Awutu	29489.6	1.4
Accra Meteo	3207.9	1.3

Using RUSLE to estimate deposition areas in the Densu basin

USLE is known to underestimate soil loss (Mitasova *et al*., 1996). Revised Soil Loss Equation (RUSLE) replaces the hillslope length factor by upstream contributing area to estimate LS. However, RUSLE estimates low soil loss in the valleys and deposition areas (Fig. 4d). It can be seen from Fig. 4b that slope length ends where deposition areas begin. Fig. 4b can, therefore, help identify depositional areas in the basin.

Conclusion

Universal and Revised Soil Loss equations have been developed by using PCRaster GIS to estimate soil loss risk maps of the Densu basin. The mountainous areas of the basin exhibited high risk of soil loss that exceeded tolerance level of 5 t ha^{-1} yr^{-1}, and districts found on mountainous part of the basin are more erodible. Channel erosion dominates in the valleys of Densu river while there are also evidence of splash and rill erosion occurring upstream. Proper soil management can use these risk maps to make decision on soil conservation.

References

Abrahams R. and **Ampomah B**. (2010). *Improving the Ecological Health of the Densu Basin of Ghana.* Ghana Water Resources Commission, Accra.

Beskow S., Mello C. R., Norton L. D., Curi N., Viola M. R. and **Avanzi J. C**. (2009). Soil erosion prediction in the Grande River Basin, Brazil using distributed modeling. *Catena* **79** (1): 49–59.

Burrough P. A., and **McDonnell R. A.** (1998). *Principles of Geographical Information Systems*: Oxford University Press, London.

Commission W. R. (2011). *River Basin Activities. Retrieved* 19–08–2011, from Water Resources Commission of Ghana: *http://www.wrc-gh.org/riverbasinactivities.html*

De Roo A. P. J., Wesseling C. G. and **Ritsema C. J.** (1996). LISEM: a single-event physically based hydrological and soil erosion model for drainage basins. I. Theory, input and output. *Hydrol. Proces.* **10**: 1107–1117.

Dion T. R. (2002). *Land Development for Civil Engineers*. John Wiley & Sons, Inc. New York. .

Flanegan D. C., and **Nearing M. A.** (1995). *Water Erosion Prediction Project (WEPP) – Hillslope profile and watershed model documentation.* USDA-ARS National SoilErosion Research Laboratory, USA.

Jha M. K. and **Paudel R. C.** (2010). Erosion Predictions by Empirical Models in a Mountainous Watershed in Nepal. *J. Spat. Hydrol.* **10** (1).

Karssenberg D. (1996). *PCRaster Environmental Software. PCRaster Workbooks*. Faculty of Geographical Sciences, Utrecht University, The Netherlands.

Karssenberg D. (2002). *Building dynamic spatial environmental models* Utrecht University, Utrecht.

Mitasova H., Hofierka J., M. Zlocha M. and **Iverson L. R.** (1996). Modeling topographic potential for erosion and deposition using GIS. *Int. J. Geogr. Inf. Sci.* **10** (5): 629–641.

Mitasova H., Mitas L., Brown W. M. and **Johnston D.** (1998). *Multidimensional Soil Erosion/deposition Modeling and visualization using GIS*. University of Illinois, Urbana-Champaign.

Morgan R. P. C. (2001). A simple approach to soil loss prediction: a Revised Morgan-Morgan-Finney model. *Catena* **44**: 305–322.

Morgan R. P. C., Quinton J. N., Smith R. E., Govers G., Poesen J. W. A., Auerswald K., Chiscl G. and **Torri D.** (1998). The EUROSEM model. In *Global Change: Modelling soil erosion by water,* (Vol. 1). (J. B. D. Favis-Mortlock, ed.), pp. 373–382. Springer-Verlag, London.

Ramos M. C. and **Martínez-Casasnovas J. A.** (2006). Erosion rates and nutrient losses affected by composted cattle manure application in vineyard soils of NE Spain. *Catena.* **68** (2–3): 177–185.

Renard K. G., Foster G. R., Weesies G. A. and **Porter J. P.** (1991). RUSLE: Revised Universal Soil Loss Equation. *J. Soil Wat. Conser.* **46** (1): 30-33.

Renschler C. S., Mannaerts C. and **Diekkrüger B.** (1999). Evaluating spatial and temporal variability in soil erosion risk—rainfall erosivity and soil loss ratios in Andalusia, Spain. *Catena* **34** (3–4): 209-225.

Rodríguez J. L. G. and **Suárez M. C. G.** (2010). Estimation of Slope Length Value of RUSLE Factor *L* Using GIS. *J. Hydrologic Engng* **15**(9): 714–717.

Schertz D. L. (1983). The basis for soil loss tolerances. *J. Soil Wat. Conserv.* **38** (1): 10–14.

Schwab G. O., Fangmeier D. D., Elliot W. J., and **Frevert R. K.** (1993). *Soil and water conservation engineering*. John Wiley & Sons, Inc, New York, USA.

Sthiannopkao S., Takizawa S., Homewong J. and **Wirojanagud W.** (2007). Soil erosion and its impacts on water treatment in the northeastern provinces of Thailand. *Envir. Int.* **33**(5): 706–711.

Van Deursen W. P. A. (1995). *Geographical Information Systems and Dynamic Models: development and application of a prototype spatial modelling language.* Utrecht University, Utrecht.

Wischmeier W. H., and **Smith D. D.** (1978). *Predicting rainfall erosion losses: a guide to conservation planning*: USDA-ARS, USA.