

# Determination of Soil Erosion and Sediment Yield in the Bonsa River Basin Using GIS and Revised Universal Soil Loss Equation (RUSLE)\*

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Asare A. and Boye, C. B. (2021), "Determination of Soil Erosion and Sediment Yield in the Bonsa River Basin Using GIS and Revised Universal Soil Loss Equation (RUSLE)", *Ghana Mining Journal*, Vol. 21, No. 2, pp. 1-11.

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## Abstract

The Bonsa river is an important tributary of the Ankobra river in the Western Region of Ghana. The catchment of the Bonsa river has been undergoing rapid land cover changes due to human activities such as farming, illegal mining, population growth, among others which are likely to promote soil erosion and sediment yield in the river basin. To estimate the amount of soil eroded over a period and subsequent sediment yielded along the Bonsa river basin, the Revised Universal Soil Loss Equation (RUSLE) was integrated with Geographic Information System (GIS) to model the spatial distribution patterns in soil erosion and sediment yield within the catchment. Data used included annual rainfall records, soil map, Digital Elevation Model (DEM) and land-use map of the study area. Parameters of the model were determined and converted into raster layers using the raster calculator tool in ArcMap to produce a soil erosion map. The concept of Sediment Delivery Ratio (SDR) was applied to determine the annual sediment yield by combining a raster SDR layer with soil erosion map. The predicted soil loss and sediment yield values were found to be low. This may be due to high soil protective cover provided by vegetation as well as low topographic relief in the river basin. Though, the elements and processes responsible for soil erosion and sediment yield prevailing in the basin was found to be low, adverse situations could be developed with time if the prevailing conditions are not checked, as soil erosion is a natural gradual slow process. The gains made could be sustained by putting measures in place to control human activities, particularly, illegal mining (*galamsey*) in the basin, indiscriminate cutting down of trees and farming activities along the Bonsa river basin. This study will support monitoring, planning of water resources and help to improve sustainable water quality.

**Keywords:** Soil Erosion, Sediment Yield, Geographic Information System

## 1 Introduction

Measurement of soil erosion and sediment yield have become increasingly crucial in order to monitor, sustain, and maintain soil and water ecology and quality as a result of human activities and their effects on the environment and the globe at large (Patil *et al.*, 2014). The Bonsa river is one of the important tributaries of the Ankobra river in the Western Region of Ghana. The catchment of the Bonsa river is undergoing rapid land cover changes as a result of human activities such as illegal mining, farming, cutting down of trees, among others. One of the main causes of land cover change is rapid population growth. As population grows, the need for farmlands and other amenities such as roads, industries and buildings increase, subjecting the land to gradual degradation. Also, human activities such as cutting down of trees for firewood, furniture and charcoal also contribute to the rampant clearing of the vegetation. When the vegetation is cleared by these human activities, the topsoil of the land is left bare and gets exposed to erosion particularly when rain falls.

Another cause of land cover change is mining activities. The Bonsa river, which serves as the main water source for most parts of the Tarkwa Nsuaem Municipality, has been exposed to open pit surface

mining and illegal small-scale mining (*galamsey*) activities. The activities of these illegal miners do not only disturb the soil particles but also exposes them to erosion. This causes the soil particles such as silt to move into the water body through rigorous action of the illegal miners resulting in turbidity of the water. Some effects caused by the illegal miners on the environment include pollution and destruction of aquatic ecology, erosion of the topsoil which exposes the bare soil and results in the formation of gullies and loss of soil fertility. Aside from these, illegal small-scale mining also affects the quality of water supply and the country's economy, as large sums of money are required to treat the water to make it potable. According to existing research, over a 21-year study period, there is a report of vegetative loss of 932.92 km<sup>2</sup> as a result of mining activity in the area at a rate which is very alarming if left to continue (Kumi-Boateng *et al.*, 2012) and hence the need to determine the amount of soil erosion and sediment yield in the Bonsa river.

Soil erosion is the detachment and movement of topsoil or soil material from the upper part of the soil profile by wind, water and glaciers (Buydos, 1988; Zachar, 2011). Soil erosion is a naturally occurring slow process which can be alarming if left unrestrained. In humid areas, water is the most likely effective agent of soil erosion (Mantey and Aduah, 2020). Sediment yield, on the other hand, is the total

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\*Manuscript received August 10, 2021

Revised version accepted December 14, 2021

<https://dx.doi.org/10.4314/gm.v21i2.1>

amount of solid particles that are transported and deposited by a river through the outlet within a specific period (Boakye *et al.*, 2018). Soil erosion and sediment yield occur when rain droplet splashes the ground and the dislodged topsoil is transported and deposited at another place within a specific period.

Several studies have been conducted in the past (Kusimi *et al.*, 2015; Mantey and Aduah, 2020; Fernandez *et al.*, 2003). Kusimi *et al.* (2015), studied soil erosion and sediment yield modelling in the Pra river basin of Ghana using RUSLE. Mantey and Aduah (2020) determined the soil erosion vulnerability in the Lafa basin of Ghana using RUSLE and GIS, and Marques da Silva *et al.* (2014) also predicted the soil erosion and sediment yield in the Tapacurá catchment with minimal accuracy. Some of the rivers considered in these studies were only rivers with large basins. However, rivers with relatively smaller drainage basins are as important as those with large drainage basins (Milliman and Syvitski, 1992; Boye *et al.*, 2019). Smaller river basins have less area for sediment storage and therefore their sediment yield is said to increase as much as sevenfold for each magnitude decrease in basin area (Milliman and Meade, 1983). This study therefore applied RUSLE and GIS techniques in modeling soil erosion and sediment yield along the relatively small Bonsa river basin.

The RUSLE method is relatively fast, widely used, effective and efficient tool for predicting long term soil erosion assessment, analyzing continuous and raster data, and a good estimator of spatially distributed soil erosion and sediment yield (Fernandez *et al.*, 2003). Also, this method is used because there are a lot of illegal mining (*galamsey*) activities happening in the vicinity, causing soil erosion and turbidity of the river. This study sought to determine the rate at which the soil is being eroded and the amount of sediment yielded by the Bonsa river.

### 1.1 The Study Area

The Bonsa River flows through Tarkwa Nsuaem Municipality in the Western Region of Ghana, with Tarkwa as its municipal capital. The Bonsa catchment is located between latitudes 5° 00' and 5° 40' N and longitudes 1° 50' and 2° 10' W. The municipality covers an area of approximately 905.2 Km<sup>2</sup>. Fig. 1 shows the map of the study area.

The Bonsa River and its tributaries, which include the Buri, Anoni, Sumin, and Ayiasu rivers, have a dendritic pattern. The Bonsa catchment has generally low relief, with elevations ranging from 30 to 340 m above mean sea level, and it drains an area of 1 482 Km<sup>2</sup> (Aduah *et al.*, 2015). The municipality

falls within the forest dissected plateaus physiographic region (Appau, 2016). The area of the municipality is generally undulating with few scraps ranging between 150 m to 300 m above sea level.

The municipality of Tarkwa-Nsuaem has one of Ghana's highest rainfall patterns. It has a mean annual rainfall of about 187.83 mm. The rainfall regime is bimodal, ranging from 1 578 mm to 1 982 mm per year. The annual average minimum and maximum temperatures are 22 °C and 32 °C, respectively. Thick evergreen and secondary forests predominate, with scattered shrubs and farms (Aduah *et al.*, 2015). The municipality of Tarkwa-Nsuaem is located in the south-western equatorial climatic zone. Climbers and lianas that can reach the upper tree layer abound in the forest. Mahogany, wawa, odum, and sapele are examples of economic trees. Tarkwa-Nsuaem has large forest reserves such as the Bonsa reserve, Ekumfi reserve, Neung south reserve, and Neung north reserve, as well as high relative humidity of 70-80 percent all year (Samlafo and Ofoe, 2017).

The geology of the basin is characterised by Birimian and Tarkwaian rock systems, and the soil is primarily composed of Ferric Acrisols, according to the Food and Agricultural Organizations' (FAO) soil classification system, and forest oxysols, according to the Ghana soil classification system. Tarkwa Nsuaem Municipality has a population of about 90 477 representing 3.8% of the Western regional population according to the 2010 population and housing census. The sex distribution of the population indicates that there are more males (51.6%) than females (48.4%). The municipality is predominantly rural with 69.7% of its population residing in the rural areas (Anon., 2014). The Municipality has a very good proportion of the working age group that is 15 – 64 years. The dependency ratio is about 83.1% meaning less pressure on the workforce. The Economically active population is 68% with 63% employed and 5% unemployed. The remaining 32% who are economically inactive are homemakers, students, too old or young to work, feast pensioners or disabled (Anon., 2016).

The major occupation found in the Tarkwa Nsuaem Municipality are open-pit gold mining, quarry, agriculture such as rubber cultivation, small-scale cocoa and food crop production and among others.

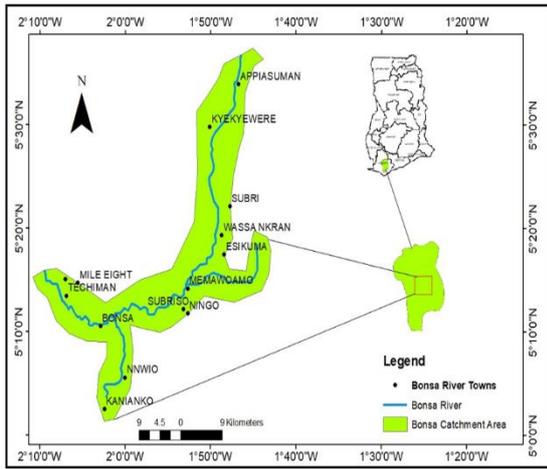


Fig. 1 A Map of the Study Area

## 2 Resources and Methods Used

The following materials and methods were used:

### 2.1 Data Used

The input datasets used to generate parameters for the RUSLE and SDR formulas include: Annual rainfall data, Soil map, Digital Elevation Model (DEM) of the study area and Land use map. The input data for the conceptual model of the RUSLE include: soil, rainfall, and DEM and its derivative slope map. The following maps were generated from the input data: Topographic Factor (LS), Conservation Practice Factor (P), Rainfall and Runoff Erosivity Factor (R), Soil Erodibility Factor (K) and Cover and Management Factor (C). The soil erosion map was then combined with the sediment delivery ratio (SDR) to derive the sediment yield map.

### 2.2 Methods Used

The RUSLE and SDR together with GIS were used to achieve the objectives as demonstrated in Fig. 2.

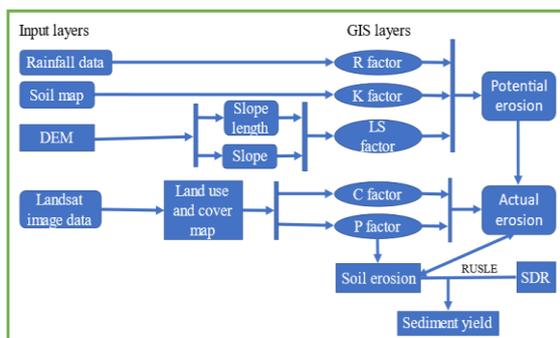


Fig. 2 A Flow Chart Showing the Methods Used

### 2.2.1 Estimation of Annual Soil Loss Using RUSLE

The RUSLE is defined mathematically as shown in Equation (1).

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

where:

A, is the annual soil loss (t/ha/yr.);  
R, the rainfall run-off erosivity factor (MJ mm ha/h/yr);  
K the soil erodibility factor ( $t \text{ h MJ}^{-1} \text{ mm}^{-1}$ );  
LS the slope length and steepness factor;  
C, the vegetative cover factor; and  
P, the conservation practice factor.

The LS, C and P factors are dimensionless.

Raster maps of the parameters of RUSLE formula were generated. The raster maps were multiplied using the raster calculator tool in ArcGIS to generate soil erosion maps of cells depicting varying magnitude of soil loss along the Bonsa river. The approach for deriving each parameter is discussed below.

#### Estimation of Rainfall Erosivity Factor

The ability of rainfall to erode a soil is called erosivity (R) and it depends on rainfall intensity and amount. Rainfalls with high intensity are more likely to easily splash or remove top soil and can also cause transportation and deposition of top soil. In ArcGIS, rainfall map of the study was generated using Inverse Distance Weighting (IDW) interpolation technique from the acquired rainfall data. R factor was generated with the equation according to Lee and Kang, (2013) as shown in Equation (2):

$$R = 38.5 + 0.35 * Pr \quad (2)$$

With the help of raster calculator where Pr is the average annual precipitation of the study area.

#### Estimation of Topographic Factor

The topographic factor (LS) was estimated in the following steps using the DEM of the study area. The DEM of the area was generated using the mosaic to new raster tool of the Arc tool box. Slope was generated in degrees with slope tool using the DEM as input layer. Fill was also generated with the fill tool using the DEM. Flow Direction map was calculated using flow direction tool with the fill as the input while Flow Accumulation was estimated with flow accumulation tool, using the flow direction map as input. LS factor was then calculated using Equation (3) according to Mantey and Aduah (2020):

$$LS = Pow \left( [flow\ accumulation] * \frac{resolution}{22.1,0.4} \right) * pow \left( \sin \left( \frac{slope\ of\ the\ DEM}{0.09,1.4} \right) * 1.4 \right) \quad (3)$$

where, pow means power in the raster calculator of the spatial analysis tool.

#### Estimation of the Soil Erodibility Factor

The Food and Agricultural Organisation classification system of the K factor values of soils found around the basin were used to produce a raster layer of K factor map from the acquired soil map of the study area to shows how susceptible groups of soil found around the basin are to erosion (Tables 1 and 2).

**Table 1 K Factors of the Soil**

Soil Types	K Factor Values
Acrisols	0.005 – 0.015
Fluvisols	0.0646
Ferralsols	0.0280

(Source: Kusimi *et al.*, 2015)

**Table 2 Soil Erodibility Classification**

Soil Erodibility Classes	Soil K Factor Values
Very High	> 0.70
High	0.50-0.70
Moderate	0.25-0.50
Low	0.13-0.25
Very Low	< 0.13

(Source: Hagos, 2004)

#### Estimation of Crop Management Factor

The crop management factor was used to determine the erosion caused by the land cover. Normalized Difference Vegetation Index (NDVI) was derived from the Landsat 8 images. NDVI was calculated using Equation using the raster calculator as shown in Equation (4):

$$NDVI = (NIR - Red) / (NIR + Red) \quad (4)$$

where NIR and Red are the near-infrared and red bands of the Landsat 8 images of the study area. For Landsat 8, the near-infrared (NIR) band corresponds to band 5, and the red band (Red) corresponds to band 4. In this study, the formula used to calculate the coefficient of erosion by C factor is provided in Equation (5) according to Balabathina *et al.* (2020) using raster calculator:

$$C\ factor = exp \left[ -\alpha * \frac{NDVI}{(\beta - NDVI)} \right] \quad (5)$$

where  $\alpha = 2$  and  $\beta = 1$ .

#### Estimation of Conservational Practice Factor

The P factor is a support or management soil erosion control. It aids shield the top soil from erosion. The P factor ranges from 0.01 to 1 implying in a case where there is almost maximum cover to where there is no cover. The application of contour ploughing, wind breaks and crop rotation can reduce P factor value to 0.1. In ArcMap, the P factor was generated as follows:

Land use data was used to generate a land use map. Slope map was created in degrees with slope tool. Classification was done using reclassify tool. The map was then converted from raster to polygon.

The conservational practice factor is calculated based on the relation between terrain and slope of the Bonga basin. The map was then converted back to raster. The P factor map was then generated.

#### 2.2.2 Estimation of Annual Sediment Yield Using RUSLE and SDR

The annual sediment yield of the watershed was estimated by multiplying the soil loss map and the sediment delivery ratio map as expressed by Equation (6) according to Kusimi *et al.* (2015):

$$Y = A \times SDR \quad (6)$$

where:

Y is the sediment yield (t/ha/yr);  
SDR is the sediment delivery ratio; and  
A is the RUSLE (gross erosion per unit area above a measuring point).

SDR is defined as the ratio of sediment delivered at a given area in a stream system (sediment yield) to the gross erosion or the fraction of gross erosion that is transported from a given catchment in a given time interval. For each land cell, SDR depends upon several physical characteristics of the watershed including surface roughness, land slope, soil hydrologic conditions, and length of the travel path (flow length) to the stream and vegetative cover (Borselli *et al.*, 2008; Bahremand, *et al.*, 2007). The sediment delivery ratio for each cell<sub>i</sub> (SDR<sub>i</sub>) is a function of travel time.

$$SDR_i = exp(-\beta t_i) \quad (7)$$

where:

t, is the travel time for each cello to the nearest channel cell down the drainage path; and  
 $\beta$  is a watershed-specific parameter regarded constant.

The total travel time along a flow path is expressed as in Equation (8):

$$ti = \sum_{i=1}^m \frac{li}{vi} \quad (8)$$

where:

$l_i$  is the flow length (i.e., the length of each segment) in the flow path (m), which is equal to the length of the side or diagonal of a cell depending on the flow direction in the cell; and

$v_i$  is the flow velocity for the cell (m/s).

Flow velocity is derived from Manning's equation which is a function of the land surface slope and the land cover characteristics.

$$vi = aiSi^{0.5} \quad (9)$$

where:

$S_i$  is the slope of the  $i$ th cell; and

$ai$  is a land use coefficient.

The final flow velocity for the overland flow was estimated. Sediment yield falls within a  $\beta$  range of 0.1 to 1.5 with an incremental value of 0.1 and it was found that sediment yield was insensitive to  $\beta$  value so  $\beta$  value was taken as 1 for computation.

#### Estimation of Flow Length

Slope was generated in degrees with slope tool using the DEM as input layer. Fill was also generated with the fill tool using the DEM. Flow Direction map was calculated using flow direction tool with the fill as the input while Flow length was generated and estimated with flow length tool, using the flow direction map as input.

#### Estimation of flow Velocity

The flow velocity was obtained by multiplying the assigned land cover map by the square root of slope for each grid cell using the raster calculator tool in ArcMap as shown in Equation (9).

### 3 Results and Discussion

#### 3.1 Estimation of Annual Soil Erosion

The following are the results and discussion for the parameters of RUSLE to estimate the annual soil loss.

##### 3.1.1 The Topographic Factor

The results obtained from the topographic factor is shown in Fig. 3. From the figure, the values for the LS factor for most parts of the Bonsa river basin (coloured yellow) had low values with a mean of 0.06, giving an indication that the terrain of the basin is fairly flat with very few elevated portions (blue patches).

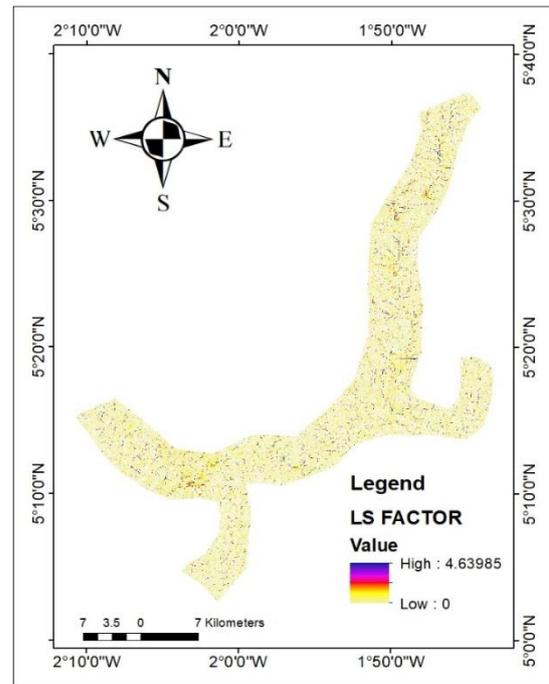


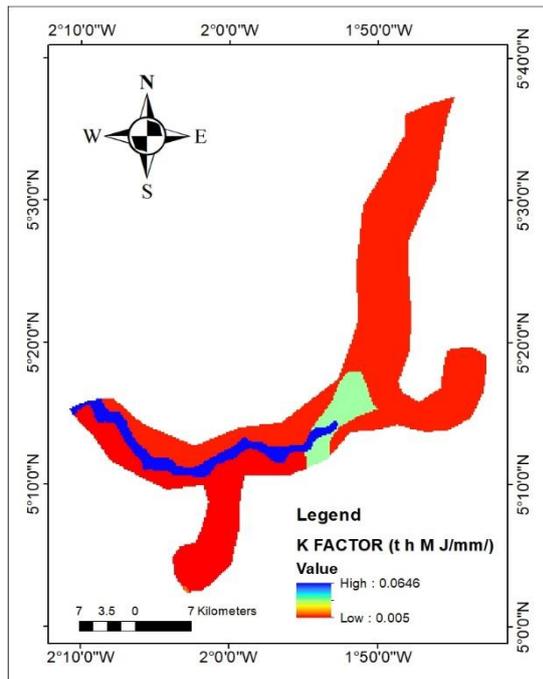
Fig. 3 LS Factor

The low topographic slope of the basin makes it difficult for movement of detached soil particles to be transported from the basin, thus the effect of topography on soil erosion in the basin is very minimal.

The LS factor, which consists of slope length and slope angle, is the ratio of soil loss at the Bonsa basin to that of a site with standard slope of 9% and slope length of 22.1 m (Das *et al.*, 2021). It shows how terrain undulations influence soil erosion, thus the longer and steeper the slopes in the topography, the higher the risk for soil erosion.

##### 3.1.2 The Soil Erodibility Factor (K)

The results obtained for the soil factor is shown in Fig. 4. The K factor describes the susceptibility of the type of soil found around the study area to erosion according to their permeability, organic matter content and many more which affects the K factor.

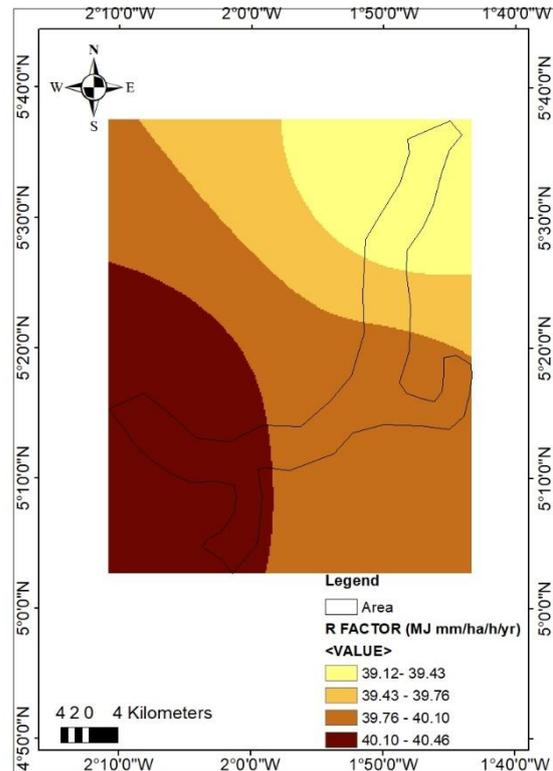


**Fig. 4 K Factor**

From Fig. 4, the K factor of the study area ranges from 0.005 - 0.065  $t h MJ^{-1} mm^{-1}$ . The study area is underlain by three major soil types (acrisols, ferralsols and fluvisols), with acrisols having erodibility values of 0.005 and fluvisols being the most erodible ( $0.065 t h MJ^{-1} mm^{-1}$ ). The red part is the acrisols, the lemon green part is the ferralsols and the blue is fluvisols part. The most erodible soils (fluvisols) are concentrated along the river valleys, thus soil erosion due to the vulnerability of the soil type would be limited to the valleys only. From the legend of Fig. 4, the erodibility of the ferralsols has intermediate while the Acrisols found in the study area, which covers over 70% of the site, are classed as having very low erodibility when exposed.

### 3.1.3 The Rainfall Erosivity Factor

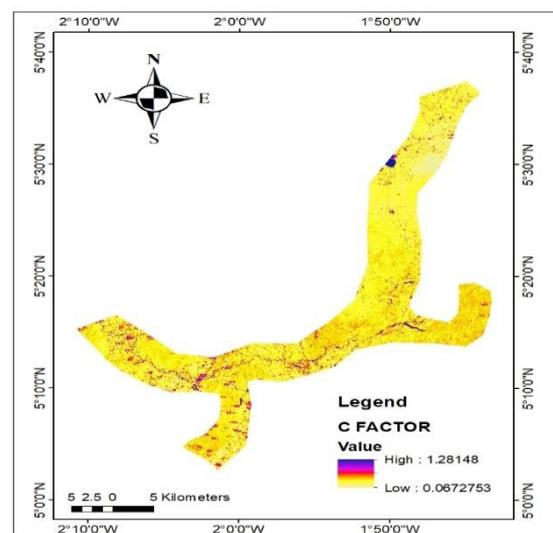
Fig. 5 shows the result obtained for the rainfall erosivity factor. The R factor has a direct relationship with the precipitation values in the catchment area. From Fig. 5, the R values range from 39.12 – 40.46  $M J mm/ha/h/year$  with a mean R value of about 40  $M J mm/ha/h/year$  which is one of the highest in the country. Generally, high amount of precipitation is recorded in the study area. It can be seen from Fig. 5, that the R values increase slightly from the northeastern part of the study area to the southwestern, where the highest R values are recorded. The greater the intensity and the duration of the rainfall, the higher the erosion potential and this varies with geographic location. Zones of high erosivity will be more erosive due to the higher intensity of rainfall events.



**Fig. 5 R Factor**

### 3.1.4 The Crop Management Factor

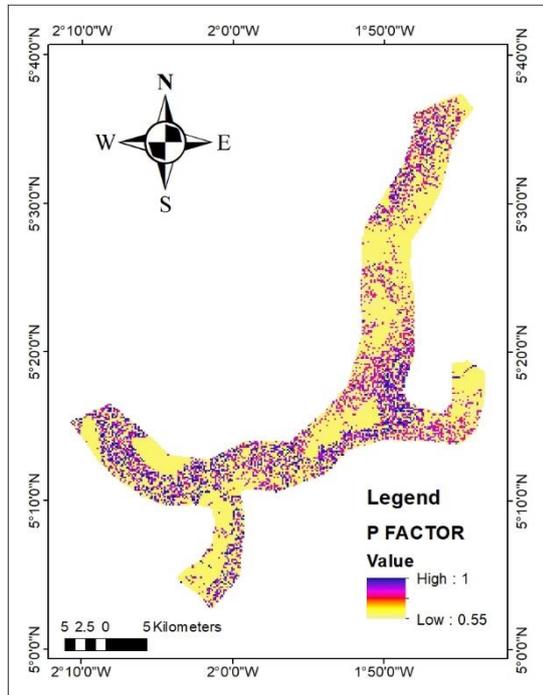
Fig. 6 shows the crop management factor obtained from the study. The C factor varies from 0.067 to 1.281 with most parts of the study area recording low values corresponding to the yellow colour in Fig. 6. Low C factor values of about 0.07 correspond to a denser vegetation cover with few high values (blue patches) of 1.28 which matches with barelands. The C factor is an important factor with regard to policy and land use decisions which can be managed to reduce erosion (Panagos *et al.*, 2015).



**Fig. 6 C Factor**

### 3.1.5 The Conservation Practice Factor

The results obtained for the conservation practice factor is shown in Fig. 7. The P factor ranges from 0.55 – 1. The P factor reflects the land use and land cover of the basin.

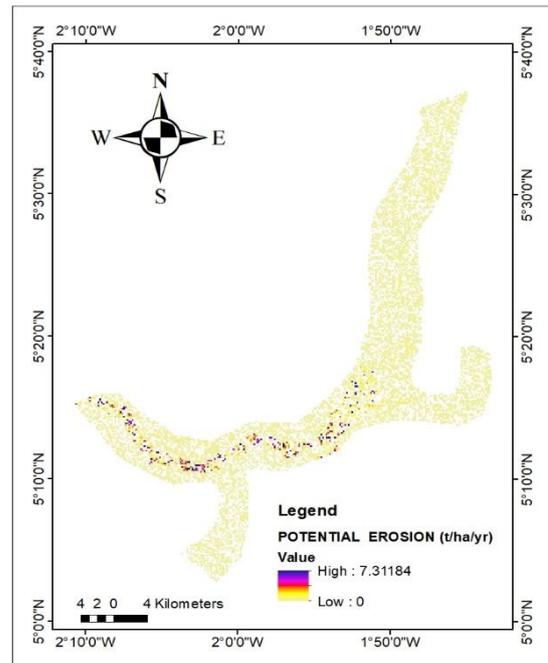


**Fig. 7 P Factor**

The study area was observed to have medium to high P factor values. This shows that the vegetation in the study area is more than the bare lands or built-up areas and hence the risk of the study area to erosion can be low.

### 3.1.6 Potential Erosion

The results obtained for the potential erosion is shown in Fig. 8.

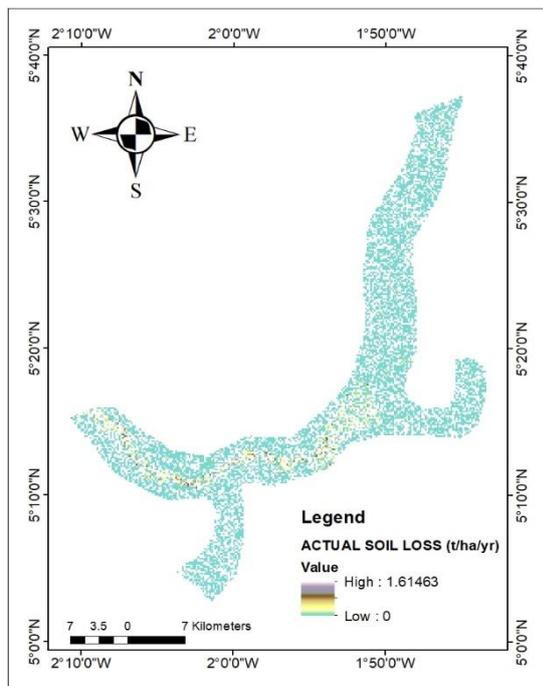


**Fig. 8 Potential Erosion**

From Fig. 8, the potential erosion has a range of 0 – 7.31 t/ha/yr with the locations shown as blue and purple patches recoding high values. These parts also correspond with the fluvisol soil group having the highest erosion potential followed by the ferrasols.

### 3.1.7 Actual Soil Loss /Erosion

Fig. 9 shows the results obtained for the actual annual soil loss. The annual soil loss estimated ranges from 0 - 1.615 t/ha/yr from each cell which is low. Comparing the value of soil loss to the classification scheme of Food and Agricultural Organisation (1967) according to Silva *et al.* (2010) in t/ha/yr: < 10 = very low, 10 - 50 = moderate, 50 - 120 = high, and > 120 = very high, the catchment is characterized by very low soil loss risk. The low soil erosion risk is due to the well protected terrain by vegetative cover and low gradient of the topography. Areas prone to moderate to high erosion risks are very few and these may occur in *galamsey* site where the soil is exposed and also along steep slopes and within the river valleys underlain by fluvisols which are very susceptible to erosion.



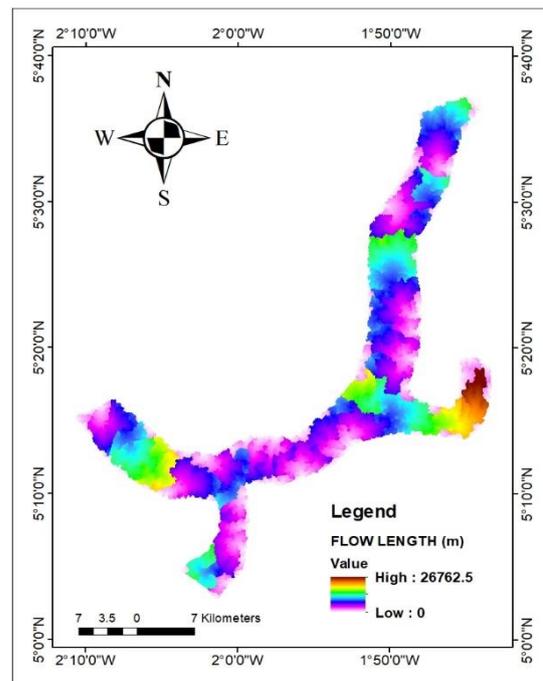
**Fig. 9 Actual Annual Soil Loss**

### 3.2 Estimation of Annual Sediment Yield

The following shows the results and discussion of the parameter used to determine the SDR and the final combination of the SDR and the RUSLE to estimate the annual sediment yield by the Bonsa river.

#### 3.2.1 The Flow Length (li)

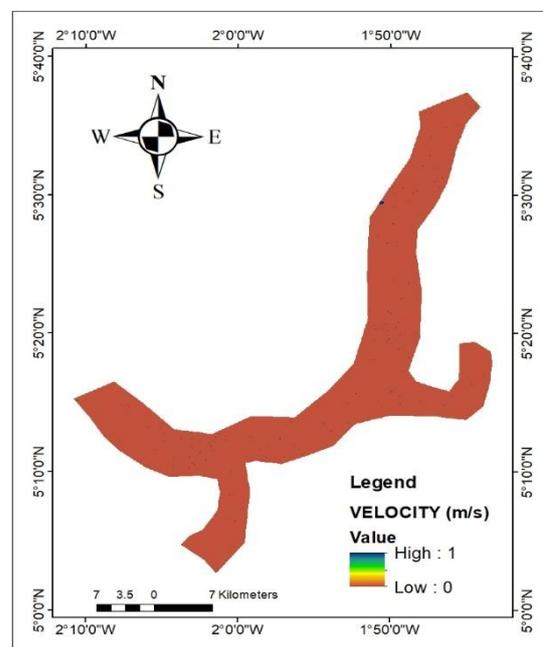
The results obtained for the flow length is shown in Fig. 10. The flow length for each cell of the flow path ranges from 0 – 26 762.5 m. A greater part of the study area has it flow length cells ranging from low to medium.



**Fig. 10 Flow Length**

#### 3.2.2 The Flow Velocity (vi)

The results obtained for the flow velocity is shown in Fig. 11.

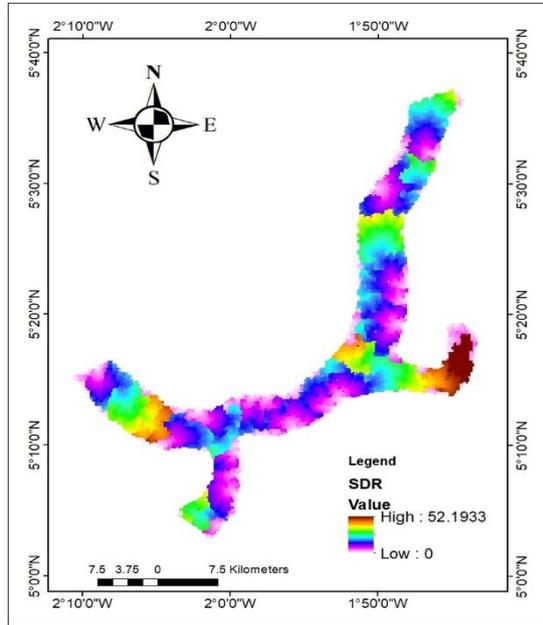


**Fig. 11 Flow Velocity**

The flow rate or velocity of each cell ranges from 0 -1  $\text{ms}^{-1}$ . zero shows areas with no or less flow and one show a higher possibility of flow.

### 3.2.3 The Sediment Delivery Ratio (SDR<sub>i</sub>)

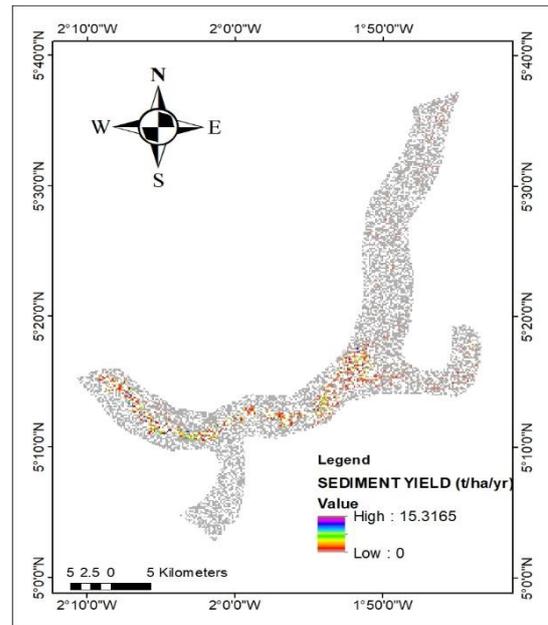
The results obtained for the Sediment Delivery Ratio is shown in Fig. 12. The Sediment Delivery Ratio (SDR<sub>i</sub>) for each cell of the travel time ranges from 0 – 52.193. A greater part of the study area has its SDR<sub>i</sub> cells ranging from low to medium.



**Fig. 12 SDR<sub>i</sub>**

### 3.2.4 The Annual Sediment Yield

The results obtained for the annual sediment yield is shown in Fig. 13. The Annual Sediment Yield was estimated to be in the ranges of 0 – 15.317 t/ha/yr which is low. Higher Sediment Yield values may result in areas with steep slope and low sediment yield values may be as a result of the vegetative cover.



**Fig. 13 Annual Sediment Yield**

## 4 Conclusions and Recommendations

### 4.1 Conclusions

The study has demonstrated an effective combination of RUSLE and GIS in mapping the spatial patterns in soil erosion and sediment yield. The soil loss and sediment yield derived for the Bensa river basin were predicted to be generally very low. This was attributed to presence of vegetative cover and low topographic slope gradient at the study area. Areas which were predicted to have a higher soil loss and sediment yield in this study were areas with higher rainfall intensity, steeper slope, bare lands and river valleys underlain by fluvisols which are susceptible to erosion. Although soil loss and the sediment yield were predicted to be very low, it could become severe if illegal small-scale mining and indiscriminate clearing of the vegetation is allowed to continue in the area as these human activities can promote soil erosion which will increase the amount of sediment yield.

### 4.2 Recommendations

The authors recommend that measures like green projects should be put in place by state institutions to protect the vegetative cover of river basins to conserve water and soil ecology. Further studies should also be conducted by using artificial neural network to model soil erosion and sediment yield for planning and monitoring of soil loss and sediment yield by rivers.

## Acknowledgements

The Authors are grateful to the Department of Geomatic Engineering of the University of Mines and Technology, Tarkwa for their support.

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