Soil Erodibility Assessment for Erosion Management in Sokoto State, Nigeria

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Abstract
The large scale erosion and flooding experienced in Sokoto state and environs in 2010 left scars of gullies in some areas that have continued to grow in magnitude. Thus, this study aimed at assessing soil erodibility ($K_{fac}$) in the study area as a component of a larger study targeted at sustainable erosion management. Soil properties were obtained from 75points covering the study area:55 randomly dug soil profiles and 20 purposively selected points from the World Harmonized Soil Database (WHSD). Particle size was determined by the Bouyoucos hydrometer method, while Soil Organic Matter (SOM) was determined by Walkley-Black method. $K_{fac}$ was determined by Zwischmeier and Smith method, while saturated hydraulic conductivity ($K_{sat}$) was derived using Cosby’s Pedotransfer function. Soil structural index was based on textural classification of Ontario Centre for Soil Resource Evaluation. Inverse Distance Weighting (IDW) was used to interpolate values of soil variables within ArcGIS 10.2.2, while soil texture was mapped within QGIS 3.4. Contribution of predictors to $K_{fac}$ was also modeled in QGIS 3.4 using multiple linear regression. Results showed that the study area is characterized by sandy clay (5.10%), sand (10.11%), loam (12.50%), loamy sand (22.51%) and sandy loam (49.78%). About half (48.31%) of the study area is either highly or moderately erodible. $K_{fac}$ is negatively correlated with sand, clay, SOM, $K_{sat}$, structural susceptibility but positively correlated with silt. These variables account for 77.2% of variance in $K_{fac}$ at P<0.05. It was concluded that the soils of the study area are highly erodible and that increase in $K_{fac}$ is largely a function of increase in silt content of the soil. It was recommended that tree planting should be promoted in areas of high $K_{fac}$, while crop residues should be retained on farmlands to increase SOM for sustainable soil erosion management.


Introduction
Soil is perhaps the most important component of the terrestrial ecosystem; it serves as a medium of food production, reservoir for water resources, life support and carbon sink (Jeloudar et al., 2018; Schmidt, 2018). Soil erosion on the other hand has been recognized as the major cause of land degradation worldwide (Valentin et al., 2005). Globally, water erosion has affected 1.1 billion ha of soil, representing 56% of degraded landmass while 28% of degraded land is caused by wind erosion (Okorafor et al., 2017). The topsoil contains most of the soil’s nutrients, organic matter (OM), and pesticides which are moved from a given site, leaving behind soil with poorer structure, lower water-holding capacity, different pH values, and low nutrient levels (Schmidt, 2018). Soil erosion can impact water quality by transporting and depositing soil sediments and attached nutrients and chemicals into surface waterways.

Many factors have been adduced to soil erosion. Besides the anthropogenic influences and climate change impact which have accelerated the phenomenon in the last decade, site conditions such as rainfall erosivity, erodibility ($K_{fac}$) of the soils, degree and length of the slope and vegetation cover are also elements of erosion (Lal, 2001). These factors result in changes that render the soil susceptible to erosion and degradation and need to be considered in the modelling of erosion for the sustainability of soil resources (Schmidt, 2018).

Soil/land degradation has become a major global issue during the 20th century and will remain high on the international agenda in the 21st century (Nerandra et al., 2012). However, information on erosion in Nigeria at both state and national levels are either scanty or unavailable, whereas evidence abounds to show that Nigeria is plagued with diverse ecological problems which are climate change related (Bello et al., 2012). Thus, the Federal Government...
initiated Nigeria Erosion and Watershed Management Project (NEWMAP) to restore degraded lands and reduce longer-term erosion vulnerability in some targeted states.

Sombroek and Zonneveld (1971) acknowledged occurrences of considerable erosion particularly from sheet floods and rill wash in the study area, aggravated by overgrazing and bush burning. The large scale erosion and flooding experienced in the study area in the year 2010 left scars of gullies in some areas that have continued to grow in magnitude (Abdulrahman and Eniolorunda, 2012). Thus, Sokoto-Rima basin is one of the few areas fingered for having more acute climate change impact in Nigeria (Odjugo, 2010). As recent trends tend to suggest a recovery of rainfall leading to wetter conditions in the Sudano-Sahelian zone of Nigeria (Ati et al., 2009; Ekpo and Nsa, 2011; Akinsanola and Ogunjobi, 2014), erosion and flooding are likely to be accelerated. Thus, this study aims at assessing $K_{fac}$ as a component of a wider study for marshalling action plans towards sustainable soil erosion management in Sokoto State.

Materials and Methods

Study Area

The study area covers the entire Sokoto State of Nigeria, covering 31,862 km² within latitudes 11.58° to 13.89°N and longitudes 4.13° to 6.79° E (Figure 1). It is bordered by Niger Republic in the north, Kebbi State in the west and south and Zamfara State in the east, all of which are parts of the Sokoto-Rima Basin.

There are two physiographic units in the area: The Sokoto plains located in the east and the marine lowland of the Niger and lower Rima valley (Swindel, 1984). The Sokoto plains form monotonous lowland derived from sedimentary rocks with an average height of 300 metres. The marine lowland is essentially the floodplains of rivers Rima and Sokoto which are below 300 m. The rivers are the most prominent, draining the study area. Their floodplains are about 4 km wide and are complex in nature (Adeniyi, 1993; Ifabiyi and Eniolorunda, 2012). The basin is compact with a high sediment delivery ratio and high volume of precipitated water of 14,511,439,620 m³/year. These are clear indications that the basin has high flood potential. Two major geological formations underlie the area. The first is the basement complex comprising old volcanic and metamorphic rocks which outcrops in the extreme southern part of the state (Ifabiyi and Eniolorunda, 2012). The basement complex which is the second formation is overlain by sedimentary rocks, in the Iullemeden Basin, extending from Mali, through Niger to Sokoto (Sombroek and Zonneveld, 1971).

Figure 1: Study Area
The study area is dominated by Arenosols mainly due to aeolian deposition, the soil texture of which is largely sand with a depth of about 100cm. Because it is a semi-arid area, rainfall amounts are insufficient to accelerate weathering of the parent materials. Of lower extent in coverage is the Regosols which are also found in the east and south eastern parts of the state. It is perhaps the second most extensive soil in the area. It is characterized by a thin, organic-poor and ochric horizon. As profile development is minimal due to young age and/or slow soil formation because of low rainfall and high temperature, it lacks diagnostic horizons. Fluvisol is found in the floodplains of Rima-Sokoto river system deposited through fluvial processes (FAO, 1969; Sombroek and Zonneveld, 1971). It has profiles with evidence of stratification, weak horizon differentiation but may have a distinct topsoil horizon.

The study area falls in the semi-arid region, the vegetation of which is mainly of shrubs and grasses, with grasses averagely measuring below 1.5m. Land cultivation, bush burning, grazing and wood-fuel extraction are common livelihood activities that have implications for the marginal vegetation. The increasing consumption of the natural vegetation for various domestic purposes aggravates the environmental degradation of the Basin (Adeniyi, 1993).

**Soil Sampling and Sample Treatment**

Soil properties were obtained from 75 points (Figure 2): 55 randomly dug soil profiles and 20 purposively selected points from the World Harmonized Soil Database (WHSD). Purposive sampling was applied to specifically sample points at the fringes of the study area to ensure total coverage of the area after point interpolation. Profiles were dug to 2m depth and studied following the method proposed by Soil Science Division Staff (2017). Collected samples were bagged and transported to the Usmanu Danfodiyo University Central Laboratory for tests. The samples were air-dried for 48hours, crushed and sieved with a 2-mm mesh.

![Figure 2: Soil Sample Sites](image)

**Determination of Soil Properties**

Particle size was determined by the Bouyoucos hydrometer method following the description of Noma et al. (2011), while Soil Organic Matter (SOM) was determined using the Walkley-Black method as described by Noma et al. (2011).
Soil erodibility was determined using the Zwischmeier and Smith method (Belasri et al., 2017):

\[ K_{\text{fac}} = (1.292) \times [2.1 \times 10^{-6} f_p^{0.14} (12-P_{\text{om}}) + 0.0325(S_{\text{struc}} - 2) + 0.025(K_{\text{sat}} - 3)] \]  

--- Equation (1)---

in which:

- \( K_{\text{fac}} \) is the soil erodibility factor measured in \( \text{t} \cdot \text{ha}^{-1} \cdot \text{h}^{-1} \cdot \text{MJ}^{-1} \cdot \text{mm}^{-1} \)
- \( f_p \) is the particle size parameter;
- \( P_{\text{om}} \) is the percent organic matter;
- \( S_{\text{struc}} \) is the soil structure index;
- \( P_{\text{clay}} \) is the percent clay;
- \( K_{\text{sat}} \) is the saturated hydraulic conductivity;

The \( K_{\text{sat}} \) in this study was calculated using the Pedotransfer function of Cosby et al. (1984):

\[ K_{\text{sat}} = 7.05556 \times 10^{-6} \times (10^{0.06 - 0.0126(S_{\text{Sand}}) - 0.0064(S_{\text{Clay}})}) \]  

--- Equation (2)---

where: Clay and Sand are the percentages of clay and sand, respectively. \( K_{\text{sat}} \) is measured in \( \mu \text{m} / \text{s} \).

Soil structure is very complex and difficult to characterize due to its dynamic nature (Simansky, 2015). Thus, the soil structural index, \( S_{\text{struc}} \), was based on textural classification of Ontario Centre for Soil Resource Evaluation of 1993 as described by Belasri et al. (2017) (Figure ).

**Soil Property Mapping and Analysis**

Inverse Distance Weighting (IDW) was used to perform point interpolation for all the measured soil variables in order to generate continuous surfaces necessary for soil property pattern analysis. IDW, being the most used method of interpolation (Lu, 2007; Yasrebi et al., 2009), determines cell values using a linearly weighted combination of a set of sample points, with the weight being a function of inverse distance (Environment System Resource Institute, ESRI, 2014). Soil characteristics were interpolated within the ArcGIS 10.2.2, while QGIS 3.4 was used to combine the interpolated sand, silt, and clay layers into soil texture. To assess the contributions of variables to \( K_{\text{fac}} \), Multiple Regression Analysis was performed within the QGIS 3.4 environment, where \( K_{\text{fac}} \) map was made the dependent variable while sand, silt, clay, SOM, \( K_{\text{sat}} \) and soil structural maps were made the predictors.

**Results and Discussion**

**Soil Variables**

**Particle Size**

The spatial compositions of sand, silt, and clay are presented in Figures 3, 4 and 5 respectively. These were combined to produce the soil textural map in Figure 6. Although the proportions of sand, silt and clay are mutually exclusive at every location, the particle sizes are similar in patterns. Clay compositions range between 3.43% and 24.99%, portraying a pattern where high percentages are located closely to wet areas. Aside other factors of soil formation, rainfall through chemical weathering is specifically favourable to clay formation (Brady and Weil, 2013; Koly, 2013). Thus, as rainfall amount is small and duration is short in the study area, the pattern of clay concentrations suggests that wet areas are more active in weathering.

Silt compositions range approximately between 4.58% and 40.10% with a spatial pattern similar to that of clay. Smalley et al. (2005) argued that very little discussion has been done on the actual formation processes of silt and that discussions on silt forming mechanisms have a sand-to-silt emphasis. Silt is generally thought to occur in mixture with sand and or clay or as sediment transported by water. The abundance of silt around the wet areas is most likely due to fluvial processes. Sand proportions approximately range between 9.65% to 90%; however, the spatial pattern is largely opposite to those of clay and silt. Largest proportions are found in or close to the northwest, north and northeast of the area. Sand in this environment is mainly of aeolian origin from the Sahara desert (Yakubu et al., 2004).
The textural classes in the study area are sandy clay (5.10%), sand (10.11%), loam (12.50%), loamy sand (22.51%) and sandy loam (49.78%). These textural classes and many more have been reported of the study area by different authors at different scales of investigation (Noma and Yakubu, 2002; Yakubu et al., 2008; Yakubu et al., 2012). Among textural classes, loamy soils are acknowledged to have the highest erodibility tendency because they have high amounts of silt and very fine sands which in turn have moderate to low permeability and low resistance to particle detachment (O’geen, Elkins, and Lewis, 2005).

**Soil Structure**

The manner of particle size arrangement and how they aggregate have implication for soil erodibility. Soil structure affects the ease with which water and air flow through its interconnecting voids. Sediments containing more clay
tend to be more resistant to erosion than those with sand or silt (Blanko et al., 2010). In this study, high structural codes mean high susceptibility to erosion and vice versa (Table 1). From Figure 7, areas of moderate to high erosion susceptibility on the basis of soil structure are those with loam and sandy clay, constituting 17.6% of the study area. Such places are located in the riverine areas.

<table>
<thead>
<tr>
<th>Texture</th>
<th>Percentage</th>
<th>Structural Code</th>
<th>Erosion Susceptibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy Clay</td>
<td>5.10%</td>
<td>4</td>
<td>Highly susceptible</td>
</tr>
<tr>
<td>Loam</td>
<td>12.50%</td>
<td>3</td>
<td>Moderately susceptible</td>
</tr>
<tr>
<td>Loamy Sand</td>
<td>22.51%</td>
<td>2</td>
<td>Slightly susceptible</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>49.78%</td>
<td>2</td>
<td>Slightly susceptible</td>
</tr>
<tr>
<td>Sand</td>
<td>10.11%</td>
<td>1</td>
<td>Very slightly susceptible</td>
</tr>
</tbody>
</table>

Adapted from Belasri and Lakhouili (2016)

Figure 7: Soil Structural Code

Hydraulic Conductivity
The Saturated Hydraulic Conductivity ($K_{sat}$) values range between 3.71 and 22.42 $\mu$m/s, rating from moderate (1-<10) to high (10-<100) (Soil Science Division Staff, 2017) (Figures 8 and 9). The pattern of $K_{sat}$ is similar to that of texture. A major factor that influences the rate of water flow through soils is the size of the particles as it can be stated that the smaller the particles, the smaller the voids and the stronger the flow resistance (Gutmann and Small, 2005; Schuhmann et al., 2011). Besides, the conceptual underpinning of most Pedotransfer Transfer Functions (PTFs) for estimating $K_{sat}$ is particle size (Rasoulzadeh, 2011). In this study, high $K_{sat}$ values are associated with sand and loamy sand, while moderate $K_{sat}$ values are associated partly with sandy loam and wholly with loam and sandy clay. Although $K_{sat}$ values in areas with loam and sandy clay are moderate, such values remain the least in this study. This result is in agreement with the findings of Rasoulzadeh (2011) and Sarki et al. (2014).
Soil Organic Matter

Soil Organic Matter (SOM) obtained ranges between 1.32 to 5.43%, the values of which are low based on Omar (2011) rating. In order to demonstrate spatial variation, the values were classified using Jenks natural breaks (ESRI, 2014). Similar values have been obtained within and around the study area by different authors. Areas of highest SOM concentrations are in the northwest, northeast and the central parts, where forest reserves exist. The study area is located in the semi-arid zone where there is generally low vegetation cover, rapid mineralization of SOM due to high temperature, near total removal of crop residue, bush burning and intensive cultivation, among others. These explain why SOM concentrations are generally low (Abubakar and Eniolorunda, 2016). Soil containing high levels of organic materials are often more resistant to erosion, because the organic materials coagulate soil colloids and create stronger and more stable soil structure (Belasri, Lakhouili, and Halima, 2017; Jeloudar, Sepanlou, and Emadi, 2018).
Soil Erodibility

Figure 12 shows that erodibility ($K_{fac}$) ranges between 0.10 and 0.40 t·ha·h·MJ·mm⁻¹, while Figure 13 shows the classified $K_{fac}$ based on the rating of Stewart et al. (1975). Classes obtained are: Low (51.69%), Medium (21.07%) and High (27.24%) (Table 2). High $K_{fac}$ values are found in areas around the rivers, while areas of medium $K_{fac}$ encircle the high value areas; areas of low $K_{fac}$ surround the medium areas. The soils of the study area are erodible almost by half, 48.31%.

![Figure 12: Raw $K_{fac}$](image)

![Figure 13: Classified $K_{fac}$](image)

**Table 2: Statics of $K_{fac}$ classes**

<table>
<thead>
<tr>
<th>Class</th>
<th>Area (Km²)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>16,469</td>
<td>51.69</td>
</tr>
<tr>
<td>Medium</td>
<td>6,712</td>
<td>21.07</td>
</tr>
<tr>
<td>High</td>
<td>8,681</td>
<td>27.24</td>
</tr>
<tr>
<td>Total</td>
<td>31,862</td>
<td>100</td>
</tr>
</tbody>
</table>

The contribution of predictor variables to $K_{fac}$ was tested using multiple linear regression, where $K_{fac}$ was made the dependent variable and other variables independent. Results show that 77.2% of the variance in $K_{fac}$ (dependent variables) is explained by the $K_{sat}$, soil texture, soil structure and SOM (independent variables) (Table 3). This is statistically significant (P<0.05), meaning that the independent variables can suitably predict $K_{fac}$. On individual basis, each independent variable has impact on the prediction of $K_{fac}$ in the study area as their P values are <0.05 (Table 4). Thus $K_{fac}$ for the study area can be predicted as:

$$K_{fac} = 0.411 - 0.007(Structure) - 0.001(Sand) + 0.001(Silt) - 0.001(Gravel) - 0.002(SOM) - 0.004(K_{sat})$$

Equation (3)

From equation 3, it is clear that $K_{fac}$ has negative relationships with all the independent variables except silt. Jeloudar et al. (2018) similarly discovered a negative relationship between $K_{fac}$ and $K_{sat}$. It is no wonder that areas of high $K_{fac}$ are proximal to rivers where siltation is most prominent. Increase in the percentage of silt will make the soil tend toward being loamy, sandy loam or loamy sand (Jeloudar et al., 2018). Such soils have high to moderate erodibility (Foster et al., 2001; Foster et al., 2003) but loamy soils have the highest $K_{fac}$ tendency (O’geen, Elkins, and Lewis, 2005).
Table 3: Multiple Linear Regression Model Summary

<table>
<thead>
<tr>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>N</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.879</td>
<td>0.772</td>
<td>0.752</td>
<td>75</td>
<td>38.337</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 4: Regression Coefficients

<table>
<thead>
<tr>
<th>Model</th>
<th>B</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Constant)</td>
<td>0.411</td>
<td>0.000</td>
</tr>
<tr>
<td>Structure</td>
<td>-0.007</td>
<td>0.001</td>
</tr>
<tr>
<td>Sand</td>
<td>-0.001</td>
<td>0.047</td>
</tr>
<tr>
<td>Silt</td>
<td>0.001</td>
<td>0.010</td>
</tr>
<tr>
<td>clay</td>
<td>-0.001</td>
<td>0.022</td>
</tr>
<tr>
<td>OM</td>
<td>-0.002</td>
<td>0.000</td>
</tr>
<tr>
<td>K&lt;sub&gt;sat&lt;/sub&gt;</td>
<td>-0.004</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Conclusion

The study found out that the area is characterized by sandy clay, sand, loam, loamy sand and sandy loam with the latter two being dominant. SOM is generally low while K<sub>sat</sub> is high and moderate with high values found where the soil is sand or loamy sand. Areas of moderate to high soil structural susceptibility are those with loam and sandy clay texture, while high erodibility is associated with riverine areas which are loamy in texture. About half of the study area is either highly or moderately erodible, and erodibility is negatively correlated with sand, clay, SOM, hydraulic conductivity and structural susceptibility. It can be concluded that the study area is highly erodible, and erodibility is largely a function of how much silt is contained in the soil. Tree planting should be promoted in areas of high erodibility, while crop residues should be retained on farmlands to increase SOM. Future studies should model soil erosion in the study area for sustainable environment and soil resource.

Acknowledgements

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References


