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A GIS-based estimation of soil erosion parameters for soil loss potential and erosion hazard in the city of Kinshasa, the Democratic Republic of Congo

Martin Tshikeba Kabantu[1], Raphael Muamba Tshimanga[1], Jean Marie Onema Kileshye[3,2], Webster Gumindoga[3], and Jules Tshimpampa Beya[1]

[1]Dept. of Natural Resources Management and the Congo River basin network for research and capacity building in water resource (CB-HYDRONET), University of Kinshasa, P.O. Box 117, Kinshasa XI, Kinshasa, Democratic Republic of the Congo
[2]WaterNet, P.O. Box MP 600 Mount Pleasant, Harare, Zimbabwe
[3]Dept. of Civil Engineering, University of Zimbabwe, P.O. Box MP167 Mount Pleasant, Harare, Zimbabwe

Correspondence: Martin Tshikeba Kabantu (madeleinekabantu@gmail.com)

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Abstract. Soil erosion has detrimental impacts on socio economic life, thus increasing poverty. This situation is aggravated by poor planning and lack of infrastructure especially in developing countries. In these countries, efforts to planning are challenged by lack of data. Alternative approaches that use remote sensing and geographical information systems are therefore needed to provide decision makers with the so much needed information for planning purposes. This helps to curb the detrimental impacts of soil erosion, mostly emanating from varied land use conditions. This study was carried out in the city of Kinshasa, the Democratic Republic of Congo with the aim of using alternative sources of data, based on earth observation resources, to determine the spatial distribution of soil loss and erosion hazard in the city of Kinshasa. A combined approach based on remote sensing skills and rational equation of soil erosion estimation was used. Soil erosion factors, including rainfall-runoff erosivity R), soil erodibility (K), slope steepness and length (SL), crop/vegetation and management (C) were calculated for the city of Kinshasa. Results show that soil loss in Kinshasa ranges from 0 to 20 $\mathrm{t\,ha^{-1}\,yr^{-1}}$. Most of the south part of the urban area were prone to erosion. From the total area of Kinshasa (996 500 ha), 25 013 ha (2.3 %) is of very high ($> 15\,\mathrm{t\,ha^{-1}\,yr^{-1}}$) risk of soil erosion. Urban areas consist of 4.3 % of the area with very high ($> 15\,\mathrm{t\,ha^{-1}\,yr^{-1}}$) risk of soil erosion compared to a very high risk of 2.3 % ($> 15\,\mathrm{t\,ha^{-1}\,yr^{-1}}$) in the rural area. The study shows that the soil loss in the study area is mostly driven by slope, elevation, and informal settlements.

1 Introduction

The Soil Conservation Society of America provides a definition of soil erosion as the wearing away of the land surface due to the action of several agents, including running water, wind velocity, and gravitation creep (Ghanshyam, 2012). It represents the gross amount of soil removed or dislocated by different agents of nature, thus resulting in soil loss. The later represents the net amount of soil removed off a particular area. Soil erosion is known to cause severe land degradation, loss of soil productivity, and sedimentation of waterways (Pimentel and Burgess, 2013; Bhattacharyya et al., 2015). The Erosion Hazard assessment determines whether the risk of soil erosion is low, medium or high. While, soil erosion is influenced by geomorphological processes (Telles et al., 2013), it is accelerated by anthropogenic factors that develop spontaneously, with little or no planning (Robertson, 2009). All this has detrimental impacts on socio economic situations and the environment, especially in developing countries, thus increasing poverty.

Since 1980s, the African continent has been subjected to urban expansion, due to population growth and search for better life, but all this does not commensurate with infrastructure development (Antoine, 1991). In the Democratic Republic of Congo (DRC), the political instability and civil conflicts that have been observed over the past three decades have contributed to massive movement of people from rural areas and those hotspot areas of instability to more stable areas such as the city of Kinshasa. This has led to rapid demographic increase, deterioration of existing infrastructure, and informal settlements. For instance, the city of Kinshasa that was initially built for less than one million people, has now more than ten million inhabitants (Kinshasa-CPSRP, 2011). The expansion of the urban areas of the city is neither supported with appropriate planning nor adequate infrastructure. This situation contributes to widespread and high level land degradation and soil erosion, which is even difficult to monitor and control (Daniel et al., 2015; Bizuwerk et al., 2004). Assessing soil loss potential and erosion hazard is therefore important for best practices of soil conservation and management to reduce devastating consequences to the bio-physical and socio-economic environment. Most of soil erosion estimation approaches use parameters that require input data at appropriate spatial and temporal scales. Such data include for instance factors of rainfall erosivity, soil erodibility, land cover and slope characteristics that are difficult to acquire in data scarce areas such as the city of Kinshasa. This is where earth observation techniques such as the use of Geographical Information Systems (GIS) and Remote Sensing can be of unprecedented benefit to determine the soil erosion parameters necessary to assess soil loss potential and erosion hazard, establish a model of spreading and provide adequate management practices. A study carried out by Kitambo (2017) in one of the peri-urban catchments of Kinshasa, the N'sele catchment, estimated about $92 \pm 11\,\mathrm{t\,km^{-2}\,yr^{-1}}$ of soil loss. Mfumu et al. (2012) estimated the soil loss at the nuclear facility of Kinshasa. The study revealed that the soil loss at that the nuclear facility varies from 0 to $9\,\mathrm{t\,ha^{-1}\,yr^{-1}}$. The above mentioned studies used the Erosion Potential Model approach (Mfumu et al., 2012).

The objective of this study is to determine the parameters of soil erosion necessary for assessing spatial distribution of soil loss and erosion hazard in the city of Kinshasa using alternative sources of data, based on earth observation resources.

2 Study Area

Figure 1 shows the location of the study area, the city of Kinshasa, that is located west of DRC between 3.9 and 5.1° Latitude South and between 15.2 and 16.6° Longitude East, and extend over $9965\,\mathrm{km}^2$. The city is composed of 24 municipalities with 22 in urban part and 2 in rural (Nsele and Maluku), the rural area covers more than 75 % of the city area (Kinshasa-CPSRP, 2011). The study area is under the code AW4 climate according to the Köppen classification

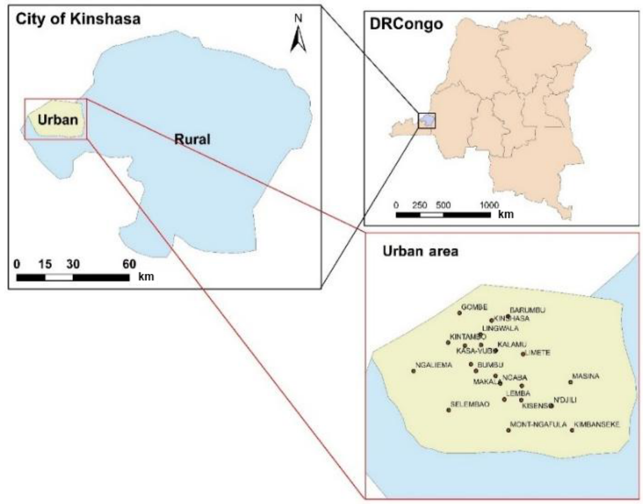

Figure 1. Location of the study area.

it is a hot and humid tropical climate, characterized by a long rainy season lasting up to eight months and often interrupted by short dry periods between January and February (Kayembe and Wolff, 2009). The temperature varies during the year from 20 to 32 °C and infrequently falls under 19 or above 34 °C. Kinshasa soil types constitute Dystric Regosols, Ferralic Arenosols, and Orthic Greyzems. The texture is generally sand, sandy loam, and coarse grained sands (FAO, 1997). The vegetation is generally savanna dotted with shrubs combined with gallery forests at low density areas. Semi deciduous sub-equatorial secondary forests and shrub lands of Guinean are observed in the study area (Kifukieto et al., 2014).

3 Study methodology

3.1 Soil erosion modelling

The study of soil erosion can be traced from centuries, but many approaches that are currently in use began over 70 years ago when Austin Zing published a relationship between soil erosion by water and land slope and length (Ghanshyam, 2012). This was followed by Dwight Smith's relationship that expanded the introduction of conservation practices in the equation (Laflen and Flanagan, 2013). One of the approaches is the Universal Soil Loss Equation (USLE, Laflen and Flanagan, 2013; Kithara et al., 2000), which is a set of mathematical equations that estimate average annual soil loss and sediment yield caused by inter-rill and rill erosion (Toy and Foster, 1998) based on rainfall pattern, soil type, topography, crop system and management practices, and has been widely used USLE (Eq. 1) in the studies of soil erosion management.

$$A = R \cdot K \cdot SL \cdot C \cdot P \tag{1}$$

Where: A = long term average annual soil loss in tonnes per hectare per year, originally calculated in tonnes per acre per year) ($\mathrm{t\,ha^{-1}\,yr^{-1}}$); R = rainfall-runoff erosivity factor in ($\mathrm{MJ\,mm\,ha^{-1}\,h^{-1}\,yr^{-1}}$); K = Soil erodibility factor ($\mathrm{T\,h\,MJ^{-1}\,mm^{-1}}$); SL = Slope steepness and length factors (dimensionless); C = Cover crop/vegetation management factor (dimensionless), and P = support practice factor which is equal to one (dimensionless) (Laflen and Flanagan, 2013).

While the availability of data required to assess soil erosion based on the above mentioned USLE model is always a challenge for data scarce regions such as the city of Kinshasa, the newly developed Water Observation and Information System (WOIS; TIGER-Net, 2014) provides an advantage of combining remote sensing input with soil erosion factors to determine soil loss potential and erosion hazard.

WOIS is an open source software for assessing water resources using Earth Observation (EO) data. The software was developed by the TIGER initiative under the European Space Agency (ESA) programme aimed at supporting at supporting the African Earth Observation Capacity for Water Resource Management and Monitoring (Guzinski et al., 2014). It uses the Quantum GIS (QGIS) software that acts as the front-end Graphical-User-Interface (GUI) with functionalities that incorporate algorithms for different spatial data analysis libraries.

3.2 Model parameters and data availability

As previously mentioned, while studies on soil erosion are required for a better planning of soil conservation practices in developing countries, it should be stressed that many of these studies have been challenged by the lack of appropriate data over the required spatial and temporal scales. In the present study, global sources of earth observation data are used to obtain the WOIS set of soil erosion parameters.

3.2.1 Rainfall-runoff erosivity factor (R-factor)

The amount of rainfall and the peak intensity sustained over an extended period are mainly indicated by the rainfall erosivity. Within WOIS, the R-factor is calculated based on the following relationship:

$$R = 0,\ 4669X - 12,\ 1415 \tag{2}$$

Where: R is the rainfall-runoff erosivity factor expressed in $\mathrm{MJ\,mm\,ha^{-1}\,h^{-1}\,yr^{-1}}$, and X represents the mean annual rainfall in mm. The mean annual rainfall used in this study was calculated from the Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) global monthly average rainfall (1991–2014) with 5 km spatial resolution.

3.2.2 Soil erodibility Factor (K-Factor)

K-Factor is the quantitative measure of susceptibility and resistance of soil to erosion. The factor is calculated based on soil texture classes. In this case the soil texture classes from the FAO Digital Soil Map of the World (FAO, 1997) was used to determine K-Factor based on the average values of the erodibility classes from the USLE fact sheet (FAO, 1997).

3.2.3 Slope steepness and length (SL-Factor)

The SL factor includes both slope length (Eq. 3) and slope steepness (Eq. 4).

$$L = (X/22,\ 13) \cdot m \tag{3}$$

Where: X is the slope length in meter and m is the weighting factor depending on the slope steepness.

$$S = \left[0.065 + 0.0456(\mathrm{slope}) + 0.006541(\mathrm{slope})^2\right] \tag{4}$$

The SL factor is dimensionless. In this study, a digital elevation model (30 m) was used to determine the SL-factor. The slope classes proposed by Nachtergaele et al. (2010) indicate six categories of slopes ranging from Flat (0–2 %), Undulating (2–8 %), Rolling (8–15 %), moderately steep (15–30 %), Steep (30–60 %), Very steep (> 60 %), and was used for slope classification in this study (Tshimanga, 2012).

3.2.4 Crop/vegetation and management factor (C-Factor)

C-Factor is obtained by assigning values of the land cover classes, which were obtained from the Glob Land Cover map with 300 m spatial resolution (CCI-LC-PUG, 2016). The algorithm assigns the C-Factor values to the specific or averaged values related to each land cover type. The table of value is available at European Space Agency, Climate Change Initiative website (http://cci.esa.int/, last access: 23 October 2016).

3.2.5 Support or Erosion Control Practice (P-Factor)

P-Factor is the influence of conservation measures on erosion for a particular area. P-Factor is representing the soil loss ratio of the conservation practice to up and down hill culture. The P-Factor ratio is usually less than 1 if the erosion control practice is effective (Gitas et al., 2009; Roger and Herbert, 2016). For this study, P-Factor is considered as 1 because in Kinshasa there is usually no erosion control practices involved.

4 Results and discussion

4.1 Evaluation of the soil erosion parameters

The results of soil erosion parameters for the city of Kinshasa are presented in Table 1.

Rainfall-runoff erosivity (R), the values of R found in this study range from 616 to 723 $\mathrm{MJ\,mm\,ha^{-1}\,h^{-1}\,yr^{-1}}$. Kinshasa

Table 1. Soil erosion parameters.

Soil erosion parameters	Min	Max	SD
Rainfall-runoff erosivity (R), in $\mathrm{MJ\,mm\,ha^{-1}\,h^{-1}\,yr^{-1}}$	616	723	75
Soil erodibility (K), in $\mathrm{Th\,MJ^{-1}\,mm^{-1}}$	0	0.290	0.205
Slope steepness and length (SL),	0	6597	4664
Crop/vegetation and management (C),	0	0.525	0.371

SD – standard deviation.

Table 2. Erosion Hazard and soil loss potential of city of Kinshasa.

Erosion Hazard/Soil loss ($\mathrm{t\,ha^{-1}\,yr^{-1}}$)	Kinshasa		Rural area		Urban area	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
Very low (< 1)	1 000 280	94.1	918 119	94.2	41 784	92.7
Low (1.1–3)	14 850	1.4	40 234	1.4	324	0.7
Low to medium (3.1–5)	8874	0.8	14 526	0.8	306	0.7
Medium to high (5.1–10)	8977.5	0.8	8568	0.8	454.5	1
High (10.1–15)	4898.25	0.5	8523	0.5	306	0.7
Very high (> 15)	25 013.25	2.3	4590	2.3	1917	4.3

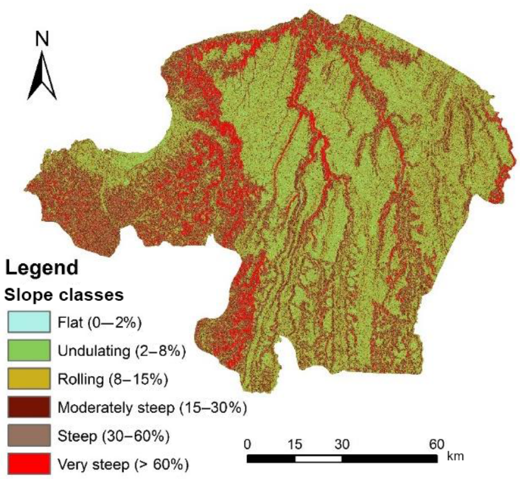

Figure 2. Slope classes of the study area.

receives precipitation characterized by thunderstorms which generate a high volume of rainfall that in turn generate runoff over a long period of time (CPSRP, 2011). When the rainfall occurs with the greater intensity, it exposes the rivers beds to the high risk of transport and sedimentation (Laflen and Flanagan, 2013; Mahabaleshwara and Nagabhushan, 2014). In such process the R-Factor values is high with greater erosivity.

Soil erodibility (K), the values of K found in this study range from 0 to 0.290 $\mathrm{Th\,MJ^{-1}\,mm^{-1}}$. K-Factor is the quantitative measure of susceptibility and resistance soil to erosion. The Kinshasa soil characteristics are high percent content of fine sand particles and low organic matter content. The soil are constitute of smaller particles detachable and easily transportable. Such kind of soils are mostly erodible. The positive side of Kinshasa soil is that the soil is permeable which lead to less runoff and reduce the risk of soil erosion at some areas (FAO, 1997).

Slope steepness and length (SL), generally, the results show that Kinshasa does not have a high concentration of steep areas and most of the areas are gentle undulating and rolling. Relatively high SL factor values are found on areas around the rivers (Fig. 2).

Crop/vegetation and management (C), From the Kinshasa Land cover map the C values range from 0 to 0.525. The C-Factor values were assigned to the specific or averaged values related to each land cover type. The table of values is available at the European Space Agency, Climate Change Initiative website. The values can vary from 0 to 1 depending on the land cover type. Thick and dense vegetation offers higher protection against erosion and thus has a lower C-factor values compared to bare soil with no protection against erosion and has a C-factor of 1.

4.2 Soil loss and Erosion hazard estimates

The soil loss using USLE equation is calculated by multiplying all four single factors including R, K, SL, and C. Figures 4 and 5 show the spatial variation of soil loss potential and erosion hazard of the city of Kinshasa. The Table 2 shows the results of soil loss in $\mathrm{t\,ha^{-1}\,yr^{-1}}$, it can be realise that these results are over estimate the soil loss when comparing to the results obtained in the previews studies in Kinshasa by Mfumu et al. (2012) where the soil loss vary from 0 to 9 $\mathrm{t\,ha^{-1}\,yr^{-1}}$. At national level, the study by Alain

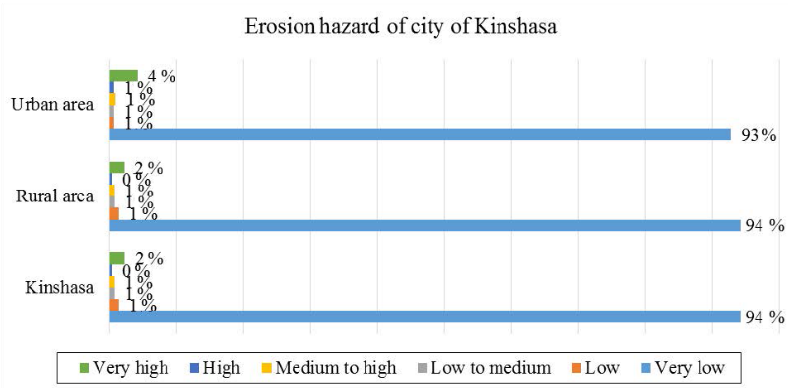

Figure 3. Histogram of erosion hazard.

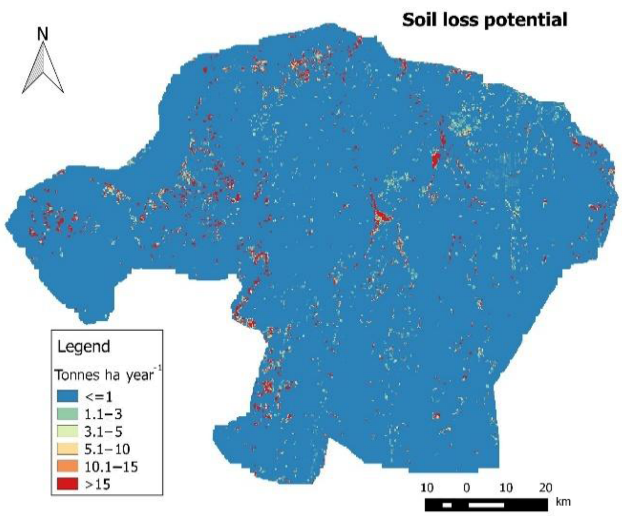

Figure 4. The spatial variation of soil loss potential.

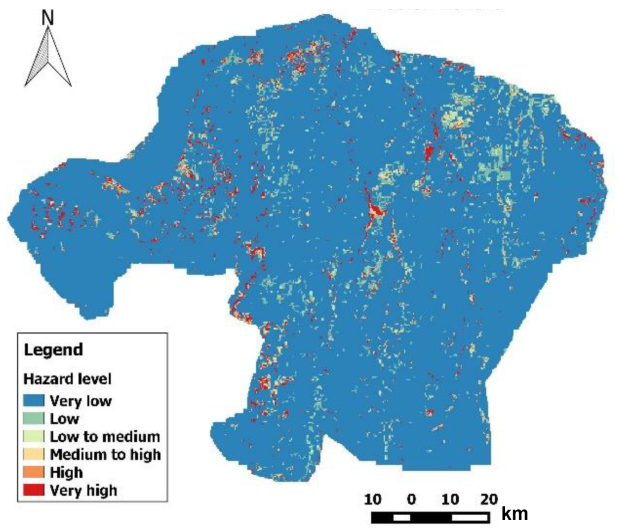

Figure 5. The spatial variation of soil erosion hazard.

et al. (2009) in the Upper Congo, tributaries shows the average rate of 8.9 range $t\,ha^{-1}\,yr^{-1}$ of soil loss in Kasai and major right-bank tributaries. So the approach used by WOIS to estimate the soil loss is over estimate the soil loss potential at local and national level. At international level in Central Africa particularly Walling and Webb (1996) found the range of 0 to $50\,t\,km^{-2}\,yr^{-1}$ where the results obtain by WOIS were under estimate. The city of Kinshasa was found with 2.3 % of area with very high risk of erosion. Same situation to the rural part of the city, contrarily to urban part where the area of very high risk of erosion was 4.3 %. The spatial variation maps show that the highest risk of erosion was found along the river or at the area with high elevation and informal settlements. It can be observed that in the urban area the most affected areas were the municipalities of Binza Kinsuka, Mbudi, Malweka, Kimbwala, Binza gendarmerie, Binza pigion, Gombele, Binza IPN, Binza Djelo, Jamaic, Cite mama Mobutu, Cite verte, cite pumbu, Livulu, Mbasa-lemba (Figs. 1 and 5).

5 Conclusion and recommendations

The city of Kinshasa faces challenges of land degradation due to soil erosion, which threaten livelihood of population. This study has shown the strength of GIS based approaches to estimate soil loss potential and erosion hazard. The major conclusions that arise from this study are:

- The urban part of Kinshasa is more prone to soil erosion than the rural counterpart. The high percentage of very high risk of erosion (4.3 %) was found in the urban part when compared to the rural part of the city (2.3 %);

- Comparing to the previous studies at local level the approach used by WOIS over estimates the amount of soil loss. At regional level the results show under estimation;

- The study recommends the soil loss ground measurements in Kinshasa for the validation of the results obtained from the approach used by WOIS;

– The validation will simplify the field work by the use of remote sensing product and approach (WOIS) when doing soil loss and water resources studies.

Data availability. Different sources of data used in this study are:

- Digital Elevation Model (DEM) 30 m of the city of Kinshasa downloaded from https://earthexplorer.usgs.gov/ (last access: 20 April 2018).
- The Glob land Cover map (2008–2012) with 300 m spatial resolution was obtained from the European Space Agency, Climate Change Initiative (CCI-LC-PUG, 2016; http://maps.elie.ucl.ac.be/CCI/viewer/download.php).
- The mean annual rainfall was calculated from the Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) global monthly average rainfall (1991–2014) with 5 km spatial resolution, the CHIRPS rainfall was obtained from the CHIRPS website (ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0/global_2-monthly/tifs/, last access: 20 April 2018).
- The USDA texture classes of the FAO Digital Soil Map of the World (FAO, 1997). And K-Factor for different soil types are available at http://www.omafra.gov.on.ca/english/engineer/facts/12-051.htm (last access: 20 April 2018).

Competing interests. The authors declare that they have no conflict of interest.

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