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Water Erosion Potential of the Congo River in the Stanley-Pool Bay

Matsouele Nzonzi Bonheur[1], Obami Ondon Harmel[1], Tathy Christian[1, 2], Moukandi Nkaya Guy Dieudonne[1], Mabiala Bernard[1, *]

[1]Mechanical, Energy and Engineering Laboratory, Higher National Polytechnic School, Marien Ngouabi University, Brazzaville, Congo
[2]Department of Exact Sciences, Higher Teacher's Training School, Marien Ngouabi University, Brazzaville, Congo

Email address:
bernamab@hotmail.com (Mabiala Bernard)
[*]Corresponding author

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Abstract: Water erosion of soil is the loosening, transport and deposition of soil particles by the flow of water. After an intense rainfall and runoff, the water flow can become concentrated. In the Republic of Congo soil erosion is a natural hazard that is exacerbated by human activities, as there is little information on the spatial knowledge of this phenomenon. In this paper, a scientific study on the understanding of the erosion and transfer processes of suspended solids or sediments from the Congo River into the Stanley-Pool Bay was conducted. For this purpose, a treatment of rainfall data over three decades (1990-2020), parameters influencing the process of erosive dynamics leading to the realization of the water erosion map using the Universal Soil Loss Equation (USLE), was done. Using open access spatial data and GIS, this USLE model allowed quantifying the rate of material transported over the three decades: a spatialization of erosion risks on the right bank of the Congo River, notably in the Stanley-Pool Bay, a topography dominated by steep slopes up to 10%, a high erosivity and erodibility and a low soil protection were revealed. Finally, the results of the study show that about 40% of the study area is subject to soil loss. The erosion risk is very severe despite the vegetation cover.

Keywords: Solid Transport, Sediments, Modelling, Models, Stanley Pool, Congo River

1. Introduction

The Congo River is the longest river in Africa (4,700 km) after the Nile, the second longest in the world after the Amazon in terms of flow (41,000 m^3s^{-1}) and has a basin area of 3.7 million km^2 at its mouth. It serves as a border in its upper part between the Republic of Congo (Brazzaville side) and the Democratic Republic of Congo (Kinshasa side) and in its lower part between Angola and the Democratic Republic of Congo (Boma and Matadi) in Bas-Congo. Understanding how it works is therefore crucial in the 21st century when water is a major issue for Africa.

Despite the proliferation of agreements and conventions on the environment (RIO+20 in Brazil), it is difficult, especially for African countries, to follow up on the implementation of the decisions of these conventions at the local level; for example, the desilting of large basins such as the Congo River basin.

Upstream of the two capital cities of the Republic of Congo and the Democratic Republic of Congo, Brazzaville and Kinshasa, lies the Stanley Pool (Mbamou Island), a vast depression 21.4 km long and 12.6 km wide on average, marked in the dry season (from June to August, sometimes until September depending on the year) by imposing sandbanks. Recent scientific hypotheses in the field also highlight the accentuation of erosion problems of an anthropic nature that affect the slopes and banks around the Stanley Pool and in the vicinity of Brazzaville. These problems considerably aggravate the silting up of the navigation channels of the Brazzaville River Port.

Numerous studies carried out at the Stanley Pool in Brazzaville and other scientific documents have shown that the

Congo River is increasingly experiencing, in the middle part of its course, active sedimentation due to a significant transport of suspended matter, the volume of which seriously disrupts, in the dry season, port activities at the level of the Ubangi and also at the level of Brazzaville in the bay of the Stanley Pool, and more specifically at the Autonomous Port of Brazzaville. Studies have revealed that river navigation on the Ubangi River has become almost impossible for more than 200 days per year since 2002 due to a longer annual low water period.

In Brazzaville, in the Stanley Pool, at the Autonomous Port, since the extension works undertaken in 1975, this port has been confronted with the problems of sediment deposits (imposing sandbanks) like those of the Oubangui, thus disrupting its river traffic, the only means of transporting people and goods to connect the cities and countries drained by this vast hydrographic network (the Congo River basin). Indeed, solutions must be found because the economic, social and cultural impacts on the local activities of the Port, but also on the hydric and biological balance of the Congo River, are very considerable. Water and soil are a necessary capital for human beings. Soil is a resource that renews itself very slowly (even on a millennial scale) and in semi-arid areas the soil is washed away by water, this is called water erosion [1]. The combined action of rain and runoff sometimes leads to irreversible soil loss, and water erosion is considered one of the causes of soil degradation [2]. On the right bank of the Congo River, for several years silting has disrupted port activity and caused economic disruption. Until now, the Maintenance Joint Service of Waterways of the Autonomous Port of Brazzaville has been dredging in some places to temporarily facilitate traffic.

With a view to finding sustainable solutions, several studies have been carried out: the quantification of matter in the Congo River by Spronck [3], the first to quantify matter in solution (82mg/l), i.e. an export of 106×10^6 tons/year. Symoens [4] quantified the transport of dissolved mineral substances on an annual basis at 46.5×10^6 tons/year in 1968, then 35.5×10^6 tons/year in 1980. In order to refine certain results, during a five-year period (1987 to 1992), the solid and dissolved matter transport of the Congo River was measured monthly at the surface, making it possible to evaluate the solid flow of the river [5]. During this study period, the Congo River had a flow of 37700 m^3/s, allowing an average export of 91.8×10^6 tons of material distributed as 7.9×10^6 tons of dissolved matter (DM). The 12% of TSS is made up of particulate organic matter (POM) and 29.5% of dissolved matter (DM). The rest of the load corresponds respectively to particulate mineral matter (88% of TSS) and dissolved matter (70.5% of DM). Compared to the world's major rivers, this interannual average concentration of these transports (76.2 mg/l) is low. Laraque et al. [6] estimate that in this year the Congo River transported 26.3 ton/km^2/year with an average runoff of 120 mm [7] and a liquid flow of 41,700 m^3/s [8]. The total distribution of this solid transport at the main station of Brazzaville, which controls more than 95% of the total basin area, shows that 30.6×10^6 tons of solids are transported per year. All assessments made on the Congo River at the Stanley Pool were made in a global and sporadic way. Kinga-Mouzeo [9], reiterating earlier results, estimates that the average annual tonnage of suspended exports is 40.56×10^6 tons. Molinier [10] carried out a series of monthly samples from January 1978 to February 1979. At the same time he tried to diversify the sampling points on the measurement sections. The results of his work are very interesting since they show that the values of the contributions in suspension vary in a significant way between the surface and the bottom, contrary to the dissolved contributions which are approximately identical along a vertical.

Several studies are being conducted to solve this problem without taking into account the relationship between various phenomena, namely (i) water erosion which carries the material into the Congo River, (ii) the different materials transported by the river current according to three modes of transport, (iii) as well as the interaction between the minor bed which is the place of deposition of the suspended material which, when the flow velocity decreases in certain places, is deposited to form sandbanks, and the major bed which transports the material.

This study is a contribution to sustainable solutions for the silting problem in the Autonomous Port of Brazzaville. Using satellite data from the MOUYONDZI, DJAMBALA, M'POUYA, SOUANKE and BRAZZAVILLE stations, the study uses hydrological modelling (Figure 1) to estimate the rate of material transported by the Congo River on the right bank over three decades (1990-2020).

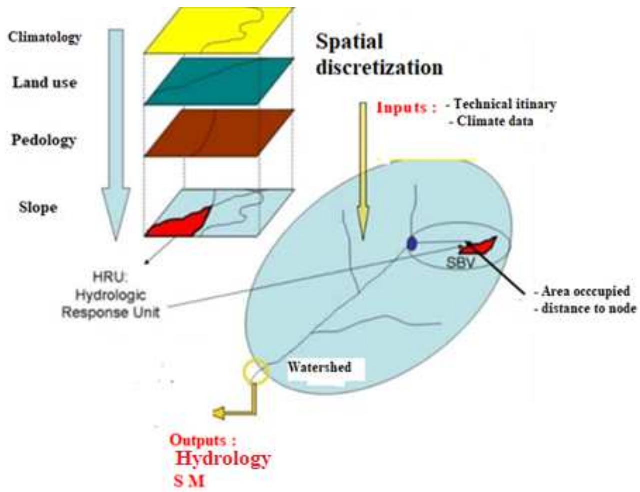

Figure 1. *Representation of a hydrological model.*

2. Materials and Methods

2.1. Presentation of the Study Area

The Congo Basin (Figure 2), with a length of 4700 km, drains a watershed with a surface area of 3,700,000 km^2 covering a large part of Central Africa, with a high density hydrographic network and a slope of about 0.033% allowing water runoff.

Several projects have been initiated to understand the hydrological, hydrogeological and hydroclimatic functioning of the Congo Basin [11]. The Stanley Pool at its entrance constitutes a control threshold for the Maluku limnimetric station.

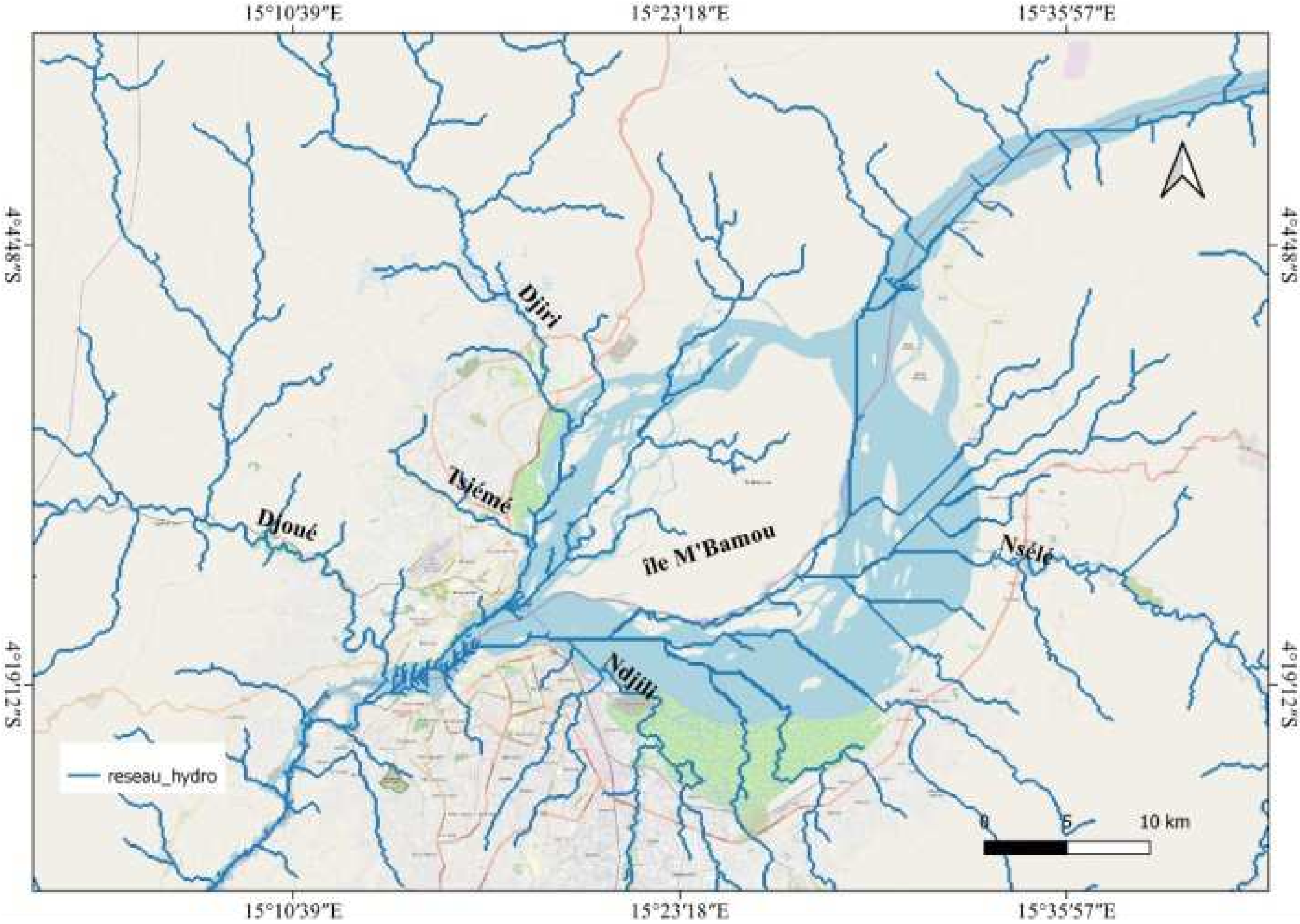

Figure 2. *Hydrographic network of the study area.*

At this point in the river, the flow undergoes a variation due to the widening of the straight section of the river. A second natural sill can be observed at the exit of the rapids which controls the scales of the Brazzaville Beach. The surroundings of the Stanley Pool are very permeable to water infiltration, thus characterizing the rich potential of the groundwater in the vicinity of the Stanley Pool; the increasing distribution of clays from the mainland to the river increases a decrease in the permeability of the soil in the vicinity of the Stanley Pool. In the area around the Stanley Pool, where the slab is absent, the sandy plateau and the Stanley Pool sandstone form a thick, permeable mass, which is favorable to the deep infiltration of rainwater.

2.2. Materials: Data and Software Used

The data (Table 1) are processed in a multi software platform (Arc Gis 10.4.1 and MS Excel 2010), in order to elaborate a very rich database allowing the manipulation, the update of these data, as well as the visualization.

Table 1. *Data and software used.*

No	Documents and download platforms Software	Logiciels
1	Digital Terrain Model, Image Shuttle Radar Topography Mission (SRTM) of 30 m resolution of 2014 Obtained from the website: http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp.	Arcgis 10.4.1. MS Excel 2010
2	Carte numérique du sol du monde « Digital soil maps of the world (DSMW), Obtained from the website: http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116	
3	LANDSAT 8 OLI satellite image of 14/08/2019 with 30 m resolution Precipitation recorded at the Brazzaville station between 1990 and 2020 Obtained from the website: https://gis.ncdc.noaa.gov/maps/ncei/cdo/alltimes	

2.3. Hydrological Modelling

The most important parameters in the hydrological modelling of the study area are rainfall, associated with the physical parameters of the catchment area (soil and slopes) which allow the determination of the hydrological regime (Figure 3).

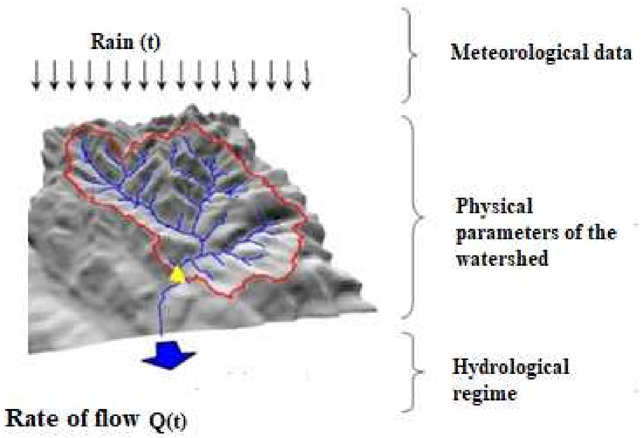

Figure 3. *Watershed modeling.*

2.3.1. Presentation of the Model

Erosion is a multiplicative function of rainfall erosivity (the R-factor which is the potential energy) multiplied by the resistance of the environment, which includes the K-factor (soil erodibility), LS (the topographical factor), C (the vegetation cover and cultivation practices), P (takes into account the anti-erosion practices) These different factors control: climatic aggressiveness, soil erodibility, slope inclination and length, land use and erosion control practices [12, 13]:

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

Where:

A is the annual rate of soil loss in ton/ha/year,

R is the rainfall erosivity factor,

K is the soil erodibility,

LS is a dimensionless factor representing slope (S in %) and slope length (L in m),

C is a dimensionless factor representing the effect of vegetation cover,

P is also a dimensionless factor that accounts for erosion control techniques such as contour ploughing.

2.3.2. Simulation

The methodology consisted in representing cartographic and descriptive information of the different factors and parameters of erosion in a GIS platform [14]. The empirical-based quantitative erosion model thus provides an estimate of soil losses, in ton/ha/year, per unit area, which corresponds, in the case of the use of a GIS-based map overlay, to the base pixel of the DTM.. This approach is illustrated in Figure 4.

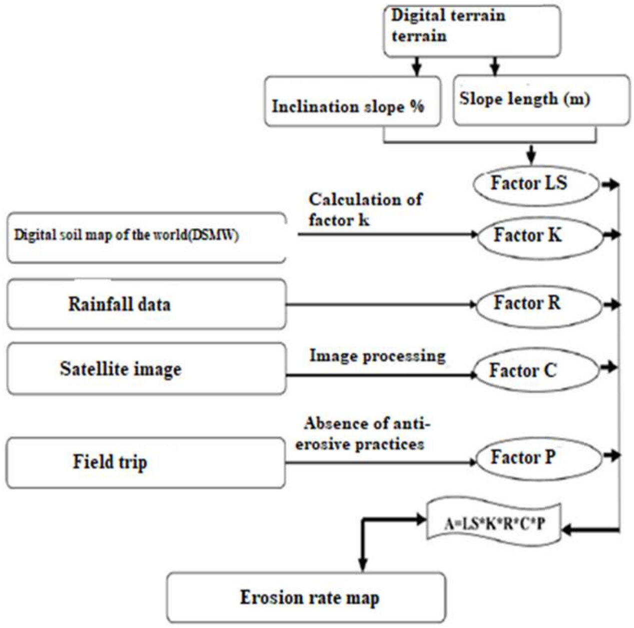

Figure 4. *Methodological approach.*

3. Results

3.1. R-factor

The R-factor (Erosivity in ton/ha/year) is calculated as follows:

$$R = 0.5 \times P \times 1.73 \quad (2)$$

With:

P: Annual precipitation in (mm). Using average annual precipitation in (mm) from different regions in and around the study area. Table 2 summarizes the different erosivity results in (ton/ha/year).

Table 2 summarizes the average annual rainfall of the different stations and the erosivity factor of each station used in the period 1990-2020. Then the R values were interpolated using an IDW interpolation method on ArcGis 10.4.1. In the calculation of the rainfall erosivity factor R. an overall assessment of the rainfall aggressiveness was made over the study area. These results show the role of rainfall in the modelling of soil erosion in the absence of precise data. Indeed, following the distribution of rainfall as a function of altitude. The spatialization map (Figure 5) shows an increase in topography values. We can see that the erosivity of rainfall increases from downstream to upstream. The values of R vary between 1141 and 1193 tons/ha/year.

Table 2. *Erosivity R in ton/ha/year in the watershed.*

Station	Name	Latitude	Longitude	Altitude	Year	Precipitation Annual average	R-Facteur
CF000004402	Mouyondzi	-4	13.95	509	1990-2020	1409.590909	1219.29614
CF000004453	Djambala	-2.53	14.77	789	1990-2020	1865.563636	1613.71255
CF000004452	Mpouya	-2.62	16.22	312	1990-2020	1403.190909	1213.76014
CF000004460	Souanke	-2.67	14.05	547	1990-2020	1232.663636	1066.25405
CF000004450	Brazzaville	-4.25	15.25	314	1990-2020	1319.109091	1141.02936

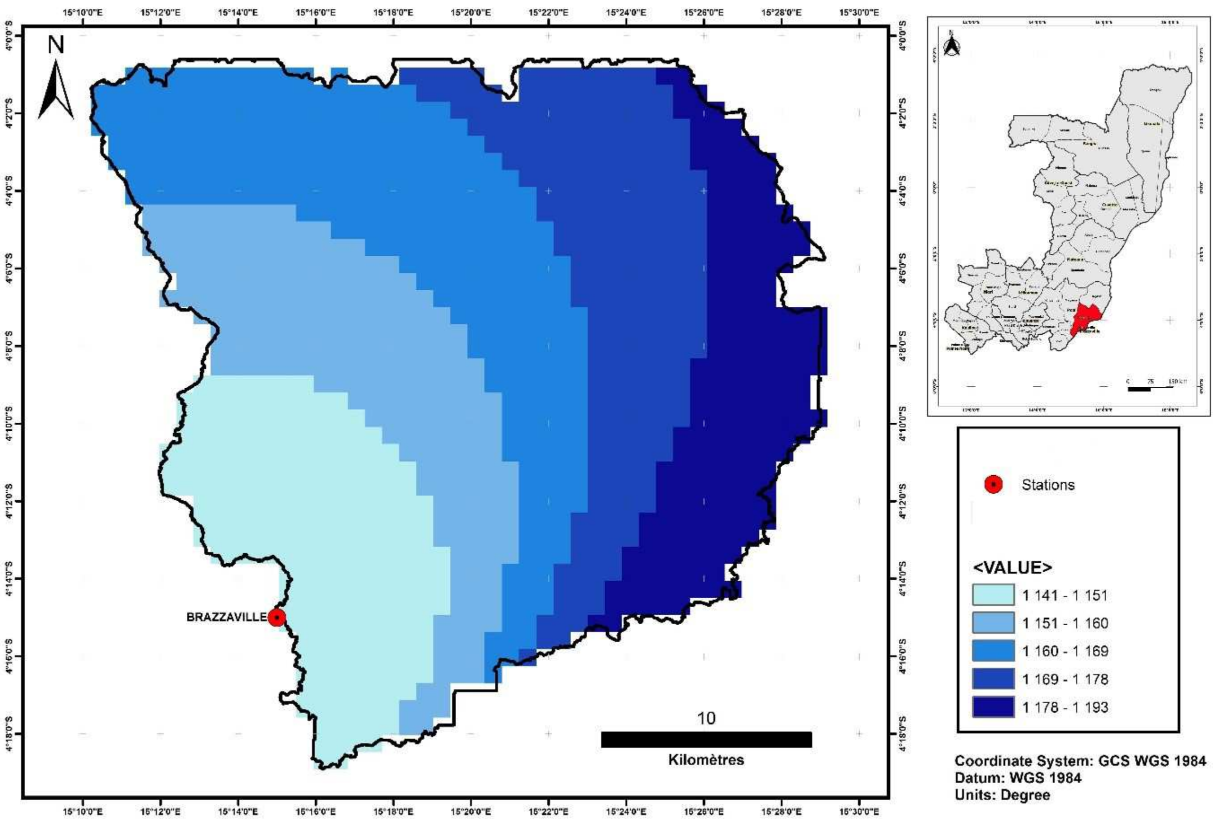

Figure 5. *R erosivity factor Map.*

3.2. Soil Erodibility Factor K

The soil erodibility factor K expresses the sensitivity of the soil to water erosion. We evaluated the K index of the different soil types using the equations of WILLIAMS [15] and using the Digital Soil Map of the World (DSMW). Processing this map in ArcGis gave us the rates of different soil types; sand, clay, silt and organic matter. The soil erodibility factor was calculated by the formula of WILLIAMS [15]:

$$FACTOR\ K = f_{csand} \times f_{cl-si} \times f_{orgC} \times f_{hisand} \quad (3)$$

Where:

f_{csand}: is a factor that lowers indicator K in soils with high coarse sand content and higher for soils with some sand.

f_{cl-si}: gives low soil erosion factors for soils with high rates of silt clay.

f_{orgC}: reduces K values in soils with high organic carbon content.

f_{hisand}: lowers the K-values for soils with extremely high sand content.

$$f_{csand} = \left(0.2 + 0.3exp\left[-0.256.m_s\left(1 - \frac{m_{silt}}{100}\right)\right]\right) \quad (4)$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3} \quad (5)$$

$$f_{org\ C} = \left(1 - \frac{0.25\ orgC}{orgC + exp(3.72 - 2.95\ org\ C)}\right) \quad (6)$$

$$f_{hisand} = \left(1 - \frac{0.7\left(1 - \frac{m_s}{100}\right)}{\frac{m_s}{100} + \exp\left[-5.5 + 22.9\left(1 - \frac{m_s}{100}\right)\right]}\right) \quad (7)$$

m_c: Soil permeability.

m_s: Sand fraction content (0.05-2.00 mm diameter) [%].

m_{silt}: Silt fraction content (0.002-0.05 mm diameter) [%].

orgC: Organic carbon content (SOC) [%].

These three equations allowed the calculation of the K-factor, the results are represented in Table 3.

Table 3. *K Erodability Factor values in the watershed.*

Soil unit symbol	sand % topsoil	silt % topsoil	clay % topsoil	OC % topsoil	f_{csand}	f_{cl-si}	$f_{org\ C}$	f_{hisand}	K-Facteur
QF	91,7	3,3	5,1	0,27	0,2	0,7555625	0,99963383	0,47215787	0,07132283
RD	82,1	6,7	11,3	0,27	0,2	0,74343104	0,99963383	0,70372903	0,10459649
QF	91,7	3,3	5,1	0,27	0,2	0,7555625	0,99963383	0,47215787	0,07132283
WR	0	0	0	0	0	0	0	0	0
WR	0	0	0	0	0	0	0	0	0
RD	82,1	6,7	11,3	0,27	0,2	0,74343104	0,99963383	0,70372903	0,10459649
RD	82,1	6,7	11,3	0,27	0,2	0,74343104	0,99963383	0,70372903	0,10459649

The calculated K values were interpolated using an IDW interpolation method on ArcGis 10.4.1 The values of the K index in the study area (Figure 6) range from 0 to 0.1, showing the fragility of the soils susceptible to erosion. The map obtained shows that more than half of the study area represents a high erodibility than the others. The rest of the area has relatively low values of the soil class showing almost no erodibility caused by the forest reserve.

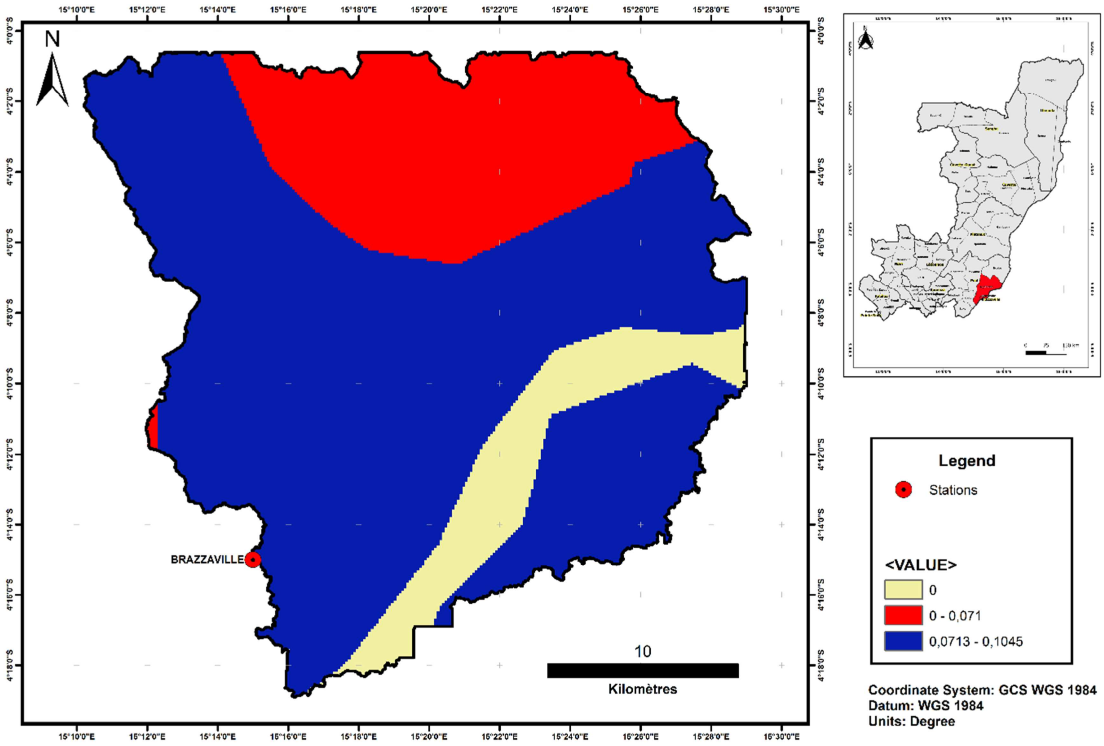

Figure 6. *Erodibility factor Map K.*

3.3. Topographic Factor LS

The topographic factor combines the effects of slope length (L) and slope steepness (S) on erosion. These two factors are calculated from the digital terrain model in Arcmap (Eq. 8).

$$LS = [0.065 + 0.0456 \times (slope) + 0.006541 \times (slope)^2] \times \left(\frac{slope\ length}{constant}\right)^{NN} \quad (8)$$

Where:
Slope = slope inclination (%);
Slope length (m);
Constant = 22.1 in Sys. Metric (72.5 in Imperial units);
NN: see Table 4.

Table 4. *NN Values.*

Slope	**< 1**	**1 ≤ slope < 3**	**3 ≤ slope < 5**	**≥ 5**
NN	0,2	0,3	0,4	0,5

The LS factor represents a ratio of soil loss under given conditions, the higher the slope, the greater the risk of erosion. In fact, upstream of the right branch of the Stanley Pool, the slope varies up to 0.1. At these locations, the risk of erosion is very noticeable (Figure 7).

3.4. Vegetation Cover Factor C

Vegetation represents the effects of plants, soil cover, soil biomass and soil destructive activities in erosion processes. The determination of this factor is developed from the mapping of vegetation density on a satellite image (LC08 Landsat 8 OLI of 14/08/2019 of 30 m resolution), the latter was analyzed on the Arcgis software platform (version 10.4.1) by calculating the NDVI (Normalized Difference Vegetation Index). Afterwards, we used equation (9) of Van der Knijff and al. [16]:

$$Factor\ C = exp\left(\frac{2-\text{NDVI}}{1-\text{NDVI}}\right) \quad (9)$$

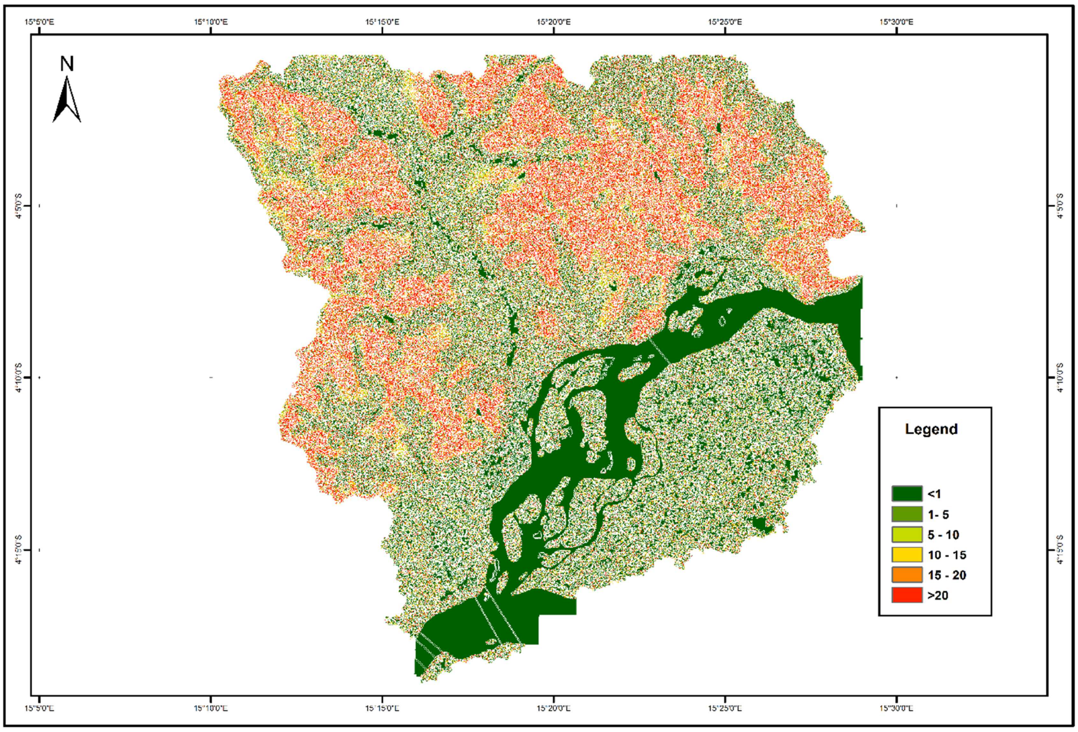

Figure 7. *Topographic factor map LS.*

The C-factor map, presented in Figure 8, shows variant values between 0.407 and 1.097. These results show that these values correspond to a better protection of the soils and are favorable for forest formations where anthropic activities are low.

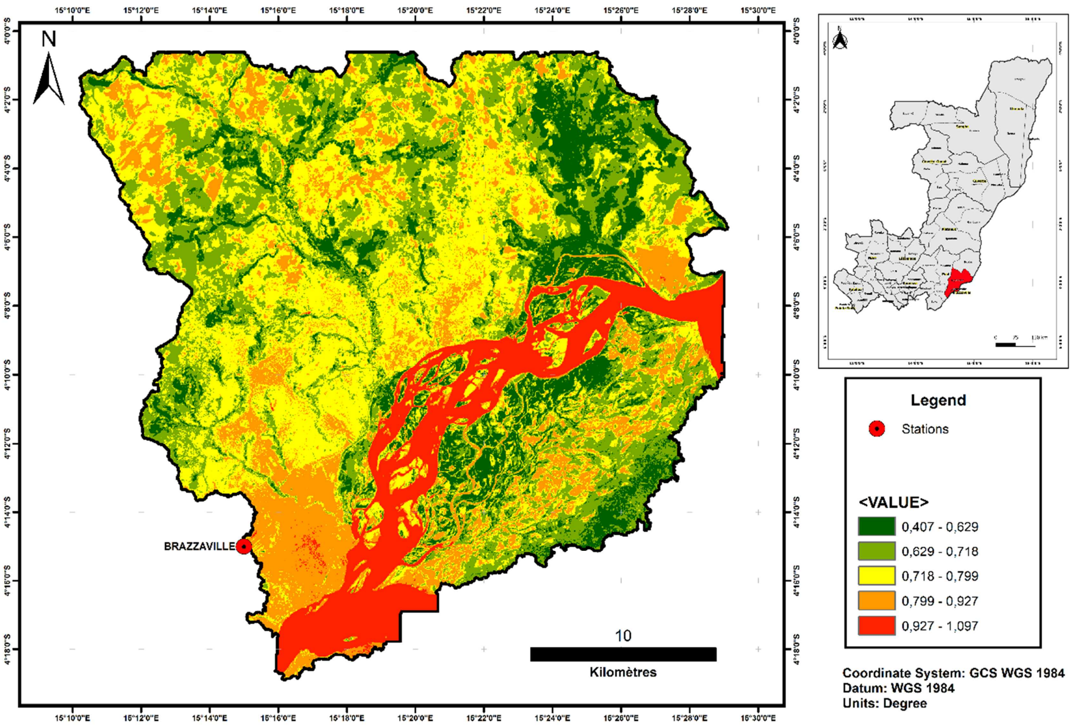

Figure 8. *Vegetation cover factor Map.*

3.5. Factor of Anti-Erosion Practices P

In the case of the watershed, there are some anti-erosion practices. Thus the factor P, referring to the reality of the field thanks to satellite images and the map in Figure 9, has been assumed to be equal to 0.8. This map (Figure 9) shows that about

60% of the study area is relatively protected while the rest is exposed to very high water erosion risks.

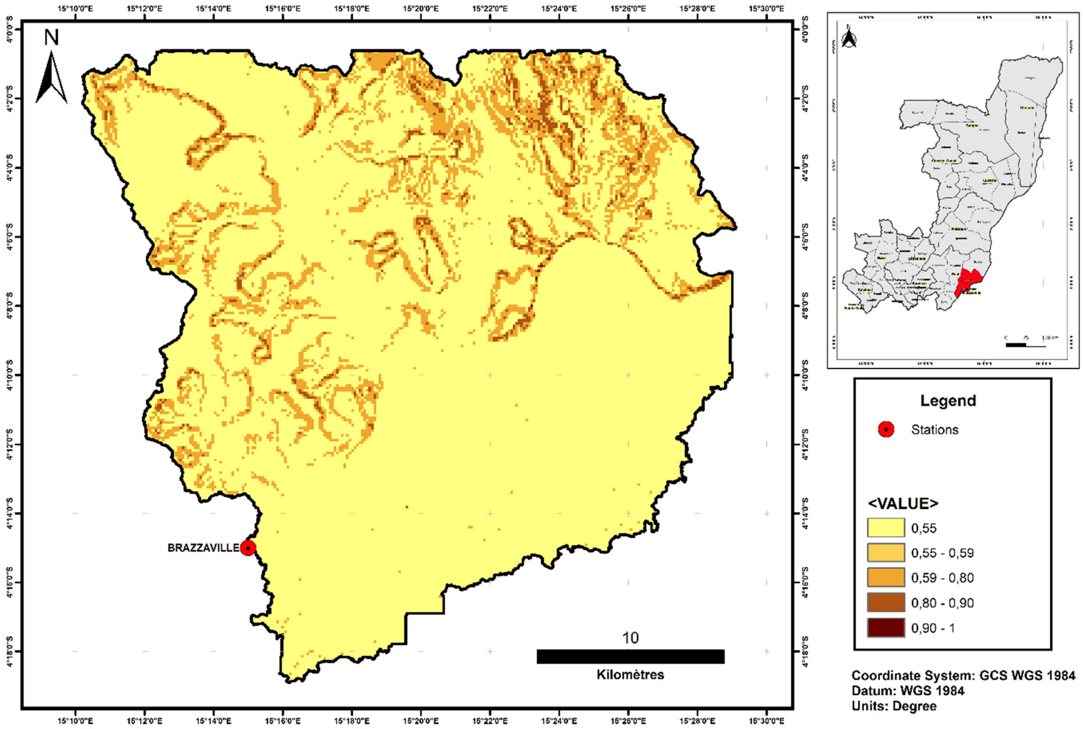

Figure 9. *Map of erosion control practices.*

3.6. Water Erosion Rates

The multiplication of the different USLE parameters under ArcGis software is given by:

$$Water\ erosion\ rate = R\ factor \times K\ factor \times LS\ factor \times C\ factor \times P\ factor \quad (10)$$

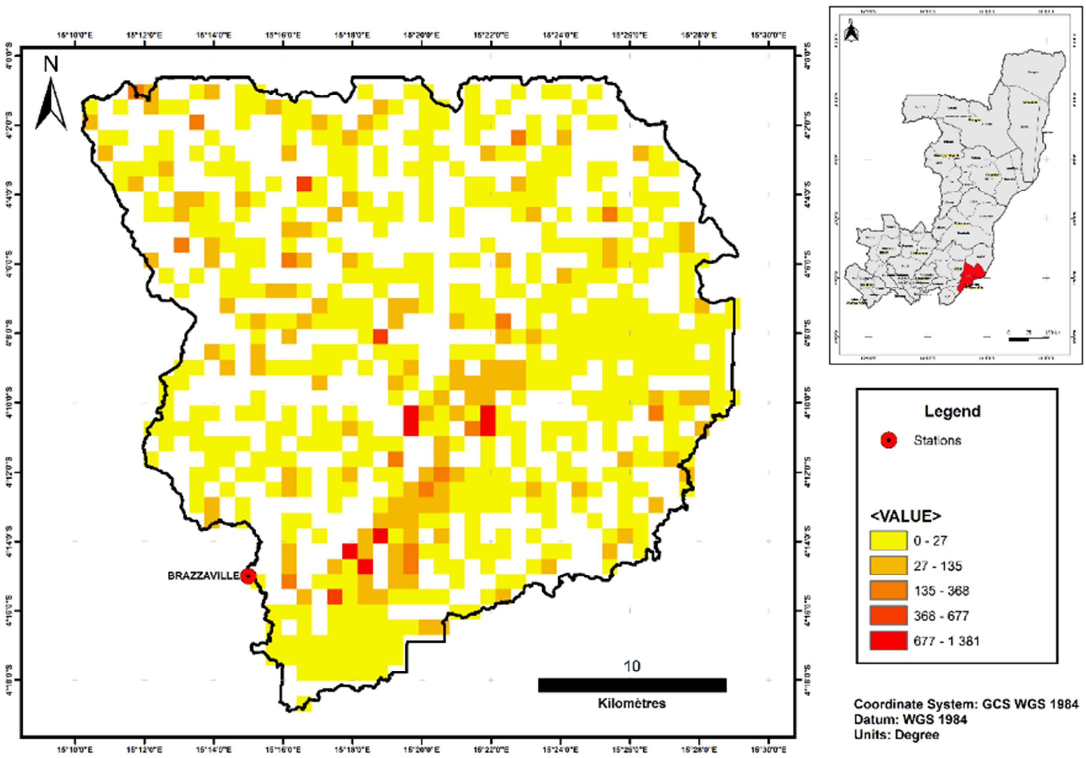

Figure 10. *Soil loss map in (tons/ha/year) in the Watershed.*

The simulation yielded the erosion risk map (Figure 10), informing on the erosion potential in t/ha/year per spatial unit (DTM pixel) at a few points of the watershed with values ranging from 0 to 1381 tons/hectares/year. This map shows a clear spatial variability of water erosion risks within the study area. The right branch of the Congo River, which is a final spillway of the hydrographic network of the city of Brazzaville, is one of the causes.

4. Conclusion

This study is based on the use of open access spatial data and GIS for a spatialization of erosion risks on the right bank of the Congo River, particularly in the Stanley-Pool bay which is the study area. It showed that in this area of the Congo River, the topography is dominated by steep slopes up to 10%, the erosivity is high, the erodibility is high and the soil protection is low. In addition, the existence of an urban and agricultural area in the steep slope zone accentuates the risk of erosion at this location. The results of this study show that approximately 40% of the area is subject to soil loss. The risk of erosion is very severe despite the vegetation cover.

The good management of the hydrographic network, the methods of soil survey by the installation of grass strips are better adapted to face the risk of erosion in this zone, the afforestation of the zones with weak vegetation cover and the support of the efforts undertaken by the population will make it possible to protect in a durable way this territory.

The use of the USLE model, GIS techniques and open access multi-source data can be applied at a reasonable cost to map the risk of erosion at the territorial scale, the analysis of the variability of erosion intensity and the identification of priority areas for soil conservation in the Republic of Congo.

5. Recommendations

The extent of the erosion revealed in this study requires the implementation of appropriate erosion control techniques in this area. Therefore, it is useful to recommend to the public authorities and environmental professionals the following: (i) to carry out geomorphological studies in the area, which would make it possible to promote the infiltration phenomenon in order to limit runoff; (ii) consider conducting a wider study upstream of the Stanley Pool, taking into account all the rivers that flow into the Congo River on both the Brazzaville (Republic of Congo) and Kinshasa (Democratic Republic of Congo) sides, a study that would lead to the establishment of a single management unit for the Congo River in the Stanley Pool; (iii) to sensitise farmers and others in the area on the anti-erosion farming practices that need to be implemented in order to reduce soil erodibility and limit run-off.

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