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Soil Loss Estimation and Change of Storage Volume Using GIS and Remote Sensing Techniques: A Case of Lom Pangar Hydroelectric Dam Watershed, Cameroon

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Abstract: For many purposes of hydropower production, many reservoirs are built throughout the planet. Because of the processes of erosion and sedimentation, these infrastructures are facing a big problem of progressive reduction of their storage capacity. Consequently, a good knowledge of the change of storage for proper planning and management is very important. The Universal Soil Loss Equation (USLE) was used to evaluate the gross erosion in the Lom Pangar catchment and the quantity of sediment that effectively reach the outlet of the catchment.

The gross erosion was evaluated to be 47.2 million tons of soil per year with an average of 6.61 million tons per year that effectively reach the outlet. On the quantity that reaches the outlet, the Brune's sediment trap efficiency was applied and 0.1% of Lom Pangar reservoir decreases per year, an amount smaller than the 1% of annual worldwide reduction of water reservoirs.

Keywords: Erosion, storage volume, reservoir, Lom Pangar Dam, Cameroon.

Introduction

Erosion refers to the detachment of the soil particles mainly by the natural forces of wind, water, ice, or vegetation. When these detached particles mix with organic and inorganic materials during the process of erosion, sediments are formed. Sediments refer to the complex mixture of organic and inorganic particles in the water. In the case of reservoir sediments, water is the major source of erosion. Soil erosion in catchment areas and the subsequent deposition in rivers, lakes, and reservoirs are of great concern for two reasons. Firstly, the rich and fertile soil is eroded in the catchment areas. Secondly, there is a reduction in reservoir capacity as well as degradation of downstream water quality. Soil loss is the result of soil erosion (El Jazouli et al., 2017). The process of sedimentation seriously affects reservoirs worldwide. As the river enters the impoundment, the flow velocities decrease and the sediment carrying capacity drops, causing sedimentation, which reduces the reservoir's storage capacity. According to Petkovsek and Roca (2014), sedimentation is the main cause of 1% of the annual reduction of water reservoirs worldwide. The majority of existing dams and other impounding structures continuously trap sediment and have no specific provisions for sustained long-term use. The life span of the storage capacity of the dam is frequently designed to be less than 100 years (Sumi and Hirose, 2009). However, sometimes the dams reach their design capacity in a shorter time due to the sedimentation problem.

Sediment yield is the net result of soil erosion and processes of sediment accumulation, so it depends on variables that control water and sediment discharge to reservoirs. Typically, sediment yield reflects the influences of climate (precipitation), catchment properties (soil type, topography), land use/cover, and drainage properties (stream network form and density)(Duru, 2015).

Erosion varies from low values in humid, low-relief catchments to very high values in arid, mountainous areas. Due to human modifications, erosion rates rise above natural levels, a phenomenon known as accelerated erosion. Accelerated erosion is a serious matter that reflects an increased population and expansion of arable land use (Chakrapani, 2005).

The present study is to evaluate the potential soil lost per year in the Lom Pangar River Basin (East Cameroon), the dynamics of sediment in the hydropower reservoir, and the establishment of its lifespan.

Materials and method

Study Area

Lom Pangar watershed is located in Cameroon in major part precisely within the East and Adamaoua regions with a small part in the Central Africa Republic, a country that borders Cameroon in his eastern part. That geographical location gives to Lom Pangar the characteristic of a trans-boundary river basin of surface area 19700 km^2. The Lom River runs throughout the Central Africa Republic for a distance of about 5 km around before reaching the Cameroonian territory. That river basin is located between latitudes 4^{o}10”00N and 7^{o}11”00N and longitudes 12 o30”00E and 15^{o}02”00E. Since 2016, the hydropower reservoir has been constructed at the outlet of the Lom Pangar river basin in the forestry part of East Cameroon (Figure 1). The Lom Pangar hydropower dam is located at about 350 km in the North East of Yaoundé, the capital city of the country, and precisely at around 120 km from the capital city of the East region Bertoua. The site of the Dam in the Lom river is 5 km downstream from the confluence of the Lom and Pangar rivers, and around 13 km to the East of the confluence of the rivers Lom and Djerem. The geographical location of the Dam is latitude N 05 º 25', longitude E 13 º 30' and has mains purposes are the regulation of the Sanaga River to increase the power generation of two hydropower plants located downstream during the dry season and generation of 51MW power for the eastern grid of Cameroon. It has 50 meters height and 610 km^2 seize for a storage capacity of six billion m^3.

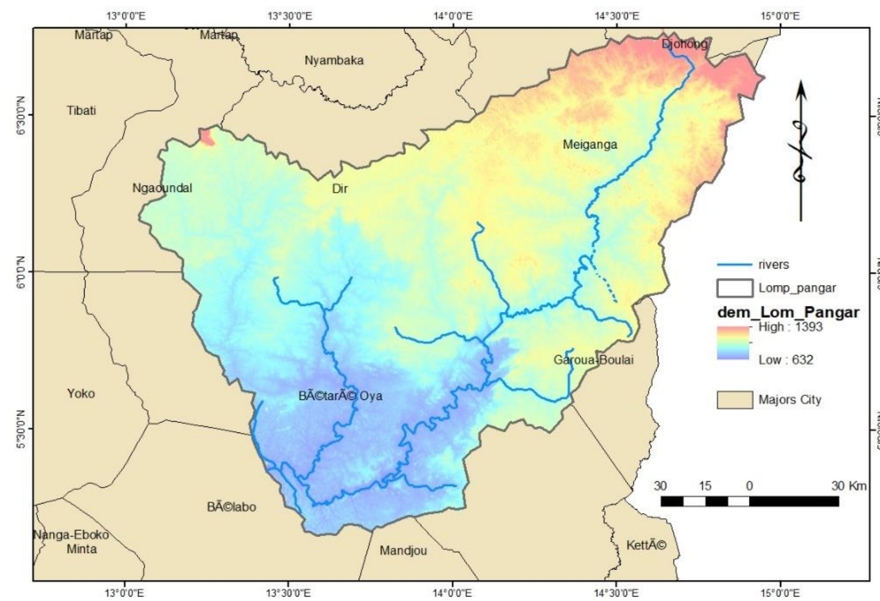

Figure 1 Lom Pangar Watershed defined in ArcGIS 10.2.2

Method

Universal Soil Loss Equation (USLE) For this study, a model-based approach was used to assess soil erosion risk. The availability of input data is a critical selection criterion when assessing soil erosion risk at the regional (or national) scale. Even though a wide variety of models are available for assessing soil erosion risk, most of them simply require so much input data that applying them at a regional or national scale becomes problematic. The well-known Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) was used because it is one of the least data demanding erosion models that have been developed and it has been applied widely at different scales. The USLE is a simple empirical model, based on regression analyses of soil loss rates on erosion plots in the USA. The model is designed to estimate long-term annual erosion rates. Although the equation has many shortcomings and limitations, it is widely used because of its relative simplicity and robustness (Beverly et al., 2009). It also represents a standardized approach.

Soil erosion is estimated using the USLE equation as follows:

$$\mathbf{A = R.\ K.\ L.\ S.\ C.\ P} \qquad \mathbf{(1)}$$

Where:

A= Mean (annual) soil loss

R= Rainfall erosivity factor (MJ/ha.mm/h),

K= Erodibility factor (t.ha.h/ha/MJ/mm),

LS= Slope Length and Steepness factor

C= Land Use/Land Cover factor,

P = Practice factor

The conservation factor P For this study was decided to be 1 to avoid an underestimation of sediment yield. That factor is defined as the ratio of soil loss from the area with conservation measures to the area without any management practices or conservation measures to control soil erosion. The value of P mainly depends on the erosion control measure adopted and varies from 0 to 1.

The procedures used to estimate the factors are explained in detail in the following sub-sections.

Rainfall erosivity factor, R

The USLE rainfall erosivity factor (R) for any given period is obtained by summing for each rainstorm the product of total storm energy (E) and the maximum 30-minute intensity (I_{30}). According to Renard and Freimund (1994), R is the sum of individual storm EI-values for a year averaged over long periods (more than 20 years).

Long-term average R-values are correlated with more readily available rainfall by Roose (1980) for the west and central African countries. The relation of R was established function of the average annual rainfall in millimeters (P).

The relation:

$$R = \left((0.5 \pm 0.05)P\right) \quad \textbf{(2)}$$

was found to work for 20 meteorological stations in Ivory Coast, Burkina Faso, Senegal, Niger, Chad, Cameroon, and Madagascar.

Soil erodibility factor, K

This factor represents the susceptibility of soil to erosion by direct rainfall and runoff water. The value of Kwas computed using the empirical equation given in equation (3) which is developed by Habtamu (2011). The equation needs only the texture of soil or the average percentage of each soil particles (Sand, Silt, and Clay) in the catchment. The formula is as given below.

$$k = a\left(\frac{\%\,silt}{\%Clay + \%Sand}\right)^b \quad (3)$$

Where, k = Soil Erodibility factor (t.ha.h/ha/MJ/mm)

% Sand = percentage of sand in the soil

% Silt = percentage of silt in the soil

% Clay = percentage of clay in the soil

a = 0.32 and b = 0.27 are constant factors

To perform this calculation, the HWSD+FAO soil map has been clipped for our area of study using ArcGis 10.2.2 under the tool Spatial Analyst Tool and extract by mask, using the shapefile of Lom Pangar catchment. Therefore, for the different soils identified in the catchment, the proportion of different component was obtained from the soil database.

Slope- and slope length factors (S and L)

The slope- and slope length factors (S and L, respectively) account for the effect of topography on soil erosion. LS is a dimensionless factor which represents inclination (S in %) and slope length (L in m), It can be estimated from a Digital Elevation Model (DEM). We used the Unit Stream Power Erosion and Deposition (USPED) model developed in Pelton et al., (2014)for calculating the LS factor because it was obvious that it could be done with the tools included in a normal ArcMap installation.

To Calculate the LS Factor in ArcMap 10.2.2 software the following steps are followed:

Step 1: Calculate Flow Direction from clipped Watershed DEM layer Using Flow Direction Tool, name this fd_ws_dem.

Step 2: Calculate Flow Accumulation with Flow Accumulation Tool using fd_ws_dem as your input raster. Name the output file fa_ws_dem

Step 3: Calculate the slope of the watershed in degrees using the Slope Tool. The clipped watershed DEM is used as the input layer. Make sure that the Output Measurement dropdown menu is set to DEGREES. Name this output file, slope_wsn

Step 4: Use the LS-factor formula below with help of Raster Calculator:

Power(“flowacc”*[cellresolution]/22.1,0.4)*Power(Sin(“sloperasterdeg”*0.01745)/0.09, 1.4)*1.4

Land Cover management factor, C

The land cover management factor, C is defined as the ratio of soil loss from cropped land under specific conditions to the corresponding loss from clean-tilled, continuous fallow (Wischmeier and Smith, 1978). The value of C mainly depends on the vegetation’s cover percentage and growth stage. Vegetation cover, after topography, is the second most important factor that controls soil erosion risk (Knijff and Jones, 2000). In the context of this study, remote sensing was used to acquire satellite images and classify them as a function of different types of covers using ENVI software to provide for each cover type, the corresponding C factor based on MODIS land-use class.

Figure 2 explains in detail the different steps of Landsat images classification.

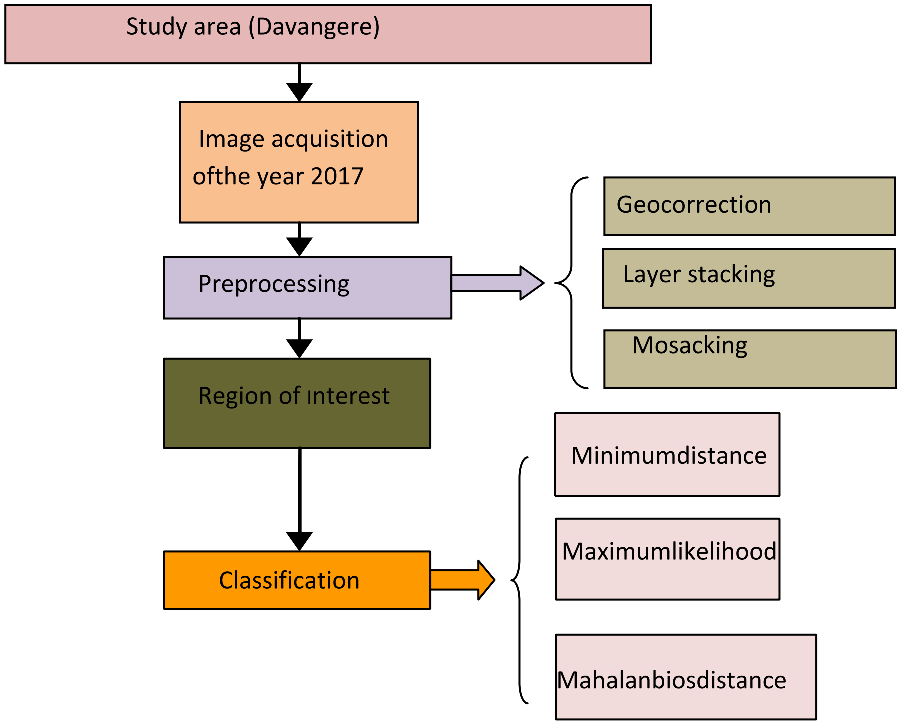

Figure 2 Different steps for images classification (Veerendra et al., 2014)

Sediment Delivery Ratio,(SDR)

The sediment delivery ratio is defined as the fraction of gross erosion that is transported from a given catchment in a given time interval (Lu et al., 2004). It is a dimensionless scalar and can be expressed as follows:

$$SDR = Y/E \tag{4}$$

Where Y is the average annual sediment yield per unit area and E is the average annual erosion over that same area.

In general, the sediment detached from the soil aggregates of the land of the watershed undergoes either deposition or is transported by the flow to reach a certain cross-section or stream. SDR accounts for the amount of sediment that is transported from the eroding sources to the catchment outlet compared to the total amount of soil that is detached over the same area above that point. It often has a value between 0 and 1 due to sediment deposition caused by the change of flow regime and reservoir storage.

Sediment delivery ratio is one of the keys factors with difficult computation to determine the sediment yield of the watershed. Currently, many researchers for its determination have developed several methods. However, in the case of this study the relation developed by Vanoni (1975), was used. It was developed using the data from 300 watersheds throughout the world to develop a model by the power function. This model is considered a more generalized one to estimate SDR.

$$SDR = 0.42\ A^{-0.125} \tag{5}$$

Where A = drainage area in square miles.

Trap efficiency of the reservoir and its estimation

To store water for multiples uses, many reservoirs have been built throughout the world during the past 100 years. In most cases, sediment has been deposited in the reservoirs and decreased the volume of live storage; that phenomenon decreases not only the economic value of the reservoirs but also shortening their operational lives. In some cases, the amount of sediment deposited in reservoirs has been similar to those that the engineers incorporated into their designs, and the reservoirs are functioning adequately. Other reservoirs have had higher rates of sediment deposition than estimated and are either providing smaller volumes of live storage during their design lives or have filled or will fill, with sediments before the design periods are reached (Jolly, 1982). Both occurrences result in serious economic losses with adverse sociological effects.

According to Sultana and Naik (2015), trap efficiency (Te) is the proportion of the stream sediment that is trapped in the reservoir. For this work, Brune’s (1944) method has been used. It is the most common method used for determining the trap efficiency of reservoirs. Brune drew the curves using the data from 44 normal ponded reservoirs in the United States and plotted Te against the reservoir C/I ratio. Brune developed an empirical relationship between trap efficiency and the ratio of reservoir capacity to the annual inflow, which is shown in equations (6)

Brune's Curve for Medium grained sediments.

$$Te = \frac{\left(\frac{C}{I}\right)}{0.00013 + 0.01\left(\frac{C}{I}\right) + 0.0000166\sqrt{\frac{C}{I}}} \tag{6}$$

Results and Discussion

Calculation of USLE Factors

Rainfall Erosivity Factor

Based on the equation developed by (Roose, 1980) for Central and West Africa, the erosivity (k) value for Lom Pangar catchment is calculated to be 852.5 MJ mm ha^{-1} h^{-1} yr^{-1}. This value is found using the average annual rainfall of 1550mm. recorded at the gauge station located at the hydropower reservoir and assuming that the rainfall is uniformly distributed in the catchment.

Soil Erodibility factor (K-factor)

The erodibility factor for this study is obtained from the FAO map. For that, different soil texture has been identified in the catchment using ArcGis 10.22 to clip the world FAO soil map. Therefore, based on USDA soil texture class identified in the catchment, the k factors have been calculated according to Habtamu (2011). The erodibility value (K) for the entire catchment has been obtained according to the different sizes of the area and different soil texture with different K values as shown in Figure 3 and Table 1.

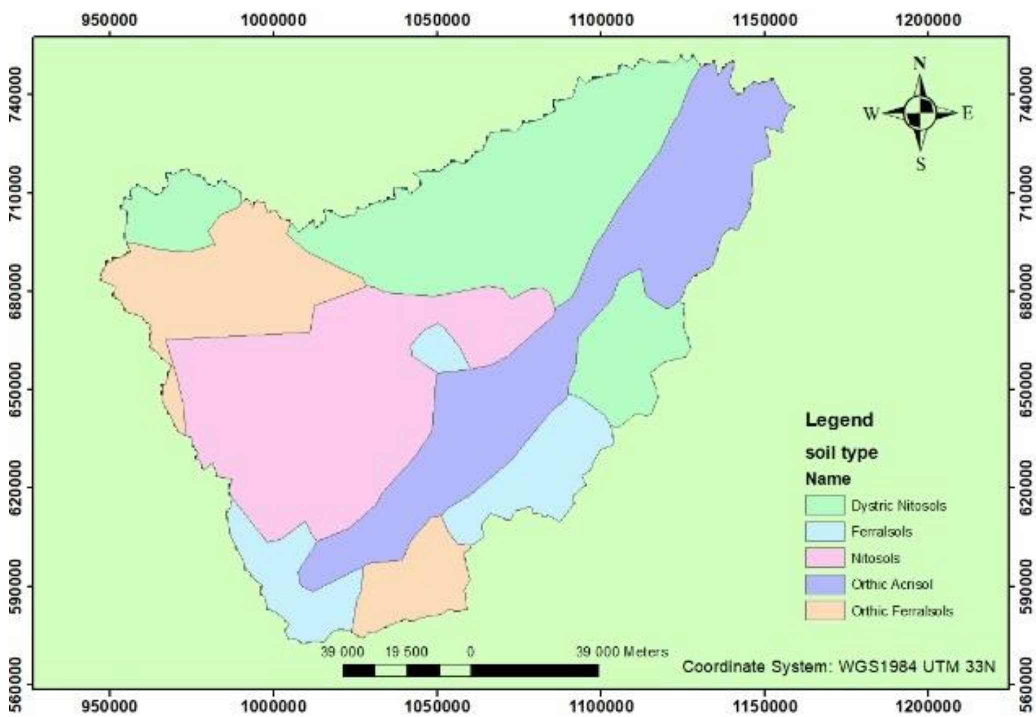

Figure 3. Lom Pangar River Basin soil Map (HWSD +FAO)

Table1. Soil texture and average K_factor of Lom Pangar Catchment

Soil type	%Sand	%silt	%clay	Area in km^2	%	K_factor per soil type and Area	Mean K(t. ha. h (ha MJ mm)
Orthic Ferral sols	60	14	26	2857	14.19	0.196	0.232
Orthic Acrisol	49	27	24	4570	22.7	0.24	
Ferralsols	60	14	26	1887	9.37	0.196	
Dystric Nitosols	22	23	55	5949	29.5	0.23	
Nitosols	44	33	23	4870	24.19	0.264	
				20 000	100		

Slope- and slope length factors

The LS factor accounts for the effect of topography on erosion in (R) USLE. The slope effect L represents the effect of Slope length on erosion and the slope steepness factor (s) reflects the influence of slope gradient on erosion. Following the methodology given above, the results are shown in Figure 4. The maximum value of the slope length factor is 56.247 while the minimum is 0 with an average of 2.21.

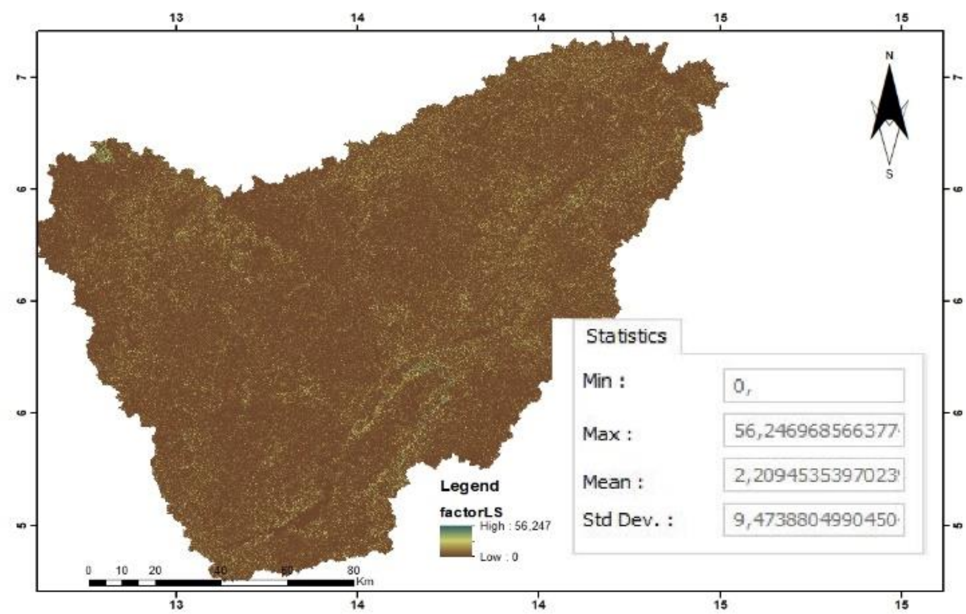

Figure 4. Lom Pangar Catchment LS map

Plant cover factor C

Plant cover is effective in preventing erosion to the extent that it absorbs the kinetic energy of raindrops, covers a large proportion of the soil during periods of the year when rainfall is most aggressive, slows down runoff, and keeps the soil surface porous. After supervised classification, of the Landsat 8, we came up with four main classes, which were – a forest that represents 34.1% of the total catchment, water bodies covering 1.5% of the catchment area, savannah covering 63.1%, and built-up area covering 1.27% of the catchment (see Figure 5 and Table 2).

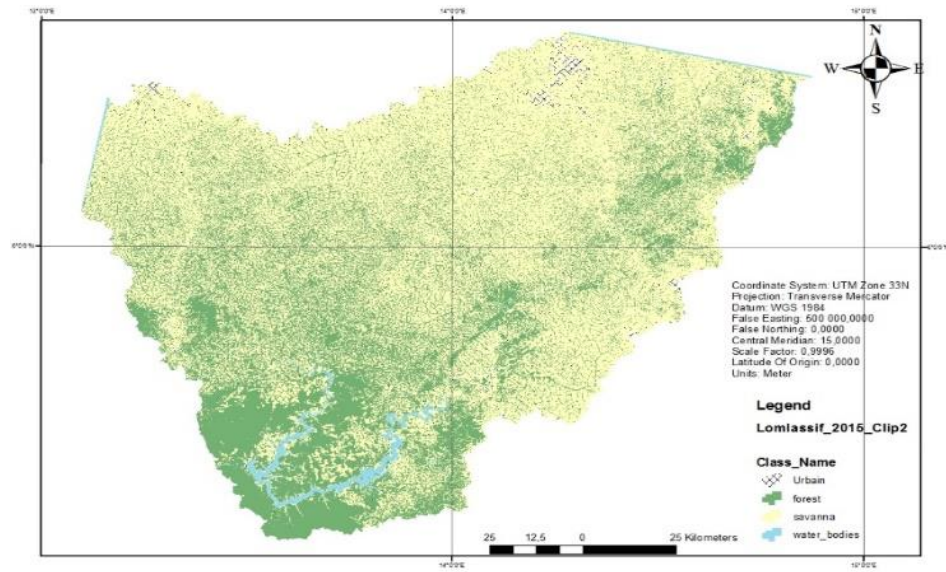

Figure 5 Land Cover Map 2015 of Lom Pangar River basin

Table 2: Different k_factors in Lom Pangar Catchment based on Land Use

Land Cover	Coverage in %	MODIS C_factor	Mean C_factor
Forest	34.1	0.01	0.054
Savannah /Shrub land	63.1	0.06	
Bare and built up	1.27	1	
Water bodies	1.5	0	

Soil loss from the catchment

To evaluate the soil loss from the watershed using the USLE model, the topographic map of 30 m x30m resolution was used in ArcGIS software to generate the LS factor which average was 2.21. To determine the erodibility factor, the FAO map was used to generate different soil types, present in the catchment, and come up with different mineral components. The average erodibility was evaluated to be 0.232 t. ha. h (ha MJ mm). The Roose (1980) equation and the average annual rainfall were used to generate the erosivity factor which average for the watershed was 852.5 MJ mm $ha^{-1} h^{-1} yr^{-1}$. Concerning the cover factor, the MODIS table and the classified map were used to come up with an average C factor of 0.054. To avoid underestimating the soil loss, the practice factor was considered to be one. Following the determination of different USLE factors, the average rate of soil loss from the Lom Pangar catchment per hectare has been found to 23.6 ton/ha/year. The table below gives a summary of different factors.

Table 3. Values of different USLE factor and total soil loss

USLE_FACTORS	Values
R= Rainfall Erosivity Factor (MJ/ha.mm/h)	852.5
K=Erodibility Factor (t.ha.h/ha/Mj/mm)	0.232
LS=Slope length and Steepness Factor	2.21
C=Land Use/ Land Cover factor	0.054
P= Conservation measures	1
A=Mean (annual) soil loss(t/ha/year)	23.6

Based on the above result, it can be established according to the surface area that the Lom Pangar catchment loses 47.2 million tons of soil per year.

Sediment Delivery Ratio (SDR)

The sediment eroded from a watershed undergoes either deposition, either transportation to reach the cross-section of the stream. The ratio between the observed sediment yield at a cross-section of a stream and the total quantity of soil eroded in the catchment above that section is the sediment delivery ratio.

Using the equation developed by Vanoni (1975), the sediment delivery ratio for the catchment is 14%. Based on this, it can be computed and concluded that the Lom Pangar river annual sediment yield is 6.61 million tons per year.

Change of storage volume of the reservoir

The storage volume of the reservoir at any specific time is a function of the sediment load in the water and the capacity of the reservoir to retain that sediment known as its trap efficiency. Table 4 below gives the change of storage of Lom Pangar reservoir based on the quantity of sediment trapped.

The capacity-inflow ratio is equal to the capacity storage of the reservoir divided by the annual average inflow in m^3/year.

The trap efficiently value at the specific time is read is calculated using Brune's formula (Eq 6) based on the value of the capacity-inflow ratio

The average annual sediment inflow in m^3 is equal to the mass of the average annual sediment reaching the reservoir divided by the specific weight of sediments (1150 kg/m3)

Sediment Trapped is equal to average annum sediment inflow in m^3 multiplied by the corresponding trap efficiently

The sediment trapped in m^3 for a specific period is equal to that period (20years in our case) multiplied Sediment Trapped

The specific storage capacity is equal to specific storage capacity divided by the initial storage capacity of the reservoir.

Table 4 Calculation of Change of Storage

Period (years)	Storage Capacity $x10^6$ (m^2-m)	Av. Annual Inflow (I) $x10^6$ (m^2-m)	C/I Ratio	Brune's Trap Efficiency E(%)	Av. Annual Sed. Inflow (ISA) x106 (m^2-m)	Sed. Inflow for Period (ISP) x106 (m^2-m)	Sediment Trapped {Strap (i)} x106 (m^2-m)	% of initial Capacity % $C_{(1)}$
1-20	6000	7789.4	0.77	95.5	5.74	115	110	100.00
20-40	5890	7789.4	0.75	95	5.74	115	109.25	98.00
40-60	5780.8	7789.4	0.74	94	5.74	115	108	96.00
60-80	5673	7789.4	0.72	93	5.74	115	107	94.00
80-100	5566	7789.4	0.71	92	5.74	115	121.6	92.7

Conclusions

Sedimentation is worldwide known as phenomena that affect seriously reservoirs. This affects the reservoir by reducing the storage capacity of the infrastructure, which in our case is used to regulate the flow and stabilize the production of power in the greater Sanaga catchment.

The USLE generated a possible soil loss of 47.2 million tons per year in Lom Pangar. That total soil does not reach the outlet and the quantification of the amount reaching the outlet was done using the sediment delivery ratio formula established by Vanoni (1975) based on the area of the catchment. The result gave a ratio of 14% of the total sediment that reaches the outlet. That amount represents 6.61 million ton/year that reaches the reservoir.

Having the total sediment reaching the outlet, the reservoir capacity that is 6 billion $m^{3,}$ and the average annual inflow of 7789.4 million m^3 per year, the useful life of the reservoir was developed based on the Brune's trap efficiency curve. The change of storage is evaluated to be 0.1% per year in the Lom Pangar watershed, smaller than the 1% of annual worldwide reduction of water reservoirs. Based on the construction design parameter, the useful life of the reservoir is generally 100 years; par consequent, it can be retained from our result that the sedimentation is not a major problem in Lom Pangar reservoir.

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