

MODELLING SOIL EROSION AND RESERVOIR SEDIMENTATION USING USLE

CASE STUDY OF THE TANDJARI CATCHMENT IN THE GOURMA REGION,
BURKINA FASO

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BACHELOR OF SCIENCE THESIS
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Cover photo: Children collecting water at the Tandjari reservoir.
Photo taken on 28-03-2017 by Niels Oostveen

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ABSTRACT

Soil erosion and reservoir sedimentation is a serious problem in semi-arid regions like the Gourma region in Burkina Faso. The newly created water agency AEG in Gourma is responsible for the management of water reservoirs in the region. The young water agency is still defining its course and suitable monitoring and management plans for the area. The Tandjari reservoir is used for the drinking water supply of the nearby capital of the region Fada N'gourma. As the monitoring of the reservoir is in development, not much data is present yet. This study focused on the quantification of soil erosion in the reservoir catchment basin, and the resulting reservoir sedimentation and effect on the storage capacity. The Universal Soil Loss Equation (USLE) is used to estimate the amount of erosion on catchment scale.

The data needed for the different USLE parameters was readily available in some cases, or had to be gathered through field study, remote sensing or by investigating local databases. Because of the semi-arid climate in the region, the calculations were done on a monthly scale to account for the difference between the dry and the rainy season. The resulting mean annual soil erosion in the catchment area was calculated at 16.04 tonnes per hectare per year, with a range of error between 75 – 127 % of the mean. Erosion maps were created identifying the areas of high erosion risk. Using conversion rates accounting for the sediment delivery rate, the reservoir trapping efficiency and the sediment specific density, defined for the region and the specific catchment, the mean rate of sedimentation in the reservoir was estimated at 54.417 m³ per year, or a 1,2% loss of storage capacity per year. For the 18 years since the construction of the reservoir this is a total decrease of 979.497 m³, or 21% of the initial storage capacity, putting the half-life time at 42 years. Taking into account the error margin, the half-life lies in the range of 34 and 57 years, meaning that in the worst-case scenario the half-life is reached in 2030, and in the best-case scenario in 2053.

An attempt was made to calibrate the USLE model to the actual reservoir sedimentation rate. However, due to contradictory data on the storage capacity retrieved from different national offices, this proved to be impossible with the data currently available. Recommendations resulting from the study include the use of vegetation in the high erosion risk areas as an erosion mitigation measure, and conducting a bathymetry survey in the future to be able to calibrate the USLE model. The calibrated model can then be used to quantify the erosion and sedimentation rates in other parts of the AEG management area.

PREFACE

This report is the result of my graduation project carried out at World Waternet in Amsterdam from February until June 2017. As a graduate student Land and Water management, specializing in applied hydrology and international water management, the project offered by World Waternet, studying erosion and sedimentation working together with a local water agency in Burkina Faso, certainly suited my interest.

My activities in this project consisted of the preparation of the work in the Netherlands before moving to Burkina Faso for 6 weeks. The preparation included a large literature review and the development of the methods. Once in Burkina Faso, the field work could be carried out with the aid of the employees of the AEG. The most uncertain and challenging part of the study was the data collection in Burkina Faso, both Ouagadougou, the capital of the country, and in Fada N'gourma, the seat of the AEG. For the data collection, many offices and institutes were visited and consulted, as databases and digital files are not readily available. The sharing of data is not a matter of course as it is in the Netherlands, and many times the permission of the head of the office is needed. The employees of the AEG were in this respect extremely helpful. Personally, I have learned much during the process, bringing to light the importance of the preparation before commencing the field work in another country in addition to having learned much about erosion and sedimentation.

I would like to express my gratitude to the project leader Piet Johan and my supervisor Joost Stoffels from World Waternet for offering me the opportunity to participate in the collaboration between World Waternet and the AEG. Special thanks to my fellow student and companion in Burkina Faso, Eleni Bampalouka, for the company in the daily life in Burkina Faso. I wish to acknowledge the help of the employees of the AEG for assisting me with the fieldwork and overall in making things possible. Finally, special thanks to my university supervisor, Karen Leever, for supporting me in the process of realizing this report.

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ABBREVIATIONS

AEG	<i>Agence de l'Eau du Gourma</i> , the water agency in Gourma region
BERA	<i>Bureau d'Etudes et de Recherches Appliquées</i> , a national research institute
DEIE	<i>Direction des Etudes et de l'Information sur l'Eau</i> , a national research institute
DEM	Digital Elevation Model
WWn	World Waternet
IWRM	Integrated Water Resources Management strategy
ONEA	<i>Office National de l'Eau et de l'Assainissement</i> , the national drinking water company of Burkina Faso
TE	Trapping Efficiency
UPSED	Unit Stream Power Erosion and Deposition method
USLE	Universal Soil Loss Equation

1 INTRODUCTION

1.1 BACKGROUND

The availability of good quality drinking water is a serious issue of concern in Burkina Faso, a landlocked sub-Saharan country in Western Africa. The country has an area of 272.967 square km and a population of 18.6 million (2016) with an average population growth of 2.9% per year. Its capital is Ouagadougou. Burkina Faso gained full membership of the United Nations on 20 September 1960 (UNdata, 2017). 3 million people in Burkina Faso lack access to safe drinking water. 2800 children under the age of five die every year caused by poor water and sanitation. In some parts of the country, mining activities cause pollution to water supplies (Wateraid). Climate change has a large impact in western Africa and Burkina Faso, with decreasing precipitation and increasing temperatures resulting in a higher potential evapotranspiration (IPCC , 2014). The availability of water is already scarce in large parts of Burkina Faso as the annual rainfall is concentrated in a few months of rainy season (Mahé & Paturel, 2009). Many of the rivers and streams are ephemeral, drying up in the dry season. Land-use changes due to the increasing population result in more water being used for irrigation (Fox, Rockstrom, & Barron, 2004). Combined with the growing population, the increasing pressure on the water demand is of large concern for the future of the country.

The government of Burkina Faso, recognizing water resources management as an important issue for the future of the country, has adopted a law in 2001 defining the global strategy concerning the public action regarding water resource management. This has led to the development of the Integrated Water Resources Management strategy (IWRM) and the creation of five Water Agencies covering the area of Burkina Faso (Ministry of Agriculture, Hydraulics and Fishing Resources, 2003). With the implementation of IWRM, a lot of water related activities and responsibilities in the country have been transferred from commercial and state institutions to the newly created water agencies. The Agence de l'Eau du Gourma (AEG) is one of these new agencies. The agency is located in the Gourma region in the east of Burkina Faso (Figure 2.1).

In Burkina Faso water that precipitates in the rainy season is retained in reservoirs (In French: barrages) for year round use. The oldest of these reservoirs are over 100 years old. Dams were built to ensure the availability of water to people and their livestock in periods of drought, bridging the dry period. In 2001, there were 1053 registered reservoirs in Burkina Faso (Cecchi, Meunier-Nikiema, Moiroux, & Sanou, 2009). Approximately half of these reservoirs were built in a period of serious drought extending over western Africa between 1974 and 1987. The practice of building dams to create water reservoirs is likely to continue in the foreseeable future. The users of these reservoirs range from local villages and private users to the national drinking water company Office National de l'Eau et de l'Assainissement (ONEA).

Soil erosion and reservoir sedimentation can be a significant issue in semi-arid regions such as the Gourma region in east Burkina Faso. As the rainfall is mostly concentrated in a few months per year, the eroding factor of the precipitation is high. Land degradation due to soil erosion is one of the most serious threats to food production in western Africa (Bationo, Mkwunye, Vlek, Koala, & Shapiro, 2003). The fertility factors of a large number of tropical soils are found stored in the first

20 centimeters, and sheet erosion selectively removes the organic and mineral colloids as well as the nutritive elements that assure the chemical and water reserve of the soil (Roose, 1976). Erosion rates in Africa can exceed 100 tonnes per hectare per year in erosion hot-spots (Stocking, 1984). Moreover, the eroded soil deposits in the reservoirs, adversely affecting their storage capacity (Sally, Lévite, & Cour, 2011; Mamede, 2008; Schmengler, 2011).

1.2 PROBLEM DEFINITION

With the implementation of IWRM, the newly created water agency AEG acquired the responsibility of maintaining the reservoirs within its management area. There are 112 registered reservoirs within the management area (Agence de l'Eau du Gourma, 2014). As the Water Agency is still a young organization, the search for suitable management plans for the area continues. The main problem is the lack of financial means, knowledge and institutional management. The monitoring activities in the area are improving rapidly, but the knowledge for the right use of the data is missing. In July 2014 the Dutch non-profit organization World Waternet (WWn) and the AEG signed a letter of intent for the collaboration between both partners for the duration of 5 years. The nature of the cooperation is based on knowledge sharing, rather than financial support. The areas of collaboration range from capacity building, supporting the EAG in institution building, to technical support in monitoring and maintaining ground- and surface water. For this partnership, in 2016 a water balance has been made for the Tandjari reservoir, an important reservoir in the management area of the AEG (De Jong Posthumus, 2017). This reservoir lies close to the city of Fada N'gourma, the capital of the Gourma region with a population of 41.785 (ONEA, 2016). ONEA uses the Tandjari reservoir as its main source for water supply to produce drinking water for the city. As a follow-up on the previous study, this study has been carried out to establish the effect of erosion on the lifetime of this reservoir. The focus of this research lies on the use of the available data to quantify the erosion and sedimentation in the Tandjari reservoir and catchment basin, and to estimate the effect over time on the storage capacity of the reservoir.

1.3 RESEARCH OBJECTIVE

The aim of this project is two-sided. Firstly, the aim of this study is to gain an understanding of the erosion around the Tandjari drinking water reservoir in the management area of the AEG, and the sedimentation in these reservoirs. An important part of the study is to ascertain how much useful data is available and what data needs to be collected (either in the field, through remote sensing or from local archives). With the knowledge of erosion and sedimentation rates in reservoir basins the change in reservoir capacity over time can be calculated, which is of vital importance for proper management planning of the reservoirs, with the ever increasing water demand in the region. High erosion hot-spots will be identified for targeted counter erosive measures.

Secondly, the aim of the collaboration between the AEG and WWn is sharing knowledge and building capacity at the AEG. Therefore, the methods and results of this research and the case study at the Tandjari catchment and reservoir will be shared with the AEG, so that the employees of the AEG can obtain the know-how to duplicate these methods in other regions within their management area.

1.4 RESEARCH QUESTION

The main research question of this study is:

- *“How much erosion takes place around the Tandjari reservoir, and how does this affect the storage capacity of the reservoir?”*

To support this research question, the following sub-questions have been formulated:

- *What is the erosion rate of the catchment area of the Tandjari reservoir, and which data is needed to determine this rate?*
- *What is the sedimentation rate in the Tandjari reservoir and how does this affect the storage capacity of the reservoir?*
- *Which locations and techniques are suitable for erosion mitigation in the Tandjari catchment area?*

1.5 REPORT OUTLINE

In chapter two the study area is described. In chapter three the methods used in this study are explained. Chapter four elaborates on the results of the study. Chapter 5 is a discussion on the methods and the results of the study. In chapter six a conclusion is presented. In chapter seven recommendations resulting from the study are made.

2 STUDY AREA

The management area of the AEG lies in the east of Burkina Faso, bordering Niger in the northeast and Benin and Togo in the south. It has an area of 50.238 km². Around 1.7 million people live in the management area of the AEG (Agence de l'Eau du Gourma, 2014). Its area is divided roughly in half between sub basins of the Niger River drainage basin to the north, and of the Nakanbé (formerly named Volta) river drainage basin to the south (Figure 2.1). The seat of the AEG is in Fada N'gourma, the capital of the Gourma region, which lies 236 kilometers to the east of Ouagadougou, the capital of the country.

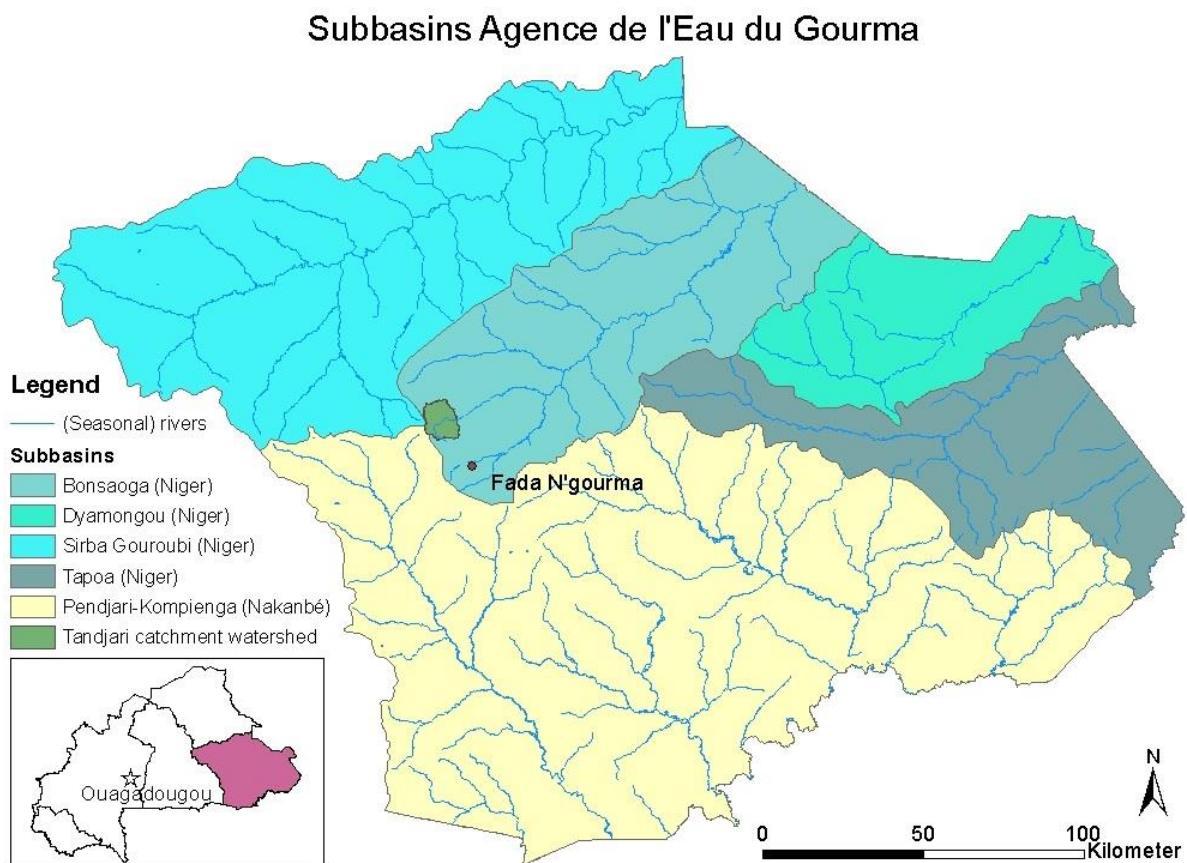


Figure 2.1. Management area of the AEG with its sub river basins. The river system in blue is mostly seasonal with flow only in the rainy season. Inset: The area of the five water agencies in Burkina Faso, the AEG highlighted in purple.

The Tandjari reservoir lies 15 km to the northwest of the city Fada N'gourma. The reservoir is formed by a dam spanning a low valley in the uppermost part of the Bonsoaga sub basin. The surface area of the reservoir varies strongly depending on the season. The Tandjari catchment area draining into the reservoir has a surface area of 105 km². The altitude varies between 369 meters and 297 meters above sea level.

The Gourma region is one of the poorest regions of the country, and the main activities are small scale farming and husbandry. An export product of the region is cotton. In the Tandjari catchment these activities are reflected by the land use (Figure 2.2). In the catchment, the surface cover is divided mainly between the two land use classes of savanna and pastoral use, beside small areas of agricultural use and forest. The Tandjari reservoir lies in the east of the catchment, with large inundation areas which are flooded regularly, but for short durations, in the rainy season. Along the perimeter of the reservoir, small plots of crops are grown and irrigated with water from the barrage, allowing the local population to grow crops year round. The pastoral areas are used by the people of the villages for small plots of crop production, including some cotton, rangeland for cattle and some fruit tree cultivation, besides being left barren. The savanna areas are characterized by a vegetation cover of shrubs and small trees, without a closing canopy. The border between savanna and pastoral use is not everywhere sharply delineated, as in some places along these lines the vegetation pattern of rangelands gradually becomes more dense and forms savanna vegetation. However, the monitoring and regulation of the land use practices are not very strong in the area and mostly organized on a local scale, hence the land use practices, particularly in the areas of pastoral use are susceptible to change. There are five villages in the Tandjari catchment, with a combined population of 8000 persons (INSD, 2006).

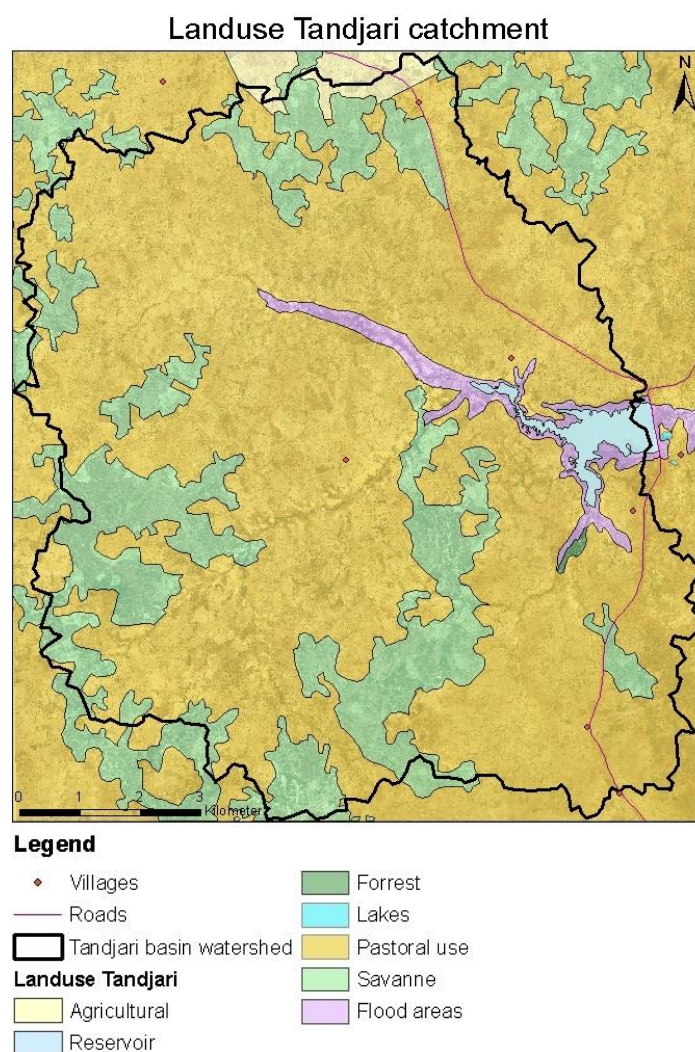


Figure 2.2. Land use map of the Tandjari catchment area.

The climate of the region is defined as hot semi-arid. It is relatively dry most of the year and has a defined rainy season. The rainy season lasts three months, from July until September, with the first heavy rains starting already in June (Figure 2.3). During and shortly after the rainy season, the area transforms from the dry barren land typical for the dry season into a lush vegetated area. This is the period the otherwise fallow croplands are cultivated. The streams feeding into the Tandjari reservoir only experience flow during this time.

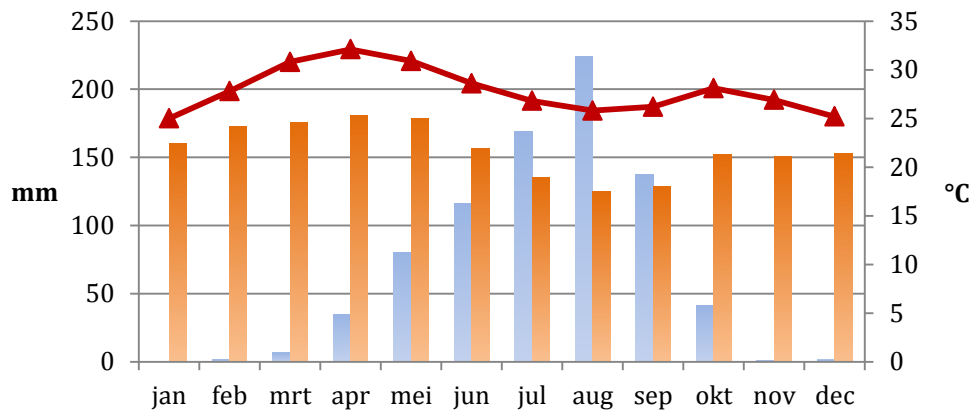


Figure 2.3. Average rainfall (in mm, blue bars), potential evapotranspiration (in mm, orange bars) and temperature (in °C, red line) per month. Derived from meteorological data from 1984 until present from the Fada N'gourma meteorological station (AEG, 2017).

The average annual rainfall amounts to 813 mm, while the potential evapotranspiration adds up to 1867 mm. Only during the three months of rainy season the rainfall exceeds the potential evapotranspiration. This large offset between the precipitation and the potential evapotranspiration underlines the need to store water during the wet season for use in the dry season.

3 METHODOLOGY

The method used for the estimation of erosion at the Tandjari catchment is the Universal Soil Loss Equation (USLE), explained in chapter 3.1. The parameters used in this model were derived from field observations, GIS analysis and literature. With the USLE calculations, the sediment yield at catchment scale can be estimated and used to derive the sedimentation rate in the Tandjari reservoir, with the appropriate conversion calculations as explained in chapter 3.2.

3.1 USLE

In many soil erosion studies, the empirical Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) is used to calculate the water erosion on land surface. This method is used to estimate the erosion in the catchment area of the Tandjari reservoir. The USLE equation determines the amount of erosion of a given area through many variables specific to the area. The equation was empirically derived from extensive soil erosion data measured using natural and simulated rainfall runoff plots in many locations, spanning many years. Since its development, numerous researchers have used the USLE equation in their studies, and many improvements and location specific enhancements to the methods for deriving the specific sub factors have been made, as explained further on in this chapter. The equation computes the average soil erosion (A) in tonnes per hectares per year, using the parameters rainfall erosivity (R), soil erodibility (K), topographic factor slope length and steepness (LS), cover and management factor (C) and the counter erosive measures in the area (P):

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

There are two types of erosion caused by hydrological processes. The first is erosion due to the kinetic energy of raindrops at impact, detaching soil particles. This is represented in USLE by the parameters R and K . The second type is erosion due to runoff. The flow of water over the soil surface detaches and transports soil particles. The LS parameter includes this factor into the equation. Finally, the parameters C and P can reduce the impact energy of raindrops, or slow down surface runoff and in this way diminish the rate of erosion. The value for each of these parameters can be calculated using certain data or properties of their respective subject, as explained further on. A USLE calculation in the catchment area is made using ArcGIS to integrate the topography and the spatial distribution of the land use and vegetation of the entire area into the equation. With the USLE equation, spatial distribution of the erosion in the area can be mapped and the high erosion risk areas can be identified.

3.1.1 RAINFALL EROSIVITY

The rainfall erosivity factor has been empirically derived by Wischmeier and Smith (1978). It was found that soil loss is directly proportional to a rainstorm parameter. This parameter is calculated from the total storm energy E , and the maximum 30 minute intensity of the storm I_{30} , resulting in an EI_{30} parameter. For western Africa, an annual average EI_{30} index has been made by Roose (1976). The study area lies on the $EI_{30} = 400$ boundary (Figure 3.1). Because the study area is in a semi-arid environment with a strong defined wet and dry season, the temporal distribution of rainfall and consequently of erosion is highly various. Therefore a monthly EI_{30} parameter is more accurate for the study area than an annual average rainfall erosivity parameter. The EI_{30} parameter in the original

USLE equation is calculated using rainfall data with a temporal resolution of at least 30 minutes intervals. As this kind of data is not available in the Tandjari catchment, the method of Loureiro and Coutinho (2001) is used. In their study, an alternative way to calculate the EI_{30} parameter using less frequent rainfall data was investigated. With their resulting equation, the monthly EI_{30} factor can be calculated using daily precipitation records. The following equation is used for the calculation of the monthly EI_{30} parameter:

$$EI_{30 \text{ month}} = 7.05 \text{ rain}_{10} - 88.92 \text{ days}_{10} \quad (2)$$

Where rain_{10} is the amount of rainfall in a month for days ≥ 10.0 mm rainfall, and days_{10} is the number of days with ≥ 10.0 mm rainfall for that month. $EI_{30 \text{ month}}$ is expressed in units $\text{MJ} \cdot \text{mm} \cdot \text{ha}^{-1} \cdot \text{hr}^{-1} \cdot \text{month}^{-1}$.

Data gathered

Daily precipitation and evaporation data is available from the Fada N'gourma weather station from 1984 until present. As this is the only weather station in the vicinity of the catchment, and the station lies around 10 km south of the study area, it is assumed that the rainfall is spatially homogeneous throughout the area (Keesstra, Temme, Schoorl, & Visser, 2014). There is a new meteorological station installed at the Tandjari dam, but as it is only operational since 2016 there is no sufficient data for this study yet from this station.

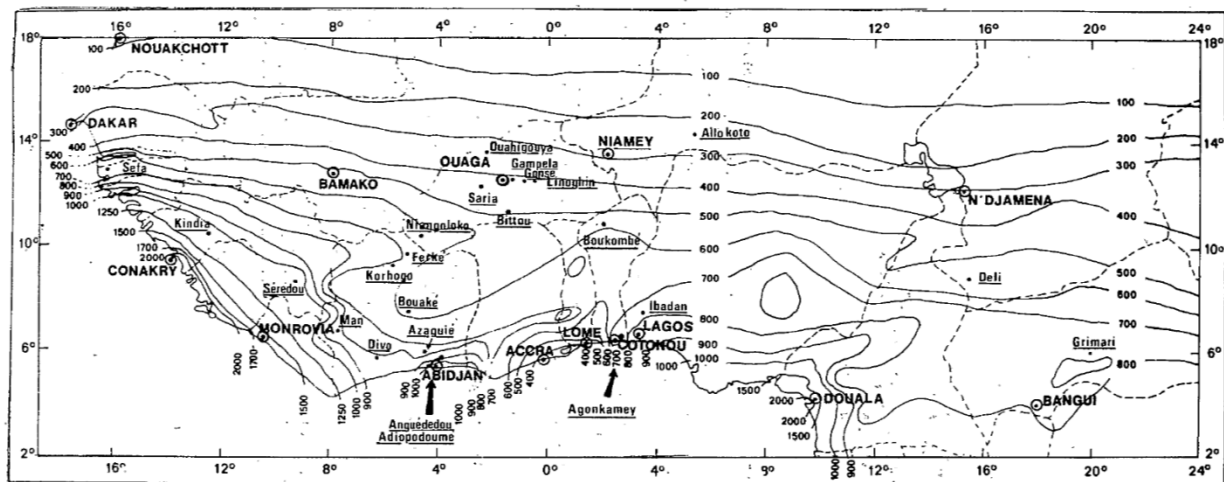


Figure 3.1. Annual average EI_{30} parameter for West and Central Africa. Reprinted from Roose (1976).

3.1.2 SOIL ERODIBILITY

The soil erodibility factor in USLE is defined as the rate of soil loss per rainfall erosion index unit (Renard, Foster, Weesies, McCool, & Yoder, 1997). Generally it is thought of as the ease with which soil particles are detached from the soil by the impact energy of raindrops and surface flow. The K-value is best obtained from direct measurements of experimental erosion runoff plots over a course of two years. As this is not feasible in many cases, several methods have been developed to determine the K-value by its relationship to soil properties. Of these methods, the most widely used and cited, and found to be the most accurate relationship is the nomograph developed by

(Wischmeier & Smith, 1978) in the original USLE equation (Figure 3.2). The nomograph allows for the K-value to be determined by a specific grain size distribution and classes for the permeability and structure of the soil. The grain size classes are defined as the percentage modified silt (0.002 – 0.1 mm), the percentage modified sand (0.1 – 2 mm) and the percentage organic matter.

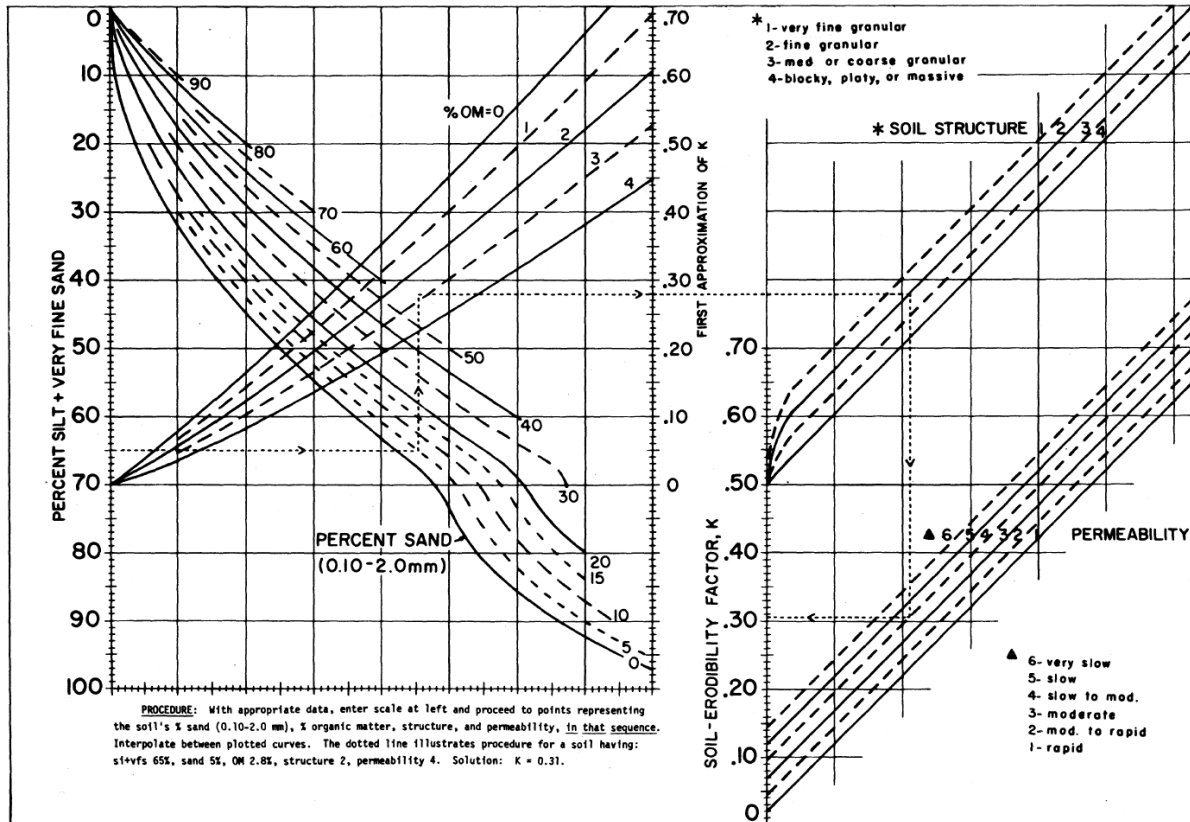


Figure 3.2. Nomograph by Wischmeier and Smith 1978. K-value in customary U.S. units, for use in SI units the K-value should be divided by 7.59.

The K-value determined with the nomograph can be algebraically approximated by the following equation:

$$K = (2.1 \times 10^{-4}(12 - OM)M^{1.14} + 3.25(s - 2) + 2.5(p - 3))/100 \quad (3)$$

Where M is the product of the primary particle size fractions (percent modified silt (0.002 – 0.1 mm) * (percent silt + percent sand)), OM is the fraction of organic matter, s is the class for soil structure and p is the class for permeability. K is expressed in the U.S. customary units of ton- acre- h (hundreds of acre * ft-tonf * in)⁻¹. To express K in SI units of t * ha * hr * ha⁻¹ * MJ⁻¹ * mm⁻¹, the value obtained should be divided by the factor 7.59.

Data gathered

The soil map available from the AEG is a rough map for the whole Gourma region. The entire Tandjari basin is covered by only one soil type on this map. A grain size distribution analysis of the soil types was not available. To acquire a reliable K-value for the USLE equation, soil samples had to be taken in the Tandjari basin to carry out a grain size distribution analysis. As there is no difference in soil according to the soil map, the soil samples were taken at locations of varying land use based on the

assumption that any variation in soil characteristics is most likely distributed along the same areas as the land use (Figure 3.3). The small areas of forest and agricultural use combined account for less than 1 percent of the total area of the Tandjari basin, so it was decided not to take soil samples in these areas. With the results of the grain size analysis at these locations, the K-value is determined with the use of the K-value nomograph. The classes for the permeability p and soil structure s (used in the nomograph) are determined from the results of the grain size analysis. For the permeability class, table 3.1 is used.

Texture	Permeability code ¹	Saturated hydraulic conductivity ² (in/hr)	Hydrologic soil group ³
Silty clay, clay	6	<0.04	D
Silty clay loam, sand clay	5	0.04-0.08	C-D
Sandy clay loam, clay loam	4	0.08-0.2	C
Loam, silt loam ⁴	3	0.2-0.8	B
Loamy sand, sandy loam	2	0.8-2.4	A
Sand	1	>2.4	A+

¹Permeability codes used in figure 3-1. See National Soils Handbook No. 430 (USDA 1983) for permeability classes.

²Rawls et al. (1982)

³See National Engineering Handbook (USDA 1972).

⁴Note: Although silt texture is missing because of inadequate data, this should be in permeability class 3.

Table 3.1. Soil-water data for permeability class determination for use in the K-value nomograph.
Reprinted from Renard, Foster, Weesies, McCool, & Yoder (1997).

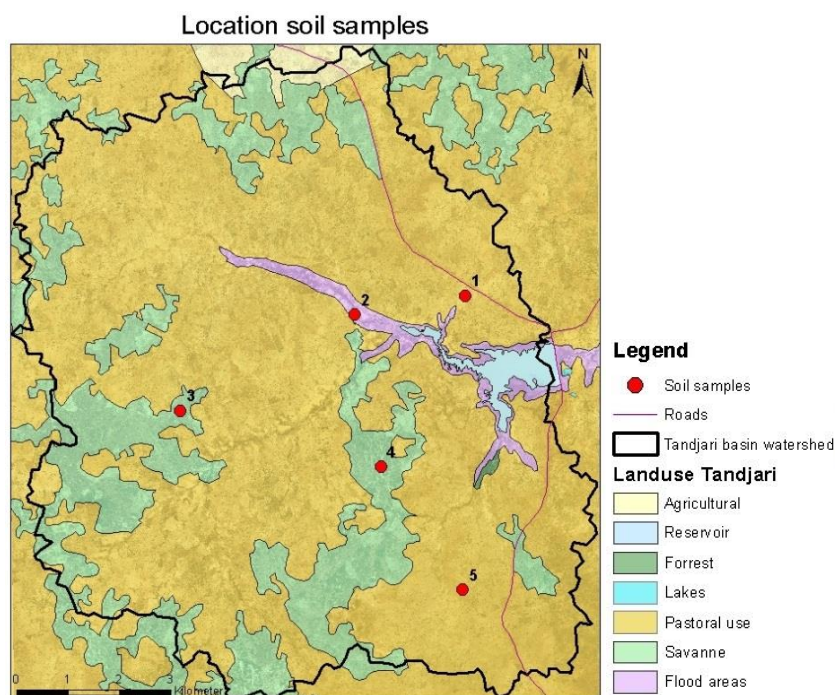


Figure 3.3. Location of soil samples taken in the Tandjari basin.

3.1.3 TOPOGRAPHIC FACTOR

In the USLE equation, the topographic factor consists of a slope length factor L , and a slope steepness factor S . The slope length accounts for the distance over which runoff can accumulate and the slope steepness factor reflects the effect of the gradient of a slope on erosion. Combined these factors produce the LS factor, incorporating a spatial factor into the USLE equation.

To integrate the topographic factor of the area of the Tandjari catchment in the erosion equation, a remote sensed digital elevation model (DEM) can be used to make a spatially distributed LS calculation. There are many ways to perform the LS -factor calculation. For this study, the Unit Stream Power Erosion and Deposition method (UPSED) is used (Pelton, Frazier, & Pickilingis, 2014). Many methods of calculating the topographic factor in GIS use the cell size of the DEM to calculate the L factor. However, with the length of a slope the L factor increases, so that the L factor at the bottom of a hill is greater than the average (Kinnel, sd). The UPSSED method compensates for such miscalculations. Instead of using a single dimension slope direction, it adds a spatial component, incorporating the upstream area contributing to flow. The L factor in the UPSSED method is represented by the following equation:

$$L = (m + 1) \left(\frac{\lambda_A}{22.1} \right)^m \quad (4)$$

Where L is the slope length factor at some point in the landscape, λ_A is the area of upland flow and m is a parameter adjusting for the soil's susceptibility to erosion.

The following equation is used to calculate the S factor for the area with the UPSSED method:

$$S = \left(\frac{\sin(0.01745 \times \theta_{deg})}{0.09} \right)^n \quad (5)$$

Where S is the slope steepness factor at some point in the landscape, θ_{deg} is the slope angle in degrees and n is a parameter for the soil's susceptibility to erosion.

The m and n exponents in both equations must be carefully selected according to the soil's erosive characteristics (Oliveira, et al., 2013). These parameters reflect the ratio of rill and sheet erosion of an area. Generally they are set between $m = 0.1$ and $n = 1$ for dispersed laminar flow with sheet erosion (and deposition) along a hillside, and $m = 0.6$ and $n = 1.3$ where furrows and concentrated flow prevail, with a strong potential for gullying. Field observations in the Tandjari catchment are carried out to estimate these parameters.

Data gathered

A 30 x 30 meter resolution DEM of the region (Figure 3.4), available from World Waternet, was used in ArcGIS to calculate the slope length and steepness factor distributed throughout the area. Using a DEM with a resolution of 30 meters raises the concern of losing detail of the topography of the area

(Schoorl, Sonneveld, & Veldkamp, 2000). However, a study in Thailand analyzed the influence of DEM's of differing resolution on the USLE equation, and found that a 30 meter resolution DEM produced accurate results, possibly due to the fact that the resolution is close to the 22.1 meter slope length used in the experimental derivation of the USLE equation (Bhattarai & Dutta, 2007).

First, a flow direction map is created using the DEM (Figure 3.5). Using this flow direction map, a flow accumulation map can be generated (Figure 3.6). These maps are generated using the standard ArcGIS Flow Direction tool and Flow Accumulation tool. On the flow accumulation map, the flow accumulation in channels can be seen in the lower parts of the catchment, in accordance with the DEM. Although not visible on the map due to the large range of flow accumulation values between the hillslopes and the channels, for each cell of the map a value of flow accumulation is calculated. This flow accumulation map is used in the calculation as the upstream area flow factor λ_A in the L factor equation. Next a slope map is generated with the DEM (Figure 3.7). This slope map shows the slope of the area in degrees. It can be noted that there is not a very steep gradient in the area, as the slope rarely exceeds 8 degrees. The slope map is used in the S-factor calculation as θ_{deg} .

After the determination of the m and the n parameters, the two equations in combination with the created maps can be used in ArcGIS to make a LS-factor map of the Tandjari catchment.

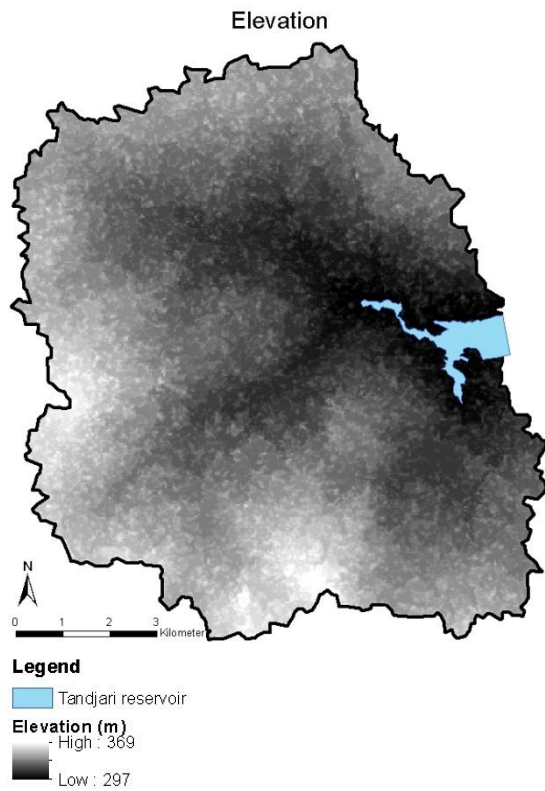


Figure 3.4. Digital elevation model (DEM) in meters above sea level

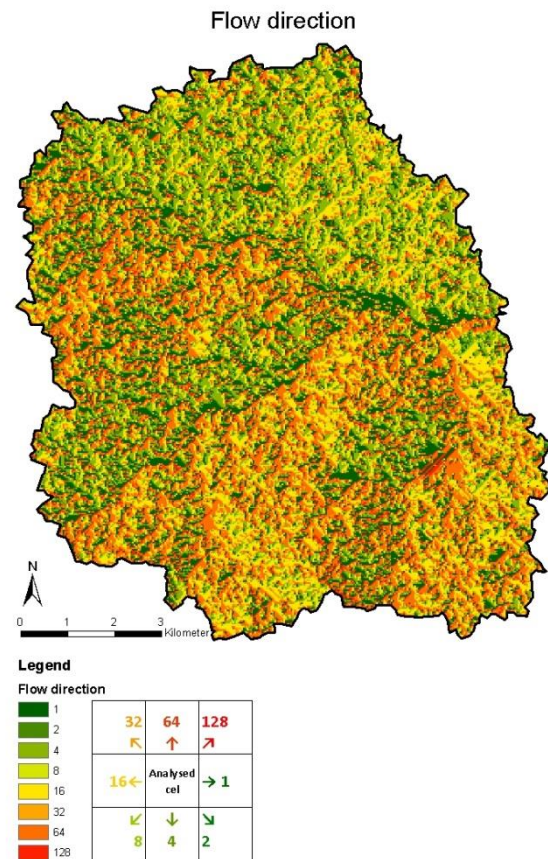


Figure 3.5. Flow direction map generated with DEM.

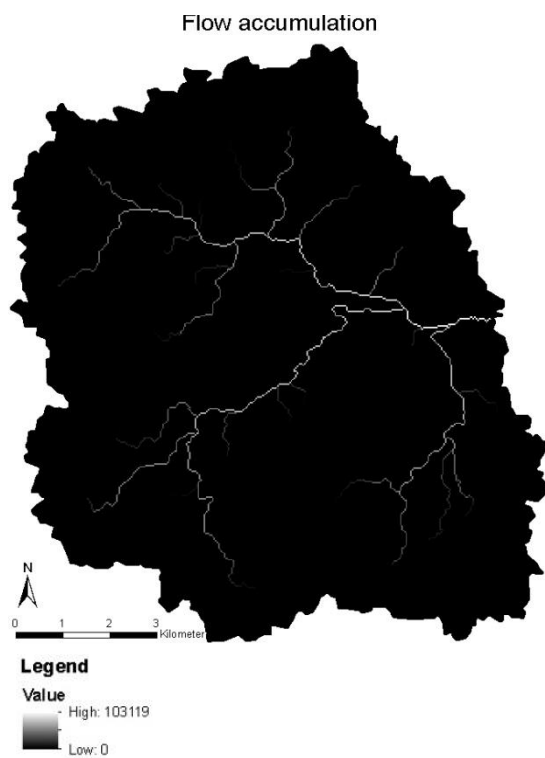


Figure 3.6. Flow accumulation map generated with flow direction map.

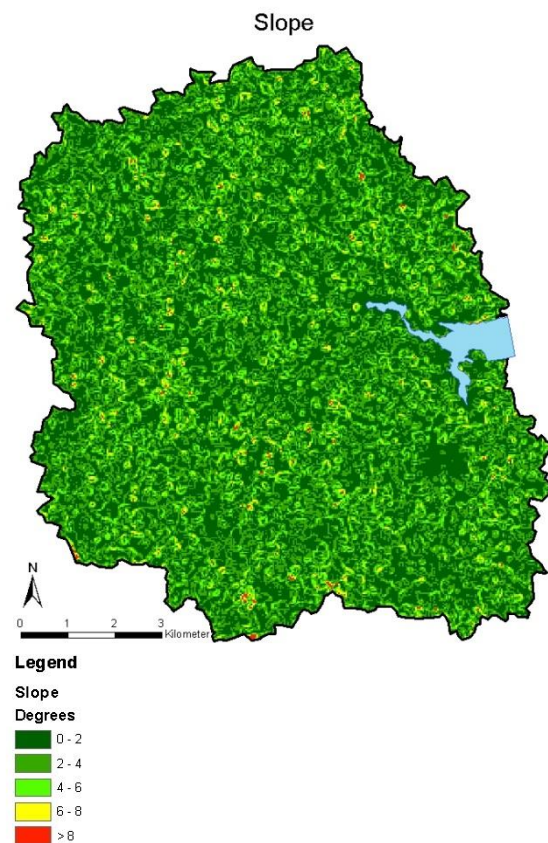


Figure 3.7. Slope map generated with DEM

3.1.4 COVER MANAGEMENT FACTOR

The cover management factor of the USLE equation is used to reflect the influence of vegetation and cover management practices on water erosion rates. For areas like rangeland or pastures with little climatic variation throughout the year, an average C-value representing the entire year may prove adequate to calculate erosion. At locations with varying conditions in time regarding vegetation and cover management practices however, it is necessary to determine the C-value per time period (Alexandridis, Sotiropoulou, Bilas, Karapetsas, & Silleos, 2014). In the Tandjari basin, there are two defined seasons; dry and rainy. In the dry season the soil is fairly barren and the fields lay fallow. During the rainy season the fields are cultivated and vegetation cover increases considerably, causing the need to determine the C factor with a time-varying approach. The calculation of the C-factor as defined in the original entails the definition of many parameters. In the original USLE handbook, Wischmeier and Smith (1978) incorporated a table for deriving the C-factor for permanent pasture, range and idle land (Table 3.2).

Data gathered

The AEG has a land-use and vegetation map of the study area available. However, this map is not very detailed and does not contain comprehensive vegetation information. Therefore it is difficult to derive a C-factor value just from this map. In the field the land use characteristics and vegetation cover are investigated and verified by ground truthing. According to the vegetation and cover management practices present in the area, the cover management factor is determined with the use of table 3.2.

Vegetative canopy		Cover that contacts the soil surface						
Type and height ²	Percent cover ³	Type ⁴	Percent ground cover					
			0	20	40	60	80	95+
No appreciable canopy		G	0.45	0.20	0.10	0.042	0.013	0.003
		W	.45	.24	.15	.091	.043	.011
Tall weeds or short brush with average drop fall height of 20 in	25	G	.36	.17	.09	.038	.013	.003
		W	.36	.20	.13	.083	.041	.011
	50	G	.26	.13	.07	.035	.012	.003
		W	.26	.16	.11	.076	.039	.011
	75	G	.17	.10	.06	.032	.011	.003
		W	.17	.12	.09	.068	.038	.011
Appreciable brush or bushes, with average drop fall height of 6½ ft	25	G	.40	.18	.09	.040	.013	.003
		W	.40	.22	.14	.087	.042	.011
	50	G	.34	.16	.08	.038	.012	.003
		W	.34	.19	.13	.082	.041	.011
	75	G	.28	.14	.08	.036	.012	.003
		W	.28	.17	.12	.078	.040	.011
Trees, but no appreciable low brush. Average drop fall height of 13 ft	25	G	.42	.19	.10	.041	.013	.003
		W	.42	.23	.14	.089	.042	.011
	50	G	.39	.18	.09	.040	.013	.003
		W	.39	.21	.14	.087	.042	.011
	75	G	.36	.17	.09	.039	.012	.003
		W	.36	.20	.13	.084	.041	.011

¹ The listed C values assume that the vegetation and mulch are randomly distributed over the entire area.

² Canopy height is measured as the average fall height of water drops falling from the canopy to the ground. Canopy effect is inversely proportional to drop fall height and is negligible if fall height exceeds 33 ft.

³ Portion of total-area surface that would be hidden from view by canopy in a vertical projection (a bird's-eye view).

⁴ G: cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 2 in deep.

W: cover at surface is mostly broadleaf herbaceous plants (as weeds with little lateral-root network near the surface) or undecayed residues or both.

Table 3.2. C-factor for permanent pasture, range and idle land. Reprinted from Wischmeier & Smith (1978).

3.1.5 COUNTER EROSIVE MEASURES

The counter erosive measures factor, or P factor, represents impact of measures taken in the area that are used with the purpose of diminishing erosion. Roose (1976) established the P factor for a number of erosion control practices in West Africa (Table 3.3). Tied ridging involves making ridges for crops, then tying or connecting these ridges with small mounds in order to increase the surface water storage and reduce runoff. Anti-erosive buffer strips is the practice of creating a buffer strip of 2 to 4 meter of grass between cultivated fields of 20 to 50 meters wide. These grass strips evolve into grass covered embankments as a result of the deposition of eroded soil between the grassy stems. A straw mulch cover several centimeters thick absorbs the kinetic energy of rainfall and reduces erosion in this way, but it is difficult procuring the large amount of straw without leaving a part of a crop yield on the field, making this method only effective on cultivated fields and when there is enough incentive for the farmer to leave part of the crop. Spraying the soil with artificial mulch can reduce soil loss by 40 to 90 percent. However, this method is too expensive for ordinary agriculture. Grass and grass-like plants are the most efficient vegetation in reducing runoff and erosion due to the many fine stems. Establishing grass or grass-like vegetation in an erosion prone area that has little vegetation will greatly reduce erosion. An engineering method is making reinforced ridges or walls stopping runoff. If there are no counter erosive measures in the study area, this factor in the USLE equation will be set to 1 (Amitrano, et al., 2015).

Data gathered

There was no previous data available about counter erosive measures in the Tandjari catchment. The counter erosive measures (P) in the area were investigated in the field and the P-value was determined with table 3.3.

Conservation Practices	P Factor
Tied-ridging	0.20 to 0.10
Antierosive buffer strips from 2 to 4 meters width	0.30 to 0.10
Straw mulch	0.01
Curasol mulch (60 gr/l/m ²)	0.50 to 0.20
2-3 years of temporary grassland	0.5 to 0.1
Reinforced ridges of earth or low dry stone walls (ridge elevation : 80 cm above channel) + tillage + cultivation and balanced fertilization.	0.1

Table 3.3. P factor for conservation practices in West Africa. Reprinted from Roose (1976).

3.2 TANDJARI RESERVOIR SEDIMENTATION RATE

Literature research was done in order to gather data for the Tandjari reservoir, such as the year of construction, the initial storage capacity at the time of construction of the dam and the storage capacity at another point in time. Comparing the reservoir storage capacity at different points in time gives an insight into the sedimentation rate. The results from the USLE calculations can then be compared with the actual sedimentation rate of the reservoir. An erosion rate cannot be directly interpreted as a sediment yield rate at catchment scale without the appropriate adjustments. Below

the three factors sediment delivery ratio, trapping efficiency and sediment specific density are explained.

3.2.1 SEDIMENT DELIVERY RATIO

The material eroded in the catchment does not all end up in the lowest point of the catchment. The difference between the total eroded sediment and the actual sediment yield at the reservoir is the sediment delivery ratio. A study in western Burkina Faso established the sediment delivery ratio of two case studies at approximately 50% (Schmengler, 2011). Another soil erosion and sediment yield study of the Nakanbé (White Volta) basin also found 50% to be the sediment delivery ratio there (Tamene, Le, Brunner, & Vlek, 2008). The total eroded sediment calculated with USLE should be adjusted according to this value in order to get a reliable estimate of the reservoir sedimentation.

3.2.2 TRAPPING EFFICIENCY

When calculating reservoir sedimentation rates, it is important to regard the trapping efficiency (TE) of the reservoir. The trapping efficiency is the rate of sediment flowing into a reservoir that becomes settled compared to the total inflow of sediment:

$$TE = \frac{\text{Sediment inflow} - \text{Sediment outflow}}{\text{Sediment inflow}} = \frac{\text{Settled sediment}}{\text{Sediment inflow}} \quad (6)$$

There are many methods for estimating the trap efficiency of reservoirs. For the estimation of the TE for a normally ponded retention reservoir (i.e. a reservoir normally filled with water, with the outlet at the top of the embankment or spillway) like the Tandjari, the empirical model of Brune (1953), modified by the Soil Conservation Service of the United States Department of Agriculture (USDA-SCS, 1983) is adequate (Verstraeten & Poesen, 2000). Using this method, a ratio between the reservoir capacity (C) and the annual inflow (I) in the same units (e.g. m³/ m³) is used to determine the TE. A ratio lower than 1 means the water in the reservoir is completely replaced in one year, a ratio higher than 1 indicates that it is a holdover reservoir that retains water longer than a year. The longer the retention time, and thus the higher the C/I ratio, the more sediment will be deposited. Figure 3.8 shows the relation between the C/I ratio and the TE for different sediment textures. The equations used to predict the TE are shown in table 3.4. These equations will be used in combination with the results of the soil sample grain size analysis to determine the TE for the Tandjari reservoir.

	C/I > 1	1 > C/I > 0.02	C/I < 0.02
Upper curve (sand-gravel)	100	$100 - (0.485 \ln(C/I) ^{2.99})$	$124 - (6.59 \ln(C/I) ^{1.52})$
Median curve (mixture)	97	$97 - (1.275 \ln(C/I) ^{2.47})$	$128 - (11.51 \ln(C/I) ^{1.304})$
Lower curve (clay-silt)	94	$94 - (3.38 \ln(C/I) ^{1.92})$	$94 - (3.38 \ln(C/I) ^{1.92})$

Table 3.4. Equations used for the trap efficiency prediction based on C/I ratios for different textures. Reprinted from Verstraeten & Poesen (2000).

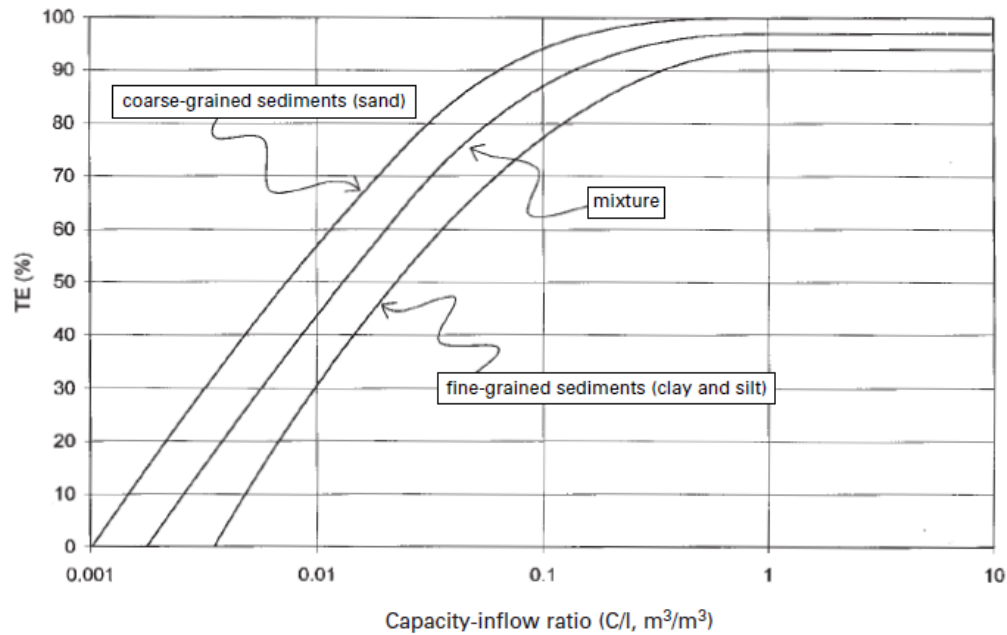


Figure 3.8. Trap efficiency related to capacity/annual inflow (C/I) ratio by Brune (1953), modified by USDA-SCS (1983). Reprinted from Verstraeten and Poesen (2000).

3.2.3 SEDIMENT SPECIFIC DENSITY

Using the USLE equation, a sediment delivery rate is calculated in weight. In order to estimate the resulting effect on the storage capacity of the Tandjari reservoir, the rate of sedimentation is needed in volume rather than weight. In an extensive study on reservoir sedimentation, Mamede (2008) found a sediment density of 1,5 ton per m³. Lamachere (1998) defined a sediment specific density for Burkina Faso, also at 1,5 ton per m³. Using this value, a relation between the sediment delivery and the effect on storage capacity can be made.

4 RESULTS

The field work has been executed in Burkina Faso in March and April 2017. With the results of the field work and the data collection, the methods described in chapter 3 have been executed. The results are described below.

4.1 EROSION TANDJARI CATCHMENT

The five different parameters used in the USLE equation have been separately investigated according to the methods explained in chapter 3.1. The results are described below.

4.1.1 RAINFALL EROSIVITY

With the data from the Fada N’gourma meteorological station the monthly EI_{30} parameter was calculated using the rainfall data of the Fada N’gourma meteorological station and equation (2). Figure 4.1 shows the distribution of the EI_{30} parameter throughout the months of the year.

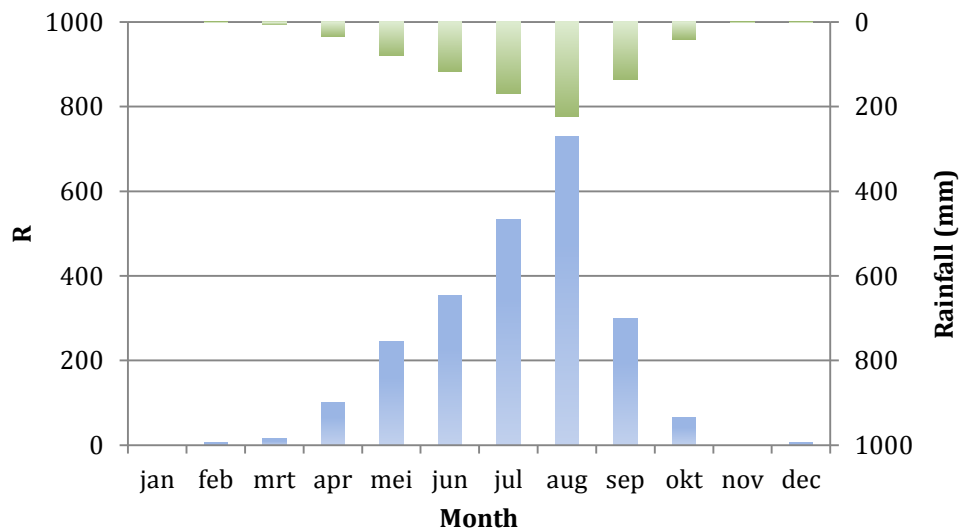


Figure 4.1. Rainfall erosivity factor (MJ mm/ha h month) in blue bars and average monthly rainfall (mm) in green bars.

The annual average EI_{30} value is 196, which does not exactly agree with the value of around 400 determined by Roose (1976), as explained in chapter 3.1.1. This can be attributed to the fact that now the EI_{30} value is calculated per month, yielding a highly varied value throughout the months of the year, with the dry months having a very low EI_{30} value. It can be noted that the distribution of the rainfall erosivity roughly follows the distribution of rainfall throughout the year, although the distribution is slightly more skew to the right, indicating that at the end and after the rainy season the intensity of the storms is less than in the start and in the middle of the rainy season. In the months January and November there is a rainfall erosivity factor of zero, due to the fact that there have been zero rainfall events larger than 10 mm in these months in the entire period of measurement.

4.1.2 SOIL ERODIBILITY

The soil erodibility factor (K) is spatially distributed and is determined using the K-value nomograph with the soil's characteristic data obtained from field measurements, as explained in chapter 3.1.2, and soil sample analysis (Appendix 1). The field work was executed on 07-04-2017. In table 4.1 the results of the grain size distribution analysis, the classification of the soil structure and permeability and the corresponding K-value are displayed.

Soil sample	% Modified silt (0.002 – 0.1 mm)	% Modified sand (0.1 – 2 mm)	% Organic matter	Structure class	Permeability class	K-value
1	16.17	78.08	0.56	3	3	0.018
2	15.00	70.25	0.58	3	3	0.015
3	8.06	86.94	0.57	3	3	0.010
4	18.52	70.98	0.58	3	3	0.019
5	32.41	57.59	0.89	3	3	0.032

Table 4.1. Results grain size analysis soil samples and corresponding K-values in t * hr/MJ *mm

The results show that the K-values do not differ much throughout the area. It can be noted that the percentage of organic matter in all of the samples is very low. In the area, the soils are poorly developed. The soil structure class is determined by field observations as well as the grain size analysis results and defined as class 3 (medium or coarse granular) for all soil samples. The permeability class is defined using the results of the grain size analysis and table 3.1 and is defined as class 3 (moderate). Using equation (3), the K-values per soil sample were calculated. In order to integrate the K-values in the GIS calculations, the values determined from samples 1 and 5, both taken in the areas of pastoral use, were averaged to a K-value of 0.025 in order to assign this value to the area in ArcGIS. The same was done for the K-values of soil samples 3 and 4 for the savanna areas, averaging at a value of 0.015, coinciding with the value of the sample taken in the inundation area. Because of the small size of the areas and similarities in land use, it was decided to assign the K-value of the areas of pastoral use to the small area of agricultural use, and the K-value of the savanna areas to the forest areas. The resulting distribution of K-values can be seen in figure 4.2.

The USLE calculations are carried out with the averaged K-values as explained above. However, the different values obtained in the same land-use areas shows that the K-value is not homogeneous throughout the catchment. USLE calculations with the maximum and minimum K-values in these areas will be considered as the error margin of the USLE calculations. Running the USLE calculation with a K-value map with the lowest K-values (0.018 for the areas of pastoral use and 0.010 for the savanna areas) resulted in a total yield of 75% of the mean values calculated with the averaged K-values. Using the highest K-values (0.032 for the areas of pastoral use and 0.019 for the savanna areas) a yield of 127% of the mean values was calculated. This error margin shows the sensitivity of the K factor in the USLE calculations.

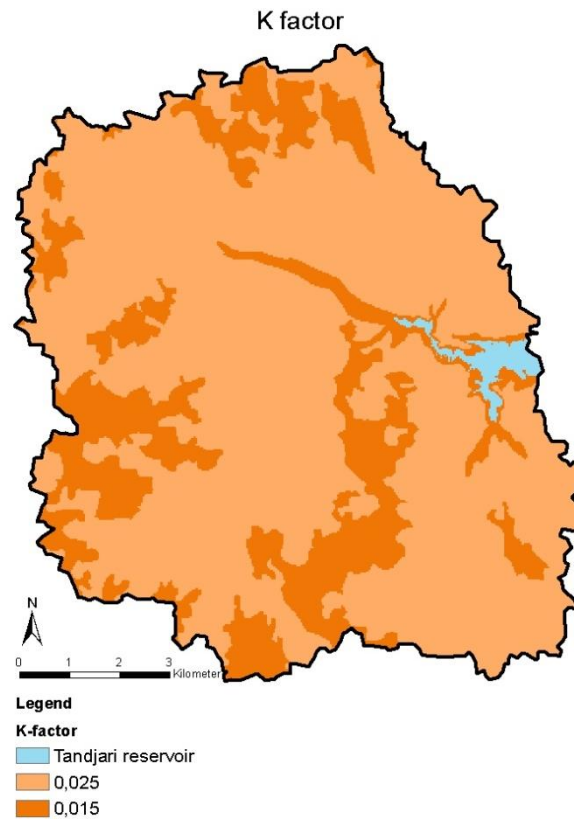


Figure 4.2. K factor in the Tandjari catchment.

4.1.3 TOPOGRAPHIC FACTOR

The spatial distribution of the LS factor could be calculated with the use of the flow accumulation map and slope map (See chapter 3.1.3). In order to perform the calculation, the m and n parameters of equation (4) and (5) respectively needed to be determined. Field excursions to the Tandjari catchment were carried out to determine these parameters. As can be seen on the slope map (Figure 3.7), the gradient in the area is not large, indicating a low level of concentrated flow. However, as the accumulated flow map shows (Figure 3.6), there is certainly concentrated flow in the lower parts of the catchment. Field observations confirm that there is a combination of laminar flow and rill erosion in the area (Figure 4.3).



Figure 4.3. Photos taken at the Tandjari catchment on 7-4-2017. Left: landscape with furrows causing concentrated flow, right: flat landscape with laminar flow.

As discussed in chapter 3.1.3, the m and n parameters are generally set between $m = 0.1$ and $n = 1$ for dispersed laminar flow with sheet erosion (and deposition) along a hillside, and $m = 0.6$ and $n = 1.3$ where furrows and concentrated flow prevail. The values selected for the Tandjari catchment are: $m = 0.4$, $n = 1.2$, which is slightly above the mean of the typical values. With the use of these values, a map of the spatially distributed LS factor was generated in ArcGIS (Figure 4.4).

On the LS-factor map, it can be seen that in the higher parts of the catchment, the LS factor has a value of 0. With descent in the area, the contributing area upstream increases, and so does the value of the LS factor, to reach the highest values at the bottom of the catchment in the streambeds, coinciding with the flow accumulation map. This indicates that according to the model the most erosion takes place in and near these streambeds in the lower parts of the catchment.

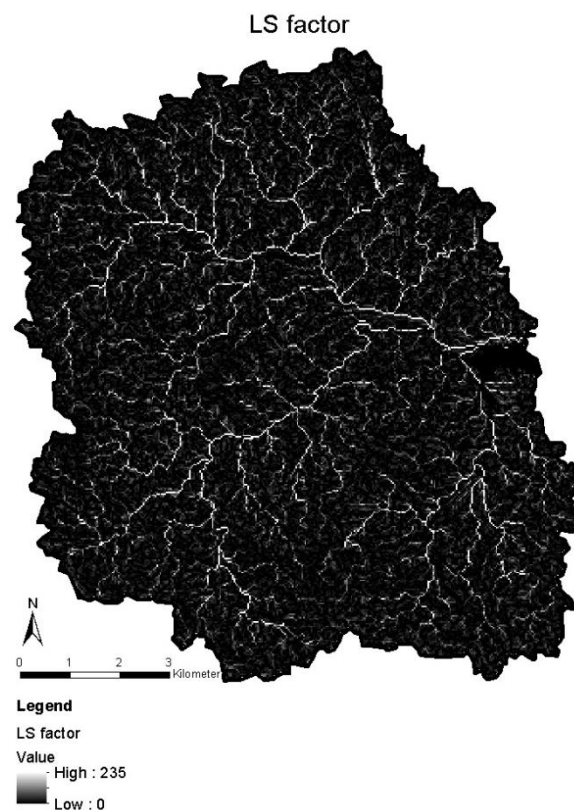


Figure 4.4. Spatial distribution of the LS factor.

4.1.4 COVER MANAGEMENT FACTOR

The Tandjari catchment is a rural area. There are some small villages present, with a population practicing small scale subsistence agriculture (See chapter 2). In the areas near the villages, fields are cultivated to produce crops, although this is mainly in the rainy season, while the rest of the year the fields lay fallow. There are some cotton plantations present in the area. A large part of the Tandjari catchment is uncultivated, and beside the savanna areas the ground in these places is mostly barren. The C factor for the area changes with time, as the vegetation changes drastically between the rainy and dry season. For the different land use classes, different C factors are determined, giving the C factor a spatial and a temporal variation. Table 4.2 shows the C-factor values that have been determined per season for the Tandjari catchment area:

Land use class	Dry season	Rainy season
Pastoral use	0.24	0.15
Savanna	0.18	0.09
Inundation areas	0.45	0.20
Forest	0.17	0.09
Agricultural	0.24	0.15

Table 4.2. C-factor for the Tandjari catchment area for the dry and the rainy season.

These values have been determined using the methods described in chapter 3.1.4. The values have been extracted from table 3.2. For the areas with pastoral land use, the vegetation is defined as no appreciable canopy, with mostly broadleaf herbaceous plants on the ground. In the dry period, the vegetal ground cover is about 20%, while in the rainy season the ground cover doubles to 40%. The agricultural areas are defined the same way. In the Savanna areas the vegetation is defined as trees with a canopy covering 50% of the area, and grass or grass-like plants covering the ground. This ground cover also varies between 20% in the dry season and 40% in the rainy season. The forest is much defined in the same way as the savanna areas, but with a 75% canopy cover. The vegetation in the inundation areas is defined as no appreciable canopy, with a ground cover of 0% in the dry season and 20% grass or grass-like plants in the rainy season. Figures 4.5 and 4.6 show maps of the distribution of the C-value in the Tandjari catchment in the dry and in the rainy season.

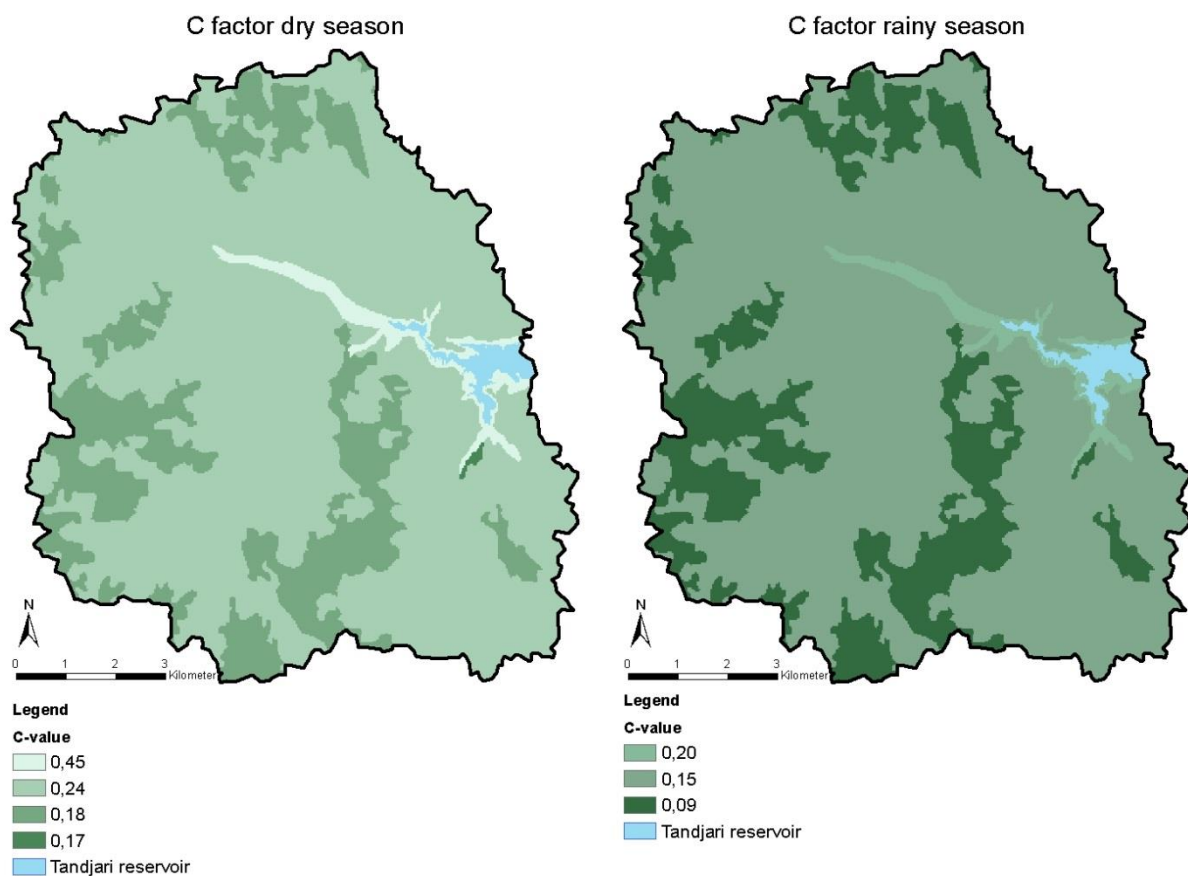


Figure 4.5. C-factor of the dry season.

Figure 4.5. C-factor of the rainy season.

4.1.5 COUNTER EROSIVE MEASURES

Some practices diminishing the effect of erosion are observed in the Tandjari catchment, whether they be intentional or unintentional. In some places, low stone ridges are made, blocking the flow of surface runoff (Figure 4.7). A similar technique with bushy hedges instead of rocks is also practiced. Most of the cultivated fields are furrowed, with ridges of soil where the crops are planted. These ridges are causing concentrated flow in the bottom of the furrows. When these fields are situated on a slope, most of the fields are cultivated so that the furrows are perpendicular to the slope angle. This so called contour farming is done in order to facilitate the equal distribution of water in the field and to keep the water from flowing out of the fields too quickly, but consequently it also reduces the speed of the runoff in the bottom of the furrows, diminishing the effect of the furrows on soil erosion.



Figure 4.6. Low stone ridges blocking surface flow. Photo taken in Tandjari catchment on 28-3-2017.

The aforementioned counter erosive measures are sparsely present throughout the area. The total amount of these measures in the entire catchment is small. Stone ridges are mainly found near the villages, and the cultivated furrowed fields are generally situated on areas with the lowest slope angles. Therefore, the effect on erosion of these measures is negligible. It is assumed that the counter erosive measures in the entire catchment have no significant effect on the erosion rate. Therefore the P factor value for the Tandjari catchment is determined as 1.

4.1.6 USLE CALCULATION

The final calculation of the erosion and sedimentation taking place in the Tandjari catchment is the product of all the factors discussed above. All the parameters of equation (1) were determined. Some are varying in time and/or in space. Table 4.3 shows the parameters used in the equation.

Parameter	Spatial variation	Temporal variation	Value	Units
R	Constant	Monthly	0 ~ 729	MJ mm ha ⁻¹ hr ⁻¹ month ⁻¹
K	Distributed	Constant	0.015 ~ 0.025	t hr MJ ⁻¹ mm ⁻¹
LS	Distributed	Constant	0 ~ 235	--
C	Distributed	Seasonal	0.09 ~ 0.45	--
P	Constant	Constant	1	--

Table 4.3. USLE parameter values and distribution

For each month, the erosion in tonnes per hectare was calculated using the values specific for that month, using the ArcGIS tool Raster Calculator with the month-specific data as input. The result is shown in figure 4.8. There is a strong difference in the calculated values for erosion between the months of the year. In the months January and November the calculated erosion is zero, this is because the R factor is 0 in these months. August is the month with the highest calculated erosion. For three non-consecutive months the distribution of erosion is shown in erosion risk maps in figures 4.9, 4.10 and 4.11. The mean annual erosion amounts to 16.04 tonnes per hectare. The range of error of 75 – 127% (see chapter 4.1.2) puts this range between 12.03 and 20.37 tonnes per hectare. Figure 4.12 shows the distribution of the yearly erosion. Appendix 2 contains maps of the distribution of calculated erosion of all the months of the year and of the yearly average.

The results of the USLE calculations show the spatial distribution of the erosion in the Tandjari catchment area. It is clear that the most erosion in the area takes place in the lower parts of the catchment, where the surface flow accumulates. This underlines the influence of the LS factor on the calculations. If counter erosive measures are to be taken in the area, these locations have the highest potential. The rainy season can clearly be identified in the pattern. The distribution roughly follows the distribution of the R factor. In the three months of rainy season in which a different C factor is used in the calculations, the impact of this factor can be clearly seen as the peak in the R factor distribution is dampened. The savanna areas for example can be distinguished on the maps as areas with a lower erosion rate, even more so in the rainy season, illustrating the impact the vegetation has on the erosion rate. The large variance in vegetation cover between the dry and the rainy season cause the earliest rainstorms to have a high impact on erosion when the denser rainy season vegetation is not yet established. However, the fact that the temporal distribution of the C factor is modelled at a seasonal timescale influences the accuracy of the calculations, as this resolution is much coarser than in reality, where the C factor gradually changes as plants start to grow.

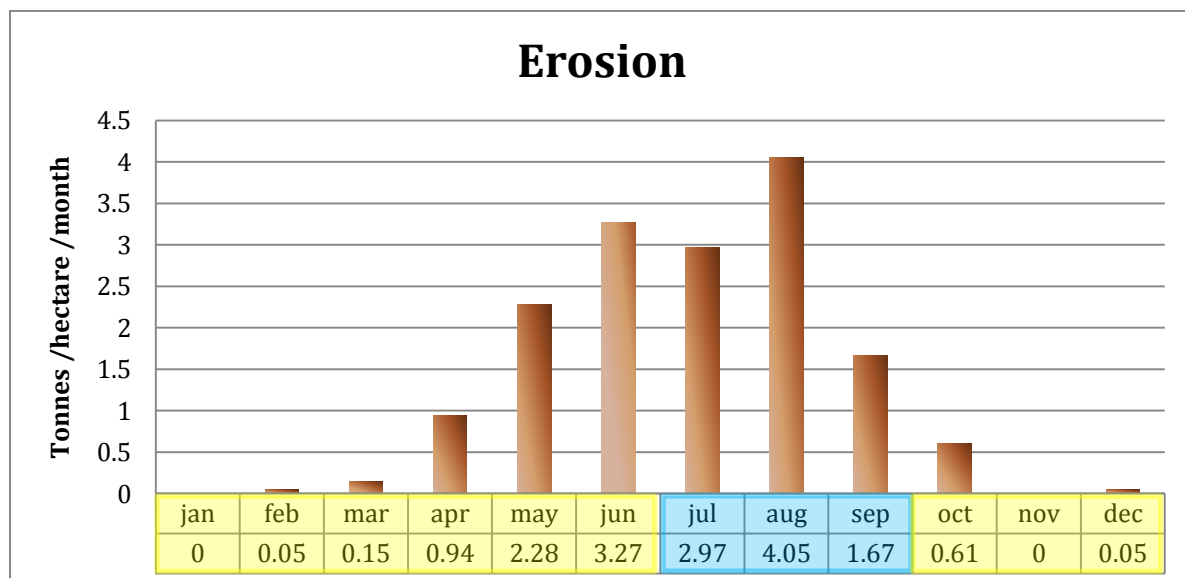


Figure 4.7. Monthly erosion in the Tandjari catchment calculated with USLE in tonnes per hectare. The months of dry season are highlighted in yellow and of rainy season in blue.

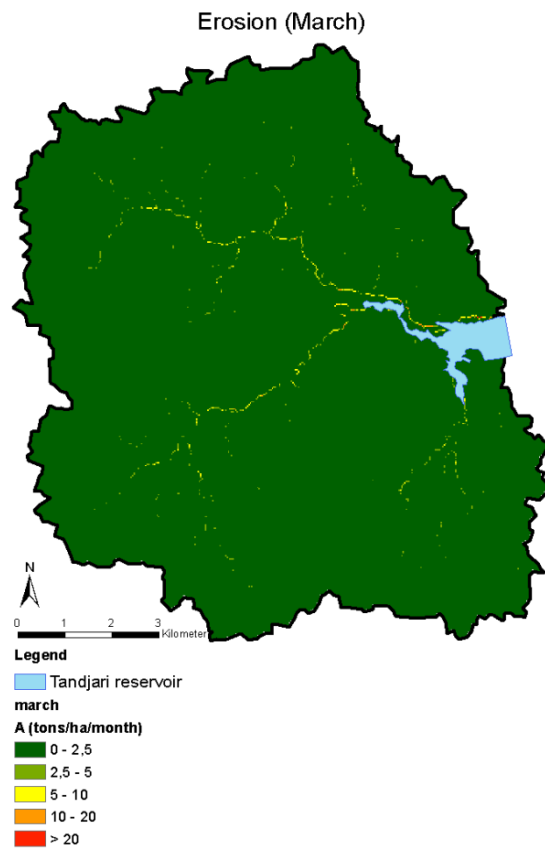


Figure 4.9. Erosion map for March.

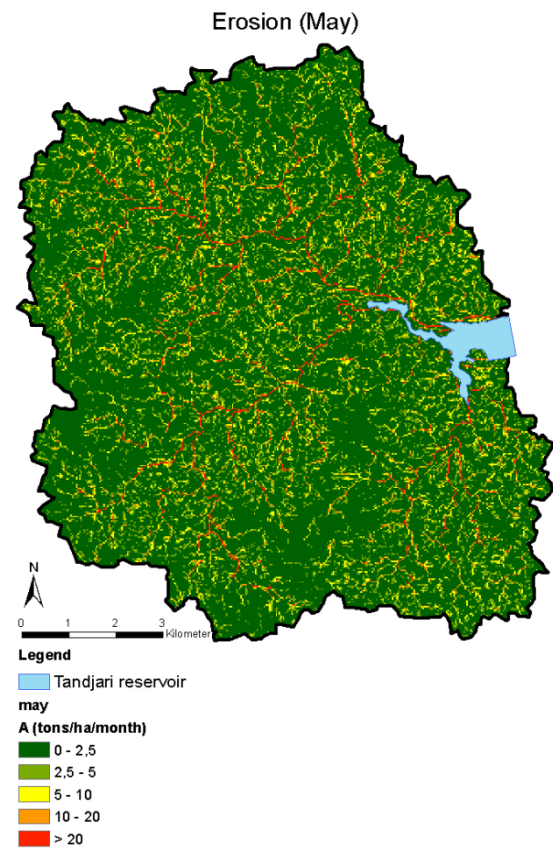


Figure 4.10. Erosion map for May.

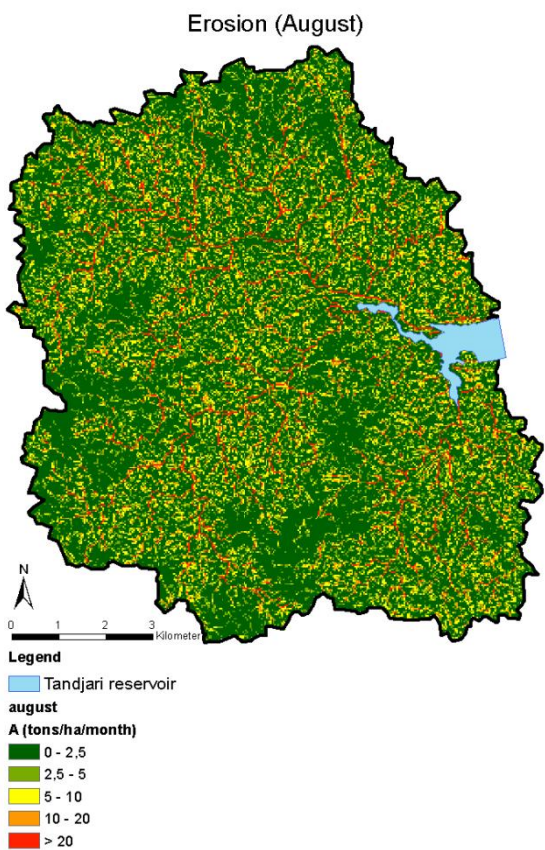


Figure 4.91. Erosion map for August.

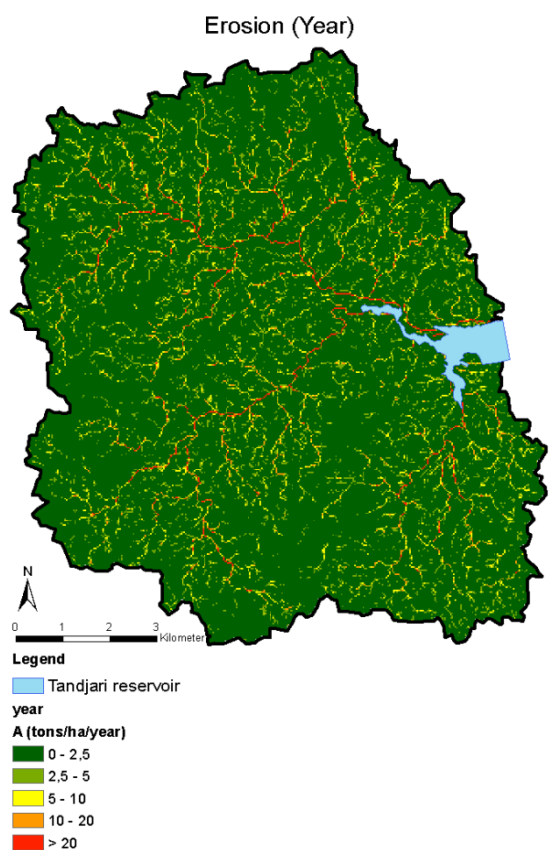


Figure 4.92. Mean erosion per year.

4.2 TANDJARI RESERVOIR SEDIMENTATION RATE

The Tandjari reservoir sedimentation rate was calculated with the use of the USLE results and the proper conversion factors, explained in chapter 4.2.1. An attempt was made to calibrate the USLE results with the use of values for the storage capacity obtained from construction and research reports on the Tandjari reservoir, described in chapter 4.2.2.

4.2.1 SEDIMENTATION RATE FROM USLE RESULTS

The trapping efficiency is calculated using the methods explained in chapter 3.2.2. The results of the grain size analysis of the soil samples from the Tandjari catchment (chapter 4.1.2) show that the dominating fraction is sand/silt/mixture. Therefore an equation for the median curve from table 3.3 is selected for the calculation of the trapping efficiency. The capacity of the Tandjari reservoir is selected at 4.600.000 m³, and the annual inflow at 6.310.000 m³ (De Jong Posthumus, 2017), giving a C/I ratio of 4.600.000/6.310.000 = 0,729. With this C/I ratio, the median curve equation for $1 > C/I > 0.02$ is selected from table 3.3:

$$97 - (1.275|\ln(C/I)|^{2.47}) \quad (7)$$

With the given C/I ratio, this results in a trapping efficiency of 96.93 %.

The result of the USLE equation for the Tandjari catchment area indicate a mean soil loss rate of 16,04 tonnes per hectare per year at the Tandjari reservoir, with an error margin of 75% - 127% (see chapter 4.1.2). With the surface area of the catchment of 10500 hectares, the gross sediment yield is 168.420 tonnes per year. The sediment delivery ratio, as explained in chapter 3.2.1, is determined at 50%, resulting in a sediment delivery at the Tandjari reservoir of 84.210 tonnes per year. With the trapping efficiency of the reservoir determined at 96,93 %, the estimated sediment remaining in the reservoir is 81.625 tonnes per year. Using a specific density of 1,5 tonnes per m³ of sediment, this translates to 54.417 m³ of sediment deposited in the Tandjari reservoir per year. Of the initial 4.600.000 m³ capacity of the reservoir, this is a decline of 1,2% per year. With the error margin taken into account, the rate lies between 75% and 127% of the mean sedimentation, between 40.813 m³ and 69.110 m³, or between 0,9% and 1,5%. Assuming this rate as constant in the lifespan of the reservoir, in the 18 years since the construction of the dam in 1996 until 2014, this is a mean decrease of 21%, or 979.497 m³ of the initial storage capacity, with a range of error between 15,8% - 26,7% or 734.623 – 1243961 m³. Bearing in mind the fact that these are values calculated by an empirical equation, with the assumption that the mean sedimentation rate has been steady since construction of the reservoir and will continue to be the rate of sediment delivery, the half-life of the reservoir will be reached in the year 2038, 42 years after its construction. The error margin puts the half-life of the reservoir between 34 and 57 years, between 2030 and 2053.

4.2.2 SEDIMENTATION RATE FROM LITERATURE

The Tandjari dam was originally constructed as a raised road to cross the valley. The potential of the dam functioning as a weir for a reservoir for the storage of water was recognized and in 1996 the dam was raised to form a full embankment and the reservoir as it exists present day was created. The national road N18 still traverses the dam and there is a bridge at the point where it crosses over the spillway. According to the database of the national office Direction des Etudes et de l'Information

sur l'Eau (DEIE), at the time of construction of the dam in 1996, the storage volume of the reservoir up to the spillway level was 4.600.000 m³ (DEIE, 2011).

In 2014, the national drinking water company Office National de l'Eau et l'Assainissement (ONEA), the largest user of the water from the Tandjari barrage, executed a detailed bathymetric survey of the reservoir. Using land surveying and ultrasonic sounding equipment, a detailed inventory of the current shape of the bottom and the shores of the reservoir was made. This bathymetric survey gave a very detailed image of the storage capacity of the Tandjari reservoir. At the time of the survey, the storage capacity of the reservoir at spillway level was 4.750.000 m³ (ONEA, 2014). A relation between the volume, water level and water surface of the reservoir was included in the report, with a precision of 1 m³ (Appendix 3).

A report of the national research institute Bureau d'Etudes et de Recherches Appliquées (BERA), reporting on maintenance and improvement works carried out on the Tandjari dam in 2014, indicates a different storage capacity. According to this report, the volume of the Tandjari reservoir was 4.360.000 m³ in 2014 (BERA, 2015).

Comparing the reported storage capacities from 2014 with the initial storage capacity as reported by DEIE, the conflicting result is a storage capacity that has either increased or decreased over time. In the 18 years between construction of the reservoir and the bathymetric survey in 2014, the volume of the reservoir would have increased with 150.000 m³ comparing the initial storage with the ONEA report, or decreased with 240.000 m³ comparing the initial storage with the BERA report. The possibility of the storage capacity having increased over time is highly unlikely, and conflicts with the results of the USLE research, indicating a decrease of storage capacity over time due to soil erosion and the resulting sediment delivery into the reservoir. An increase of reservoir capacity is possible, but only by using vigorous reservoir sedimentation management techniques such as flushing or excavation (Mamede, 2008), which are not practiced at the Tandjari reservoir. Consequently, the most likely possibility is the decrease of storage capacity, as indicated by the comparison of the initial reservoir volume by DEIE and the volume in 2014 as described in the BERA report. However, the ONEA survey is highly detailed, using modern and accurate techniques for measuring the bathymetry. Therefore it is unlikely that this report is the least accurate of the three. The assumption can be made that the initial storage capacity as reported by DEIE is either an inaccurate measurement or a very coarse calculation, stressed by the fact that the value is rounded to 100.000 m³, whereas the values in the other two reports are more precise.

5 DISCUSSION

The purpose of this study is to gain an understanding of the erosion in the Tandjari reservoir catchment basin and the sedimentation rate within the reservoir. The following research question was formulated: How much erosion takes place around the Tandjari reservoir, and how does this affect the storage capacity of the reservoir? In order to carry out this study literature research was done, field work was conducted in the Tandjari catchment and data has been collected at several relevant institutes.

Runoff erosion is a highly dynamic phenomenon. It should be noted that the estimation of erosion with the use of a theoretical equation is an approximation of the actual situation, and many simplifying assumptions need to be made. Before the field work in Burkina Faso was carried out, literature research was done into methods of quantifying erosion on catchment scale. Many methods of estimating or modelling erosion on such scales exist, but the USLE is the only method applicable to this study that is based on empirically derived, measurable parameters. Therefore the USLE produces a valid erosion estimation even without being calibrated. The individual parameters of the USLE are examined and determined as carefully as possible so as to produce the most accurate result. Nonetheless, it should still be regarded as an estimation, and the results should be interpreted with care. The error margin in this study is based on the soil samples taken in the Tandjari catchment, and underlines the sensitivity of the parameters.

The Tandjari catchment is a rural area in the east of Burkina Faso. It is not a very accessible area, with few roads traversing the region. The fieldwork had to be carried out by motorbike, diminishing the ease of carrying equipment and, for example, the soil samples.

An attempt was made to calibrate the USLE results with reservoir storage capacity values obtained from documents from different national institutes. As described in chapter 4.2.2, the values obtained from the different institutes are not in accordance with each other, possibly caused by a poor cooperation in data exchange between these institutes. The consequence of the ambiguous values provided by the different offices and research institutes is that the results of the USLE calculations cannot be compared to the actual loss of storage capacity of the reservoir. This means the calculated values for sediment delivery in the Tandjari catchment cannot be validated in this way. A comprehensive study in central Burkina Faso found the storage capacity of three reservoirs had all lost approximately 10 to 15 % of their initial storage capacity in the last 15 to 20 years (Schmengler, 2011). The 21 % capacity loss over 18 years calculated for the Tandjari reservoir is slightly higher than these values.

This study provides methods to estimate the erosion and sedimentation rates in the Tandjari catchment area. These methods could be used to calculate these rates in other areas of the Gourma region as well. The results of this research can be used as a guideline for future policy decisions regarding the use and management of reservoirs in the Gourma region. The lifetime of reservoirs is effected by sedimentation and this influences the available water in the future. Policy decisions can have a significant influence on the social and environmental development of the region. Using the results of this study, future changes in climate should be kept in mind, as this influences the quantity

of erosion and the sedimentation as well. In addition, population growth in the area might influence the water demand, and in turn the lifespan of reservoirs.

As the results of the erosion calculations show, the vegetation has a large impact on the erosion. This is confirmed by many studies (Roose, 1976; Casenave & Valentin, 1991; Panagos, et al., 2014). The lowest C-factor values (giving the highest protection against erosion) are those for land use areas with a dense vegetation, both canopy and ground cover. Consequently, many effective erosion management techniques involve vegetation management. Especially in and near the high erosion areas, having an established vegetation cover can greatly reduce the erosion rates by reducing runoff and sediment transport (See chapter 3.1.5, Counter erosive measures). As the regulation of land use practices in the Tandjari catchment is not very organized, the vegetation in the area is susceptible to changes. Assigning certain areas to an erosion mitigation plan and establishing (grass-like) vegetation in these areas is a strategy reducing the sediment delivery to the reservoir and increasing the lifespan of the reservoir.

6 CONCLUSION

In this study the USLE equation is used to estimate the amount of erosion taking place in the Tandjari reservoir catchment basin in the Gourma region in eastern Burkina Faso, and with the results the sedimentation rate in the Tandjari reservoir is determined. An extensive literature review and fieldwork in the catchment has been carried out to determine the different parameters.

The result of the USLE calculations is a mean erosion rate in the area of 16,04 tonnes per hectare per year, amounting to 168.420 tonnes per year for the entire 10500 hectare catchment. A range of error of 75 – 127% from the mean rate was determined. This erosion rate was converted to a sedimentation rate within the Tandjari reservoir between 40.813 m³ and 69.110 m³ (or between 0,9% and 1,5%) with a mean of 54.417 m³ per year. For the entire 4.600.000 m³ reservoir, this represents a mean decline of storage capacity of 1,2 % per year. Assuming these values to be constant over time, the half-life of the reservoir will be reached in 2038, 42 years after its construction. The range of error puts the half-life point between 2030 and 2053. Erosion risk maps per month and per year were created. These maps can assist in organizing targeted counter erosion measures.

Values of reservoir storage capacity at different points in time were obtained from national institutes. However, between the values obtained from the different institutes, there is some ambiguity. The values are either very coarse or unequal at the same point in time making them unusable for calibration of the calculated sedimentation rate. This ambiguity is possibly due to a poor cooperation between the national institutes. The estimation of erosion and sedimentation in the area can provide considerable support in water resource management in the region. The methods used in this study provide a good approximation of the quantity and spatial distribution of erosion and the resulting sedimentation.

7 RECOMMENDATIONS

The results of this study show that the erosion in the Tandjari catchment is highest in the lower parts of the catchment, where surface flow accumulates. Counter erosive measures, having the potential to significantly reduce the sediment yield at the Tandjari reservoir, are most effective at these locations, having the potential to reduce runoff and sediment transport into the temporary streambeds and reservoir.

As a measure to combat the erosion and sedimentation in the Tandjari catchment it is advisable to create an erosion mitigation plan. Establishing counter erosive measures in and near the high erosion risk areas (the lower parts of the catchment near the gullies and streambeds, shown on the erosion risk maps) is most effective in the Tandjari catchment. Traditional management related practices to reduce the impact of erosion at hillslope scale are terracing, strip cropping and hedge rows, in addition to contour farming and stone ridges already practiced on a small incidental scale in the Tandjari catchment, as explained in chapter 4.1.5. All the measures described in chapter 3.1.5 can be integrated into such a plan, bearing in mind their effectiveness and feasibility. Using vegetation as an erosion management technique is recommended, as this is found to be very effective, and such measures are feasible in the Tandjari catchment.

Recommendations regarding further research following on this study include conducting a more detailed survey of the land use in the Tandjari catchment, as currently the land use maps are quite coarse and there is substantial variation within the defined land use classes. With a more detailed land use map the erosion rate and resulting sediment yield at the reservoir can be more accurately calculated. As the results have shown, vegetation is a factor with a significant influence on the erosion. Uncontrolled land use changes in the area can aggravate the erosion rate. For the AEG, it would be of high value to have a more detailed understanding of the land use and cultivation practices in the area. More regulation of land use is a measure that would be beneficial to having some control on the rate of erosion in the area.

Due to the ambiguous data obtained from different institutions, the sedimentation rate in the Tandjari reservoir could not be established through this data. The 2014 ONEA bathymetry report is the most accurate measurement of the storage capacity in the reservoir. By conducting another bathymetry measurement in the future, the sedimentation rate can be accurately determined. Such measurements can be used to validate the USLE erosion calculations.

The erosion rate in the Tandjari catchment was calculated, and erosion risk maps have been generated. It can be interesting for the AEG to gain insight into the erosion rates and high erosion risk areas of other areas in their management area. When sufficient data is present, the methods used in this study can be used to calculate and map the erosion rates and sediment yields of other areas.

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APPENDIX 1: RESULTS SOIL SAMPLE GRAIN SIZE ANALYSIS

Note: Due to the working of the laboratory in Ouagadougou, the fraction modified silt (In French: Limon, 0,002 – 0,1 mm) and the fraction modified sand (In French: Sable, 0,1 – 2 mm) were divided into two classes, fine and coarse.

MINISTERE DE L'AGRICULTURE ET
DES AMENAGEMENTS HYDRAULIQUES
SECRETARIAT GENERAL
BUREAU NATIONAL DES SOLS
DIRECTION GENERALE
DIRECTION DU LABORATOIRE
D'ANALYSES

BURKINA FASO
Unité - Progrès - justice

Ouagadougou le, 28 Avril 2017

Résultats d'analyses d'échantillons de sols/ Niels OOTVEEN

N° de Laboratoire	805	806	807
N° d'origine	1	2	3
TEXTURE	S L	L S	SL
Argile %	5,75	14,75	5,00
Limons fins %	4,50	3,00	3,25
Limons grossiers %	11,67	12,00	4,81
Sables fin %	42,49	39,79	23,52
Sables grossiers %	35,59	30,46	63,42
CARBONE ET MATIERE ORGANIQUE			
Matière Organique totale %	0,56	0,58	0,57
Carbone total %	0,32	0,34	0,33

N° de Laboratoire	808	809
N° d'origine	4	5
TEXTURE	L S	L S
Argile %	10,50	10,00
Limons fins %	7,00	6,75
Limons grossiers %	11,52	25,66
Sables fin %	30,91	43,12
Sables grossiers %	40,07	14,47
CARBONE ET MATIERE ORGANIQUE		
Matière Organique totale %	0,58	0,89
Carbone total %	0,34	0,51

Le Directeur du Laboratoire d'analyses

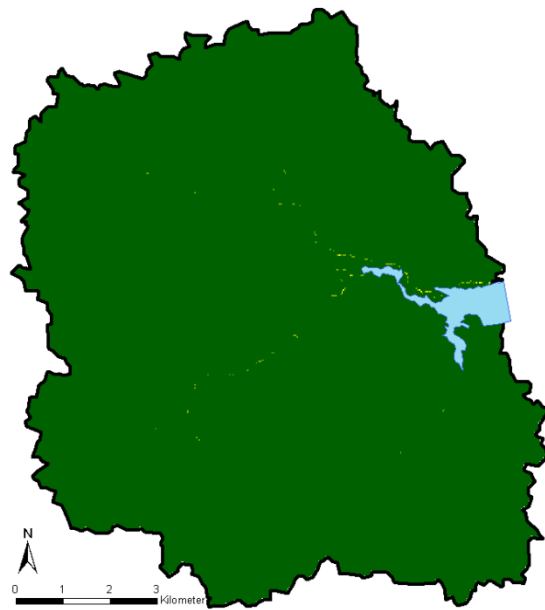


SORI S. Ibrahima

APPENDIX 2: MONTHLY EROSION MAPS

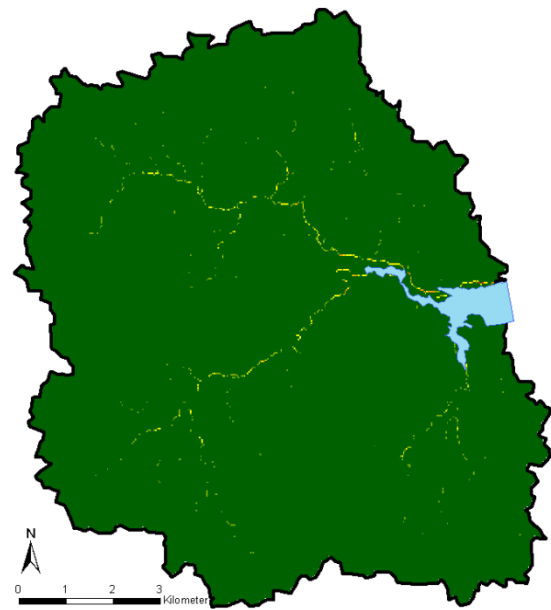
Note: For the months January and November the calculated erosion is 0, hence these maps are omitted here.

Erosion (February)



Legend
 Tandjari reservoir
 february
 A (tons/ha/month)
 0 - 2,5
 2,5 - 5
 5 - 10
 10 - 20
 > 20

Erosion (March)



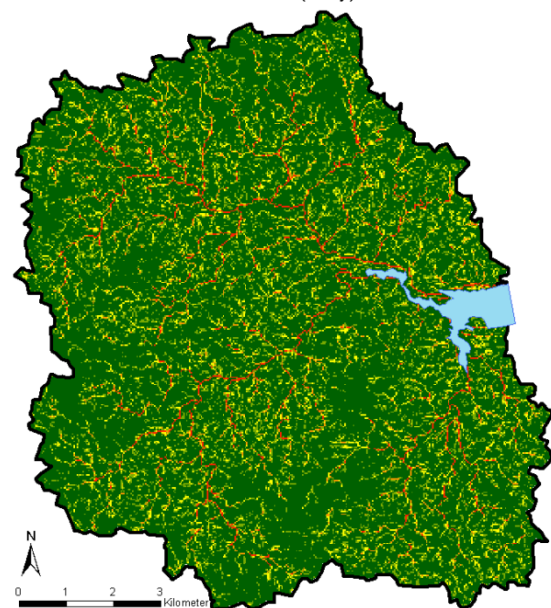
Legend
 Tandjari reservoir
 march
 A (tons/ha/month)
 0 - 2,5
 2,5 - 5
 5 - 10
 10 - 20
 > 20

Erosion (April)



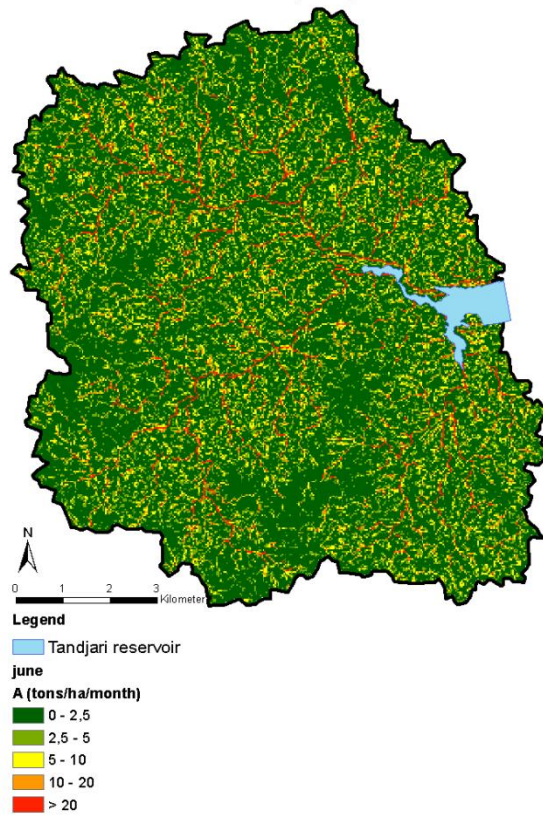
Legend
 Tandjari reservoir
 april
 A (tons/ha/month)
 0 - 2,5
 2,5 - 5
 5 - 10
 10 - 20
 > 20

Erosion (May)

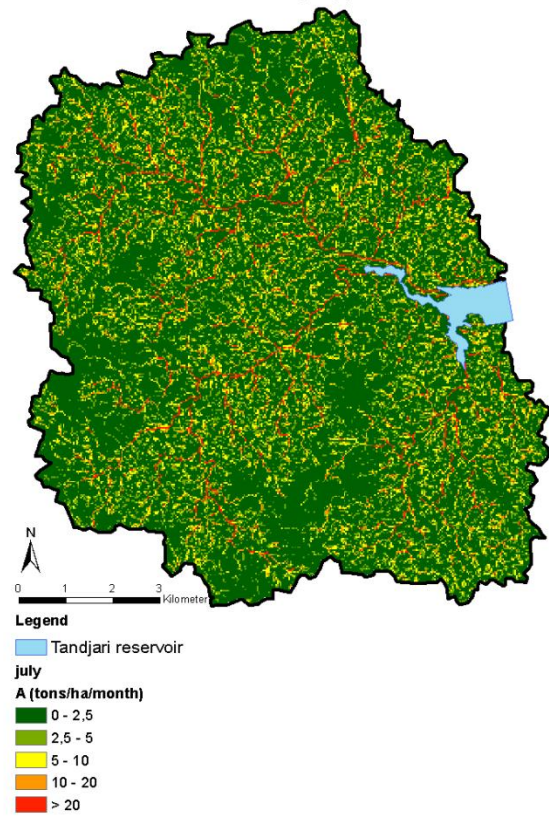


Legend
 Tandjari reservoir
 may
 A (tons/ha/month)
 0 - 2,5
 2,5 - 5
 5 - 10
 10 - 20
 > 20

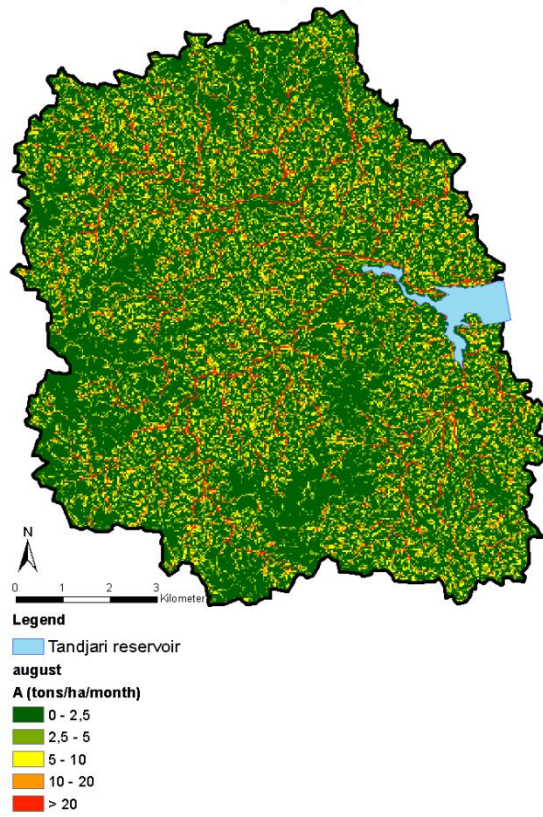
Erosion (June)



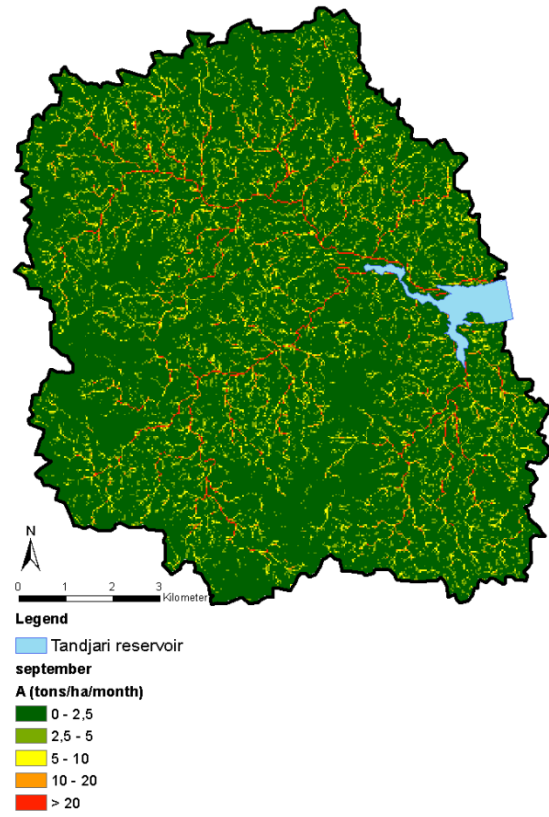
Erosion (July)



Erosion (August)



Erosion (September)

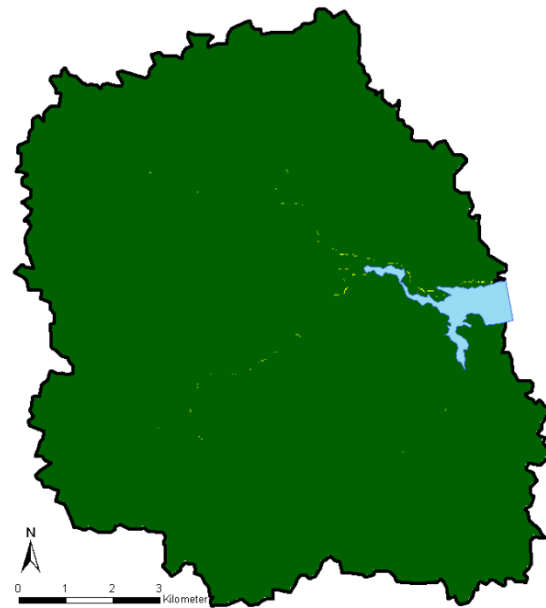


Erosion (October)



Legend
 Tandjari reservoir
 october
A (tons/ha/month)
 0 - 2,5
 2,5 - 5
 5 - 10
 10 - 20
 > 20

Erosion (December)



Legend
 Tandjari reservoir
 december
A (tons/ha/month)
 0 - 2,5
 2,5 - 5
 5 - 10
 10 - 20
 > 20

Erosion (Year)



Legend
 Tandjari reservoir
 year
A (tons/ha/year)
 0 - 2,5
 2,5 - 5
 5 - 10
 10 - 20
 > 20

APPENDIX 3: STORAGE CAPACITY TANDJARI RESERVOIR

Reprinted from ONEA (2014) paragraph 6.1.4.3. Pages 32 – 35.

6.1.4.3 Courbes hauteurs -surfaces et courbes hauteurs - volume du barrage de Tandjari
Le tableau ci-après récapitule les données Hauteurs - surfaces - volumes de la cuvette du barrage de Tandjari.

Tableau 1 : Données hauteurs - surfaces et hauteurs - volumes de la cuvette du barrage de Tandjari

Altitudes (m)	Hauteurs Echelle Limnimétrique (m)	Surfaces (ha)	Surfaces (km ²)	Volumes (m ³)
300.00	0.12	1.13	0.0113	709
300.25	0.37	2.92	0.0292	5 838
300.50	0.62	5.44	0.0544	16 075
300.75	0.87	9.08	0.0908	34 217
301.00	1.12	13.19	0.1319	62 295
301.25	1.37	17.50	0.1750	100 019
301.50	1.62	22.15	0.2215	149 511
301.75	1.87	26.79	0.2679	210 085
302.00	2.12	31.63	0.3163	283 357
302.25	2.37	37.40	0.3740	369 562
302.50	2.62	46.15	0.4615	474 494
302.75	2.87	54.70	0.5470	601 639
303.00	3.12	60.94	0.6094	745 996
303.25	3.37	67.37	0.6737	906 810
303.50	3.62	71.88	0.7188	1 080 990
303.75	3.87	75.85	0.7585	1 265 111
304.00	4.12	80.30	0.8030	1 459 767
304.25	4.37	85.20	0.8520	1 666 727
304.50	4.62	89.58	0.8958	1 885 370
304.75	4.87	94.75	0.9475	2 115 585
305.00	5.12	111.20	1.1120	2 366 840
305.25	5.37	131.09	1.3109	2 669 873
305.50	5.62	151.51	1.5151	3 024 621
305.75	5.87	169.61	1.6961	3 427 202
306.00	6.12	191.23	1.9123	3 878 858
306.25	6.37	211.38	2.1138	4 381 609
Déversoir 306.35	6.47	225.00	2.2500	4 750 000
306.50	6.62	233.80	2.338	4 938 670
306.75	6.87	256.67	2.5667	5 551 969
307.00	7.12	279.75	2.7975	6 222 167
307.25	7.37	302.89	3.0289	6 949 497
307.50	7.62	327.09	3.2709	7 735 935
307.75	7.87	351.09	3.5109	8 583 415
308.00	8.12	374.23	3.7423	9 491 530
308.25	8.37	396.64	3.9664	10 455 540
308.50	8.62	416.40	4.1640	11 472 523

Source : Données de l'étude, juin 2014

Les figures ci-après donnent les courbes hauteurs - surfaces et hauteurs - volumes du barrage de Tandjari.

En résumé, à la cote de retenue normale (cote déversoir = 306,35 m), la surface du plan d'eau du barrage de Tandjari est d'environ 220 ha et le volume d'eau stocké est d'environ 4 666 670 m³.

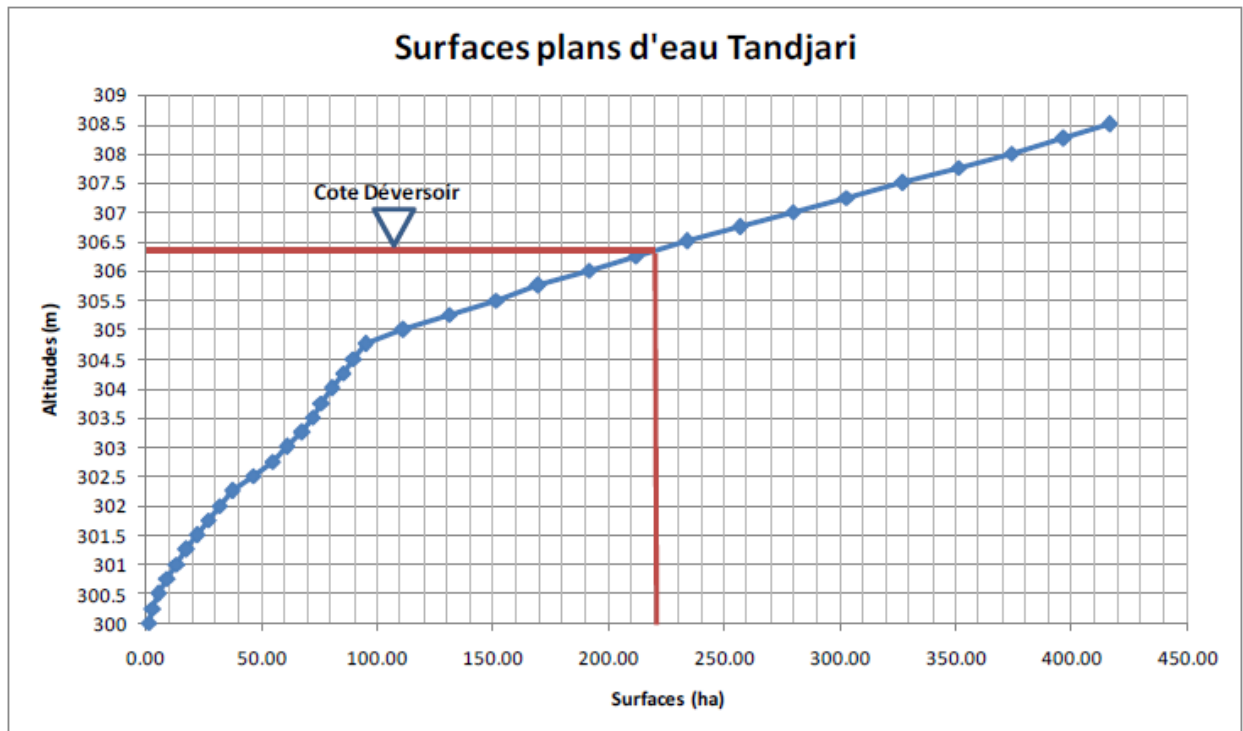


Figure 1 : Courbe hauteurs - surfaces du barrage de Tandjari

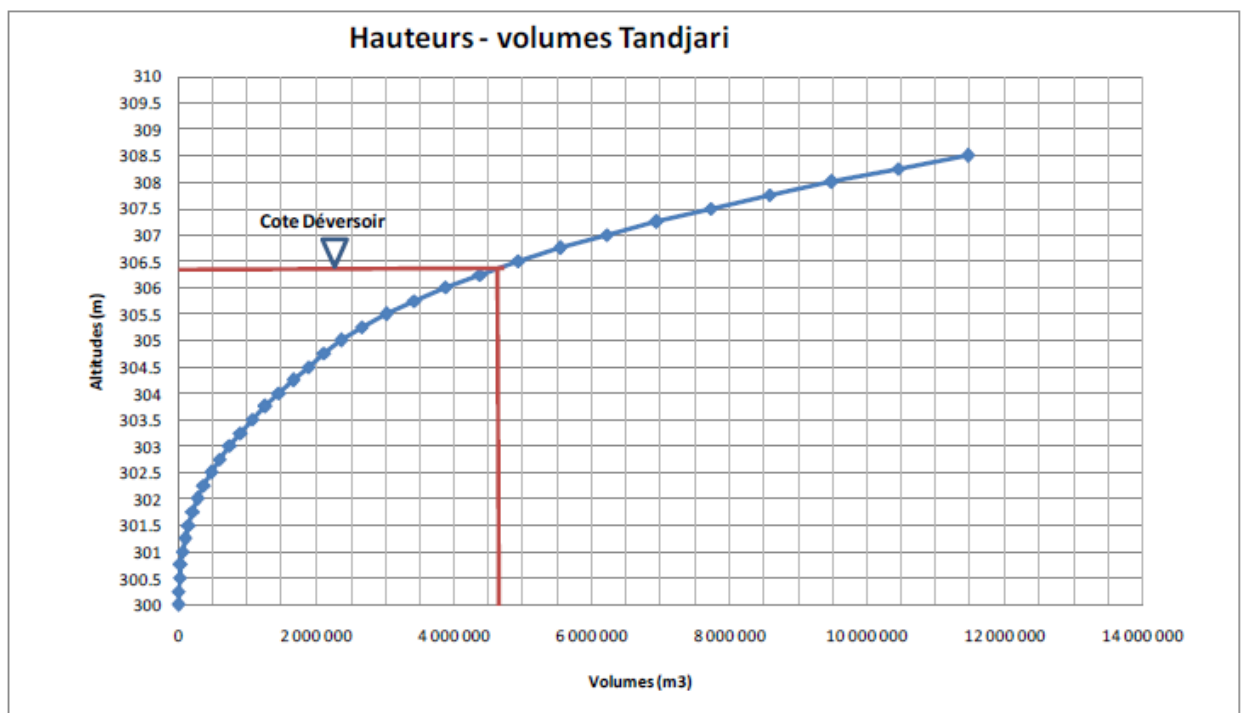


Figure 2 : Courbe hauteurs - volumes du barrage de Tandjari