

Article

Effectiveness of the VFSSMOD Model in Simulating Sediment Trapping by a Vegetative Filter Strip: Case of the Lobo Reservoir in Daloa (Central–West Côte d'Ivoire)

Tanoh Jean-Jacques Koua ^{1,*} , Kouakou Hervé Kouassi ¹, Kouakou Lazare Kouassi ¹, Koffi Alfred Allou ¹ and Jaehak Jeong ²

¹ Environmental Sciences and Technologies Laboratory, Jean Lorougnon Guédé University, Daloa P.O. Box 150, Côte d'Ivoire

² Blackland Research and Extension Center, Texas A&M AgriLife Research, Temple, TX 76502, USA; jeongj@tamu.edu

* Correspondence: kouat2018@gmail.com or koua_tanoh@ujlg.edu.ci; Tel.: +225-0758307958

Abstract: The Lobo reservoir, designed to supply water to the Daloa city population (central west of Côte d'Ivoire), is facing the phenomenon of eutrophication due to the agricultural plots located upstream of the reservoir inputs. Studies have highlighted the reservoir pollution and sedimentation problems. This study was initiated to test the effectiveness of a transfer model in the fight against the eutrophication problem. The objective of this study was to determine the optimal width of a vegetative filter strip on the banks of the Lobo reservoir, where the water intake installations of the drunk water company SODECI are located, using the VFSSMOD model. The methodological approach is structured into four (4) main stages: 1—Evaluation of runoff from the source of pollution (contributing surface) during a rainy episode; 2—Calculation of the incoming runoff volume and the sediment load; 3—Simulation of runoff reduction and incoming sediments within the grassy filter strip; and 4—Determination of the optimal width of the grassy strip. The results obtained showed a contributing source area of 13.5 ha and 2% as the average slope. A runoff volume of 4680 m³ coming from the source of pollution is reduced by 1119 m³ (24%) through a grassy strip that is 3 m wide. The sediment load goes from 132 kg to 33 kg, a reduction of 75% in the quantity of sediment entering. The scenarios tested showed that a grassy strip width equal to 3 m should allow for a reduction of 75% of upstream sediments. This grassy strip width of 3 m should be considered for implementing a vegetative filter strip around the Lobo reservoir.

Keywords: grass strip; eutrophication; pesticides; pollution; protection; VFSSMOD; Lobo; Côte d'Ivoire



Citation: Koua, T.J.-J.; Kouassi, K.H.; Kouassi, K.L.; Allou, K.A.; Jeong, J. Effectiveness of the VFSSMOD Model in Simulating Sediment Trapping by a Vegetative Filter Strip: Case of the Lobo Reservoir in Daloa (Central–West Côte d'Ivoire). *Earth* **2024**, *5*, 928–944. <https://doi.org/10.3390/earth5040048>

Academic Editor: Hossein Bonakdari

Received: 11 May 2024

Revised: 9 July 2024

Accepted: 15 July 2024

Published: 27 November 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Improving the living conditions of populations requires better access to basic services, particularly the availability of drinking water. The State of Côte d'Ivoire, like the States of Sudano-Sahelian Africa, has so well understood the challenges of access to clean water that it initiated, with the support of development partners, actions aimed at facilitating access to the public drinking water service for the greatest number of Ivoirians. Due to this political will, numerous dams were built during the 1970s and 1980s [1]. However, in recent years, most of these dams, particularly those located in agricultural areas, have undergone processes of degradation and filling of the water bodies that they constitute. This situation led to the eutrophication phenomenon [2]. Indeed, demographic pressure has led to a sharp increase in cultivated areas [3] and has expanded the consumer market for food and industrial products. To meet this strong demand and protect their crops, the State of Côte d'Ivoire, through structures such as ANADER (National Rural Development Support Agency), encourages traditional farmers and even industrialists to use agricultural

inputs (fertilizers and pesticides). However, the lack of training on the sustainable use of agricultural inputs and the non-compliance with the principles of environmental protection with regard to these inputs have caused an exacerbated use of these products, which end up in the hydrographic network, causing eutrophication problems [4]. The case of the Lobo reservoir highlighted by Maïga et al. [5] is representative.

Thus, runoff water transports particles, pesticides, and fertilizers remaining on the ground that are not used by plants. Excess pesticides and agricultural inputs drained by leaching phenomena mainly contain nitrates and phosphates [6], which are nutrients for algae growing in the reservoir. On the one hand, a small increase in algae biomass has no effect on the ecosystem and can even cause an increase in certain fish populations. On the other hand, when there are too many nutrients in the water, overly stimulating algae growth can ultimately impact water clarity. When the algae die, they are decomposed by numerous bacteria that use the oxygen in the water to breathe, causing a lack of dissolved oxygen in the aquatic environment, which threatens the survival of other living beings and of the reservoir itself [7].

The Lobo reservoir is used by the Cote d'Ivoire Water Distribution Company (SODECI) to supply drinking water to the Daloa town population and its surrounding areas, as well as to meet the water needs of agropastoral activities. The work carried out by Koua et al. [8], Soro et al. [9], and N'goran et al. [10] showed a spatial distribution of nutrients from mineral fertilizers applied to plants. This distribution predisposes Ivorian reservoirs, particularly the Lobo reservoir, to an enrichment of nutrient elements responsible for the observed eutrophication phenomenon in that reservoir. The analysis of the invasive aquatic flora on the Lobo water body by Traoré et al. [11] showed that this situation is the result of pollution and Lobo reservoir eutrophication.

Measurements of parameters characteristic of the Lobo's waters, such as chlorophyll-a and phosphorus, revealed high values of 35 µg/L and 66 µg/L, respectively. These values, compared to the threshold values of the OECD (Organization for Economic Co-operation and Development) (between 0.035 and 100 µg/L of phosphorus and 25 µg/L of chlorophyll-a) for a water body to be polluted, revealed that this reservoir is hyper-eutrophic [2]. Phosphorus accumulation in surface waters occurs via sediment transport. This accumulation leads to the proliferation of plant biomass (eutrophication). Thus, a reduction in sediments transferred to surface waters would lead to a reduction in the quantity of phosphorus and could impact eutrophication. So, a vegetation filter strip is a strip of land with permanent vegetation, mainly composed of grasses, and located between the source of pollution and the bank of a water body (Figure 1). It helps protect surface water located at the bottom of a slope by limiting the quantities of pollutants, particularly sediments, that enter it, given that it slows down runoff water and filters transported pollutants. The capacity of this strip to reduce the quantities of pollutants arriving in the body of water will necessarily have an impact on the phenomenon of eutrophication. These results were confirmed by the work of Koua et al. [8], who showed that the Lobo water reservoir is subject to significant nutrient transfer, which predisposes it to the phenomenon of eutrophication. In view of its certain interest, the contamination of this water resource by the use of pesticides and fertilizers used in agriculture, added to poor agricultural practices (slash-and-burn cultivation, soil left bare between two crops, etc.), constitutes a problem worrying for users. So, what strategies should be put in place to curb water pollution? Would vegetative filter strips be effective in curbing this pollution? To try to resolve all these questions, this study based on vegetative filter strips was carried out. The effectiveness of vegetative filter strips in the fight against surface water pollution has been demonstrated in more studies around the world. Thus, Kumwimba et al. [12] studied the influence of width, type of vegetation, and season on the effectiveness of the vegetative filter strip. The findings showed that woody vegetation within 18-m Riparian vegetated buffer strips (RVBS) exhibited 100% sediment trapping efficiency (STE), 89.8% total nitrogen (TN) removal, and 92.82% total phosphorus (TP) removal. There are also the results of the

work of Zhang et al. [13], which showed that runoff and sediment production in eroded gullies can be effectively reduced through vegetation filter strips.

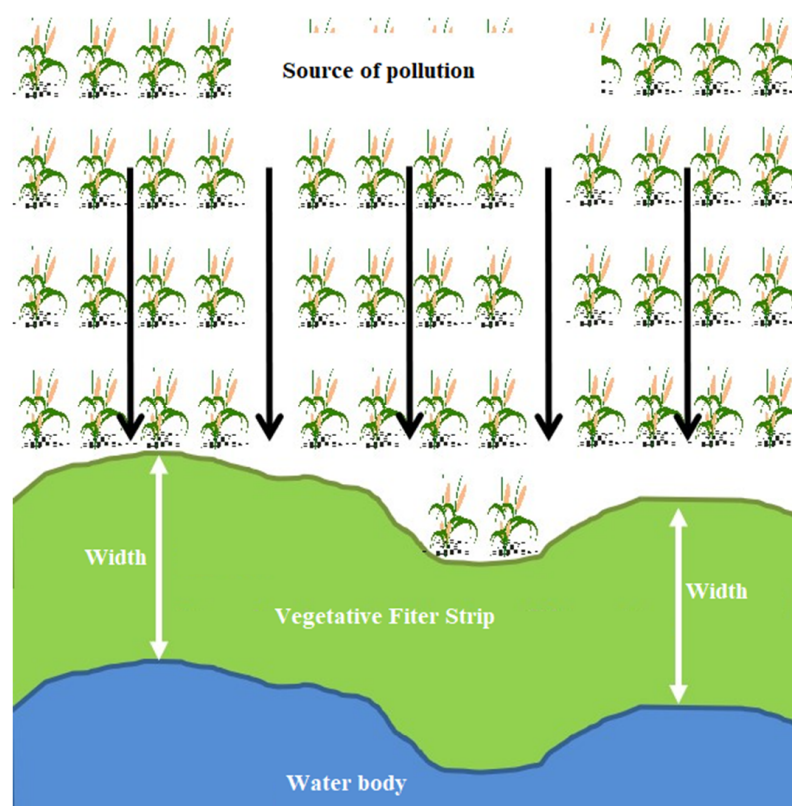


Figure 1. Sketch of a vegetative filtering strip to be implemented on a bank of the Lobo water reservoir.

The study was based on the VFSSMOD pollutant transfer model [14]. This model has shown its ability to simulate the retention of nutrients and pesticides by a vegetative filter strip [15–17]. However, the development of vegetative filter strip techniques in Cote d’Ivoire is still in its embryonic state. The proposal of this technique for the fight against eutrophication of water bodies in Cote d’Ivoire is one of the research perspectives of the thesis work of Koua [18].

The objective of this study is to determine the optimal width of a vegetative filter strip occupying less agricultural space so as not to impact agricultural production, which will be placed on the banks between the sources of pollution and the Lobo reservoir, necessary to significantly reduce the flow of sediments transferred to this reservoir, using the VFSSMOD model.

This step of the study only concerned the size. It was mainly based on theory (concepts and equations). Another step will consist of installing the vegetative filter strip on the site to carry out experiments on sediment flows.

2. Materials and Methods

2.1. Materials

2.1.1. Study Site

The Lobo reservoir is located 25 km from the town of Daloa between longitudes $6^{\circ}2$ and $7^{\circ}55$ west and latitudes 6° and $6^{\circ}55$ north (Figure 2). It belongs to the Lobo watershed, with an area of 7280 km². The city of Daloa represents the economic center of the region [19]. The Lobo River is one of the main tributaries on the left bank of the Sassandra River. The average flow of the river at the Nibéhébé hydrometric station is 12.43 m³.s^{−1} [20].

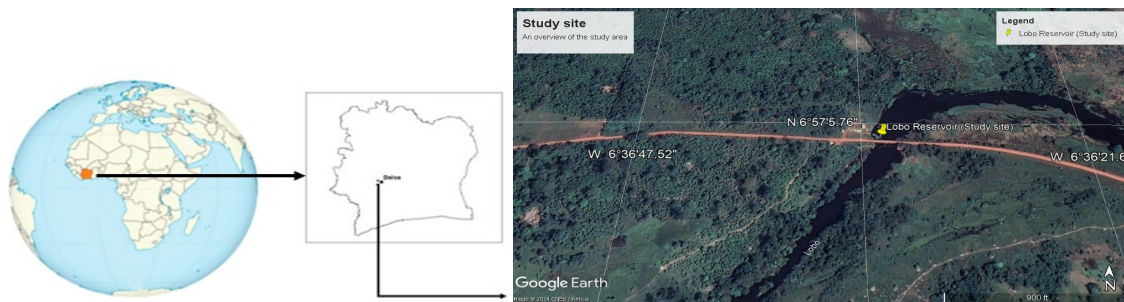


Figure 2. Geographic location of the study site (Lobo reservoir).

The climate of the basin is an attenuated transitional equatorial type. The seasons are divided between a rainy season from March to October, with a slowdown in precipitation in July and peaks observed in June and September, and a dry season from November to February, with some isolated precipitation. Dry and wet seasons alternate, with temperatures varying from 25.6 °C to 28.65 °C on average. Over the period 2000–2017, an average interannual rainfall of 1246 mm was observed at the Daloa station.

The relief of the basin is not very rugged and consists of plains and low plateaus [21]. The plains, whose altitude varies between 180 and 250 m, are located in the south of the basin and correspond to the watercourse route. The hydrographic network of the Daloa region (Figure 3) is dominated by the Sassandra River. The Lobo, the main tributary of the Sassandra, is the second-most important river. The large rivers like Dê complete the hydrographic picture of the Daloa region [19]. All these watercourses have large alluvial plains along their courses suitable for irrigated crops and other off-season vegetable crops. In dry periods, the very sharp drop in water levels and the river beds sometimes leave wide hollows interspersed with puddles. The waters of the Lobo flow mainly in the north–south direction, and the period of lowest water is observed during the first months of the year (January and February). The annual maximum rainfall is observed in September or October [19].

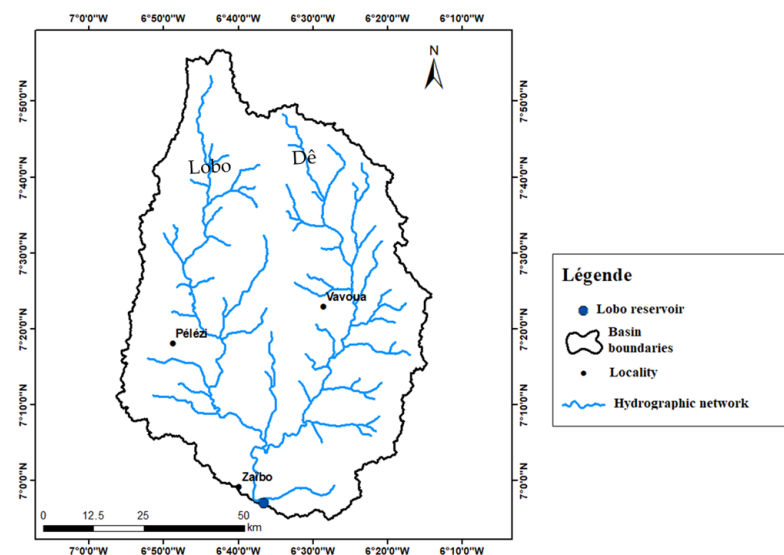


Figure 3. Hydrographic network of the study site within the Lobo reservoir watershed.

The geological formations encountered in this area, mainly made up of magmatic rocks, are of plutonic and volcanic types [22].

Hydrogeologically, the basin is located in a crystalline basement zone. There are two types of aquifers: alterite aquifers (superficial) and fractured aquifers deeper than the previous ones [23]. The estimated annual recharge varies from 66.4 to 84 mm, respectively,

in 2019 and 2020. As for the average direct recharge, it is estimated, respectively, at 44 mm in 2018 and 57.3 mm in 2019, or, respectively, approximately 4% and 5% of precipitation [24].

2.1.2. Data

To carry out this study, agronomic, soil, and climatic data were used. These are, among others:

- the soil properties of the source of pollution (the degree of compaction, grain size, and structure of the soil) from the FAO (Food and Agriculture Organization of the United Nations) database [25], the potential location of the grassy strip and land use (different crops grown in the source pollution area);
- the average concentration of sediment entering the reservoir from April to December 2019, provided by the LSTE (Laboratory of Environmental Sciences and Technology) of Jean Lorougnon Guédé University;
- rainfall and temperature data from the Daloa station at daily time intervals from 2000 to 2017, provided by SODEXAM (the Aeronautical and Meteorological Development and Exploitation Company).

2.1.3. Work Tools

The tools used to process the data consist of Microsoft Excel for processing rainfall data and for producing graphs and diagrams, the “Soil Water Characteristics” program included in SPAW (Specially Protected Areas and Wildlife) to simulate conductivity and the water retention capacity of the soil, VFSSMOD-W (vegetative filter strip modeling, Window System) in version 6.8 software to model the scenarios and define the optimal dimensions of the grassy strip, Google Earth, which allowed the extraction of topographical dimensions along the potential source of pollution, and ArcGis 10.4 to produce the different maps and determine the dimensions of the pollution source (contributing area).

2.2. Methods

The methodology adopted in this study is mainly based on the VFSSMOD transfer model.

2.2.1. Description of the VFSSMOD Model

The VFSSMOD model was developed in the United States of America by Muñoz-Carpena and Parsons [14]. VFSSMOD is a plot-scale storm-based mechanistic model designed to route the incoming hydrograph and sedimentograph from an adjacent plot through a filtering vegetation strip and to calculate its effectiveness on the flow, infiltration, and trapping of sediments. The model handles time-dependent hyetographs, spatially distributed filter parameters (vegetation roughness or density, slope, infiltration characteristics), and different particle sizes of incoming sediments. Any combination of unstable storm types and incoming hydrographs can be used. VFSSMOD consists of a series of modules simulating the behavior of water, sediments, and pollutants across the grassy strip. The modules currently available are (i) the infiltration module, a module for calculating excess precipitation and water balance at the ground surface for unbounded deep soils or shallow waters; (ii) the kinematic wave surface flow module, a 1-D module for calculating the depth and flow rates at the surface of the filtered soil; and (iii) the sediment filtration module, a module for simulating the transport and deposition of incoming sediments along the vegetative filter. VFSSMOD is essentially a 1-D model for describing water transport, sediment deposition, and pollutant trapping along the vegetative filter. Below are the different components described.

- Hydrology

In the hydrological component, it involves solving the kinetic wave approximation of Saint-Venant's equations for overland flow for the 1-D case as presented by Lighthill and Whitham [26]:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = i_e(t) \text{ (Continuity equation)} \quad (1)$$

$$S_0 = S_f \text{ (Momentum equation)} \quad (2)$$

Then, based on the Manning equation, a link between ' q ' and ' h ' can be established to define a uniform flow equation:

$$q = q(h) = \frac{\sqrt{S_0}}{n} h^{\frac{5}{3}} \quad (3)$$

where ' h ' is the depth of overland flow [L], ' q ' is the flow per unit width of the plane [L^2T^{-1}], ' S_0 ' is the slope of the plane, ' S_f ' is the hydraulic or friction slope, and ' n ' is Manning's roughness coefficient [$LT^{-1/3}$]. The initial and boundary conditions can be summarized as:

$$h = 0; 0 \leq x \leq L; t = 0 \quad (4)$$

$$h = h_0; x = 0; t > 0 \quad (5)$$

where ' h_0 ' can be 0, a constant or a time-dependent function, such as the incoming hydrograph from the adjacent field.

It also represents a link to measured data or other water quality models describing incoming runoff and pollutants from the source area.

- Sediment and chemical transport

A filtration of suspended matter model using a turf simulated by a numerical model was developed and then tested for field conditions [27–33]. It is also based on the hydraulic flow, transport, and deposition profiles of sediments in laboratory conditions. The model has the advantage of being developed specifically for the filtration of suspended matter by grass.

The advantage of VFSSMOD over other models used to simulate pollution removal is the inclusion of filter hydrology, including flow changes derived from sediment deposition, soil water infiltration depending on time, management of complex sub-models, intensity of storms, and variable surface conditions (slope and vegetation) along the filter. Considering all these advantages, this study used the vegetative filter strip model integrated into the VFSSMOD numerical model (Figure 4). The model aims to study vegetative filter strip performance on an event-by-event basis and becomes a powerful and objective design tool. The design paradigm implemented in VFSSMOD seeks to identify the optimal constructive characteristics of the filter (width, slope, and vegetation) to reduce (to a reduction objective prescribed as Total Maximum Daily Load) the output of pollutants from a given disturbed area (soil, cultivation, management practices, etc.). VFSSMOD has been tested in a wide variety of contexts (agroforestry, mining, and roads) with good model predictions against measured values of infiltration, runoff, and vegetation trapping efficiency for sediments, phosphorus (particulate and dissolved), nitrates, and pesticides. Indeed, Sur et al. [15] used it to implement the effects of shallow water tables on pesticide runoff mitigation effectiveness. Similarly, Minwoo et al. [16] conducted a study on the trapping efficiency of diffuse pollution sources in Cheongmi Stream using VFSSMOD. In the same direction, Muñoz-Carpena et al. [17] analyzed the effectiveness of the VFSSMOD model during long-term exposure to pesticide residues in vegetative filter strips.

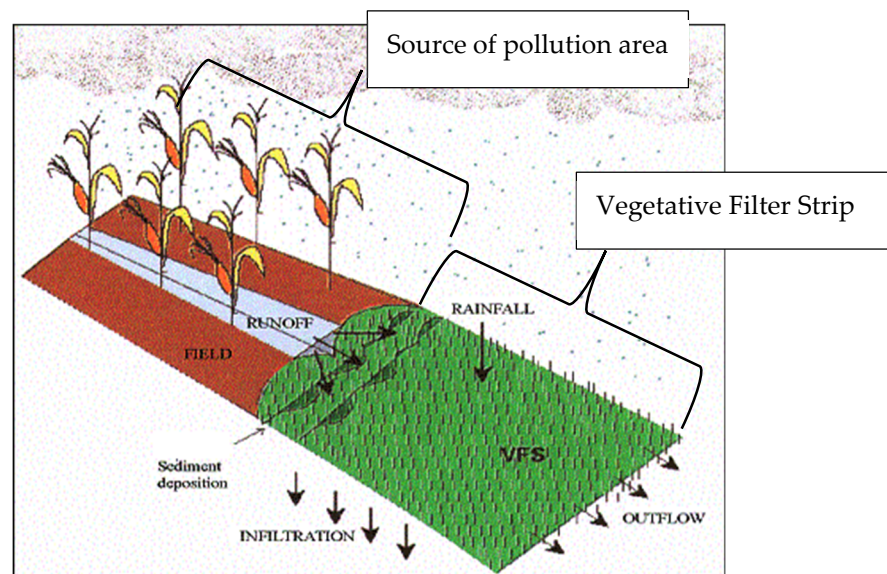


Figure 4. Source of pollution area and filter strip in VFSMOD, modified from [14].

2.2.2. Steps

The methodological approach is structured into three (3) main stages:

- Evaluation of runoff from the source of pollution (contributing surface) during a rainy episode;
- Calculation of the incoming sediment load;
- Simulation of runoff reduction and incoming sediments within the grassy filter strip.

Evaluation of runoff from the pollution source (contributing area) during a rain episode

This step begins with determining the geometry of the contributing surface and choosing the rain event. The length and surface area of the pollution source were determined using the “Measure” tool in ArcMap. Google Earth allowed the extraction of topographic coastlines in the direction of rainwater flow in order to calculate the average slope. For the dimensioning of this buffer strip, one chooses the height of the maximum daily rainfall over the period 2000–2017. This height corresponds to 121 mm. Then, the construction of the unit hydrograph (UH) was carried out. Indeed, the curve number (CN) is an empirical parameter used in hydrology to predict direct runoff or infiltration from excess precipitation [34]. The value of the curve number is chosen according to the hydrological group of the soil, the land use, the hydrological conditions, and the initial humidity conditions of the environment [34]. The land cover of the study site is scrub and wasteland with medium-moisture conditions. The hydrological group of the soil is C since the texture is clay–sandy. Thus, the CN has a value of 75. To simulate the rain event and the corresponding runoff events from the contributing area, the use of the “Hydrogram Unit” module in VFSMOD was necessary. This is based on the use of the SCS-CN method to generate the unit hydrograph. The data provided are the cumulative rainfall amount, the duration of the event, the CN, the dimensions of the pollution source area, and the erosion parameters, in particular the erodibility of the soil and the soil type. The SCS-CN method was developed by the USDA-NRCS (US Department of Agriculture–Natural Resources Conservation Service) to predict runoff volume [35]. For a given rainfall event, the runoff volume is calculated using Equations (6) and (7):

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}, \text{ if } P > I_a \quad (6)$$

$$Q = 0, \text{ if } P \leq I_a \quad (7)$$

in which

- Q (mm) is the direct runoff,
- P (mm) is the cumulative precipitation,
- I_a (mm) are the initial losses,
- S (mm) represents the antecedent soil moisture.

The antecedent soil moisture and initial losses are calculated using the following equations:

$$S = \frac{25400}{CN} - 254, \quad (8)$$

where 25,400 and 254 are the constants [35].

$$I_a = 0.2 * S \quad (9)$$

In this method, the runoff hydrograph (UH), which represents the evolution of the runoff flow as a function of time, makes it possible to directly evaluate the runoff based on knowledge of the rainfall, the curve number, and the synthetic hydrograph. For this, it is necessary to calculate the watershed delay time L , the peak time T_p , and the peak flow Q_p according to the physical characteristics of the watershed studied.

The watershed delay time L is calculated using the following equation:

$$L = \frac{\left(\frac{l}{0.3048}\right)^{0.8} * \left(\frac{S}{25.4} + 1\right)^{0.7}}{1900 * Y^{0.5}} \quad (10)$$

in which

- L (h) is the delay time,
- l (m) is the longest hydraulic path,
- S (mm) is the maximum soil retention,
- Y (%) is the average slope of the watershed.

The peak time T_p of the unit hydrograph is calculated using the following equation:

$$T_p = \frac{\Delta D}{2} + L \quad (11)$$

where

- T_p (h) is the peak time,
- ΔD (h) is the elementary rain duration,
- L (h) is the watershed delay time.

As for the peak flow Q_p , it is estimated according to Equation (12):

$$Q_p = \frac{0.208 * A}{T_p}, \quad (12)$$

where A (km²) is the drained area.

The hyetogram (temporal evolution of rain quantities) of net rain was then constructed. It is based on the determination of the volume of net rain associated with each of these elementary rains [36], that is, the part of rain that will contribute directly to the runoff genesis (the remainder being infiltrated or stored in the microtopography of the soil). For this study, we use the equations of Chow et al. [37]:

$$\text{if } P > I_a, \quad (13)$$

$$F = \frac{S * (P - I_a)}{P - I_a + S}, \quad (14)$$

$$R = P - I_a - F \quad (15)$$

$$I_a = P \text{ if } P < I_a \quad (16)$$

in which

- R (mm) is the cumulative net rain,
- P (mm) is the cumulative rain,
- I_a (mm) are the cumulative initial losses,
- F (mm) is the cumulative infiltration.

To determine the net rain associated with each elementary rain, it is sufficient to successively subtract the cumulative values obtained for each time interval [36].

Calculation of incoming sediment load

The quantity of sediment entering the strip was calculated from the MUSLE model [38]; it is the modified version of the USLE model (universal soil loss equation), which evaluates water erosion during flooding based on five erosion factors. The equation is given by Equation (17):

$$Sed = \alpha(Q * Q_p)^\beta * K * LS * C * P, \quad (17)$$

where

Sed is the sediment load (tons) corresponding to the highest one-hour (60 min) rain event, which is 121 mm over the period 2000–2017;

$\alpha = 11.8$ and $\beta = 0.56$ are two parameters of the MUSLE model;

Q is the volume of runoff (m³);

Q_p is the peak flow (m³.s⁻¹) during the flood;

K is the soil erodibility factor (t.ha⁻¹MJ⁻¹mm.h⁻¹);

LS is the topographic factor (unitless);

C is the plant cover management factor (unitless);

P is the anti-erosion development factor (unitless).

Simulation of runoff and incoming sediments trapping within the grassy strip

The modeling approach is as follows:

- integrate the runoff previously assessed and the hyetogram of the event into the VFSMOD model;
- provide information on the soil and the properties of the incoming sediment;
- execute the program for reducing the sediments and runoff flows entering the grassy strip;
- determine the optimal width of the grassy strip.

The determination of the optimal width was based on the retention capacity of the vegetative filter strip. This retention capacity is written according to Equation (18):

$$E_r = \left(1 - \frac{Q_{out}}{Q_{in}}\right) \times 100, \quad (18)$$

where

E_r: Retention capacity (%);

Q_{out}: Flow leaving the vegetative filtering band [L³T⁻¹];

Q_{in}: Flow entering the vegetative filter strip [L³T⁻¹].

Based on the Manning equation, Q_{in} can be written according to Equation (19):

$$Q_{in} = l \cdot \frac{s^{1/2}}{n} h^{5/3}, \quad (19)$$

in which

l: the width of the vegetative filter strip [L];

s: the slope of the land under the vegetative filter strip (%);

n: is Manning's roughness coefficient [LT^{-1/3}];

h : is the depth of overland flow [L].

The retention capacity of the vegetative filter strip can finally be written as:

$$E_r = \left[1 - \frac{nQ_{out}}{ls^{1/2}h^{5/3}} \right] \times 100, \quad (20)$$

The optimal width stipulates that at least 75% of the flows are retained on the filter strip, which means we target an E_r value of at least 75%. So, we will only have 25% flow at the outlet of the filter strip.

Based on this principle, if s , n , h , and Q_{out} are known, l is easily deduced from Equation (20). This value of l is called the optimal width.

In the case of this study, ten (10) scenarios were tested, with widths ranging from 0 to 9 m with an interval of 1 m.

The methodology followed can be summarized according to the diagram in Figure 5.

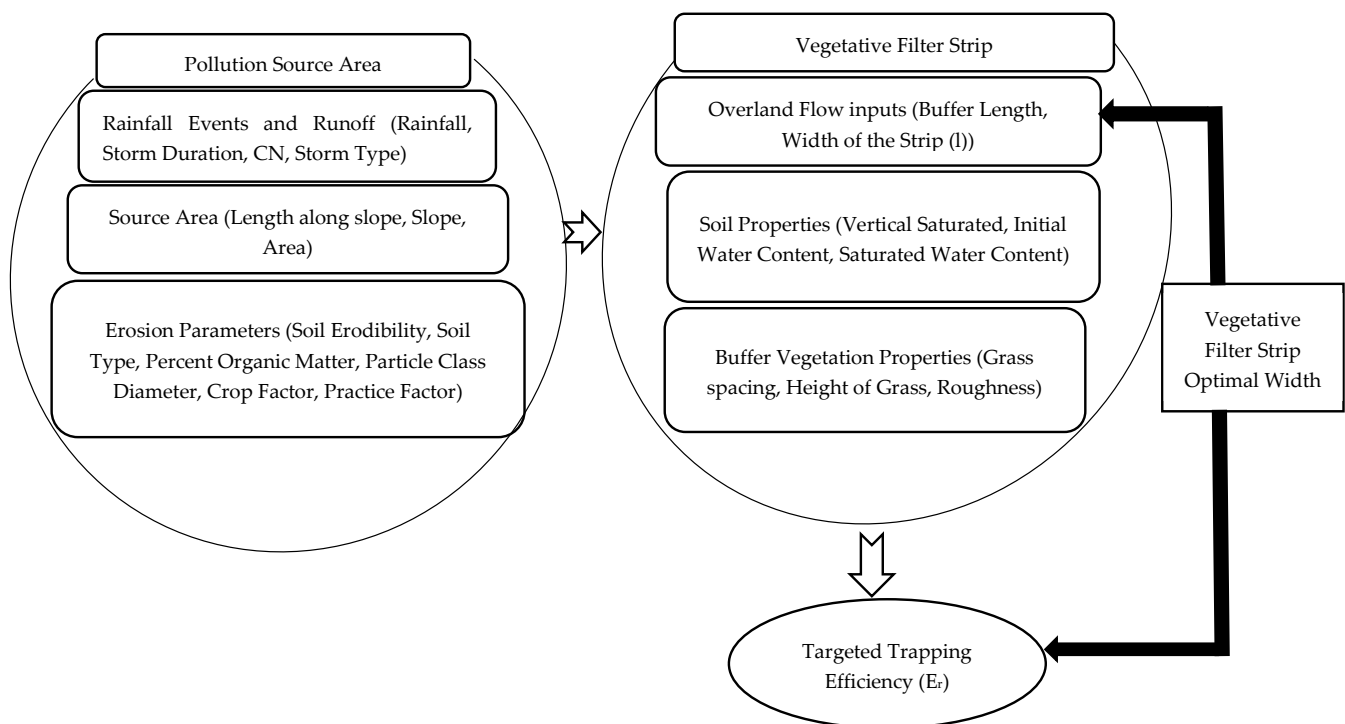


Figure 5. Summary of the methodology followed to determine the optimal width of the vegetative filter strip using VFSSMOD.

3. Results

3.1. Geometry of the Contributing Surface Area (Source of Pollution)

The source of pollution has an area of 0.135 km², or 13.5 h, for an average length of 645 m. From upstream to downstream, the slopes vary between 2.7% and 0.4%. The average slope is 2%. The contributing area extends over a width of 210 m on average. The longest hydraulic path is 519 m.

3.2. Unit Hydrograph (UH) of the Contributing Area

The results of the flow variation as a function of time are presented in Figure 6. The flood hydrograph has the shape of an asymmetrical bell curve on which four parts are observed: drying up (before the net rain) AB, flood BC, CD recession, and drying up (after the hydro-rainfall survey) DE.

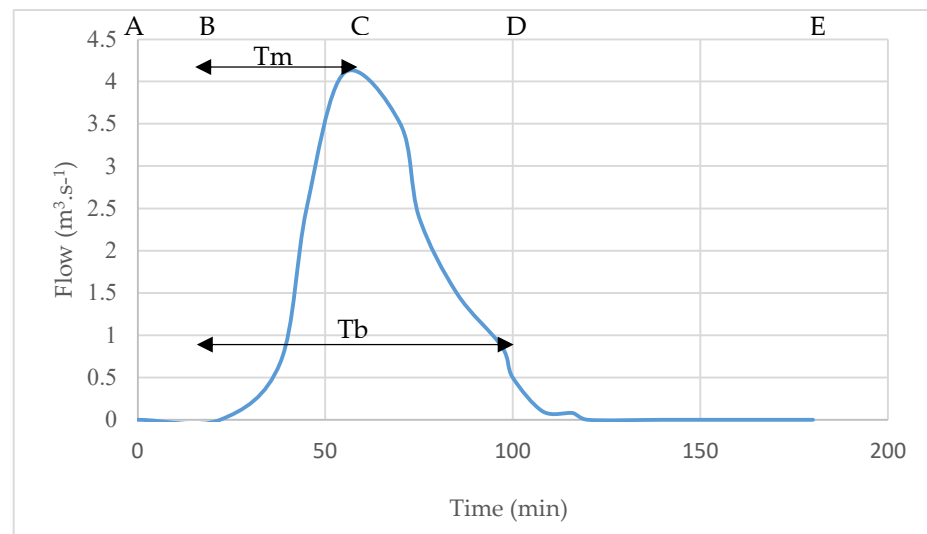


Figure 6. Hydrograph of the rain event studied.

The characteristic times obtained are the rise time T_m , which is the time that elapses between the arrival at the grassy strip of the rapid flow and the maximum of the hydrograph, i.e., 40 min; and the basic time T_b , which corresponds to the duration of runoff, i.e., 80 min. The estimated runoff volume is 4680 m^3 . It should be noted that this volume of runoff water is loaded with sediment. These sediments are carried towards the vegetative filter strip by runoff water.

It should be noted that the contributing surface area is 0.135 km^2 , and the total amount of water runoff is 35 mm, or 29% of the rain that fell.

3.3. Hyetogram of the Contributing Area

Figure 7 illustrates the evolution of rain intensity over time. The rain event considered for this study lasts one (1) hour. The maximum intensity is observed at approximately 31 min. This distribution describes a normal law with a peak of $13.77 \times 10^{-5} \text{ m.s}^{-1}$.

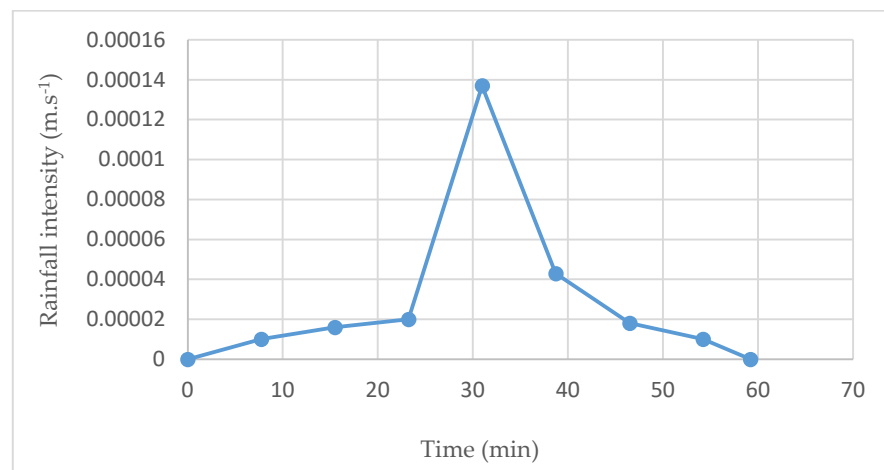


Figure 7. Hyetogram of the contributing surface area.

3.4. Runoff and Sediment Entering the Grassy Strip Trapping

The results of the filtration capacity of the vegetative filter strip as a function of its width are presented in Figure 8.

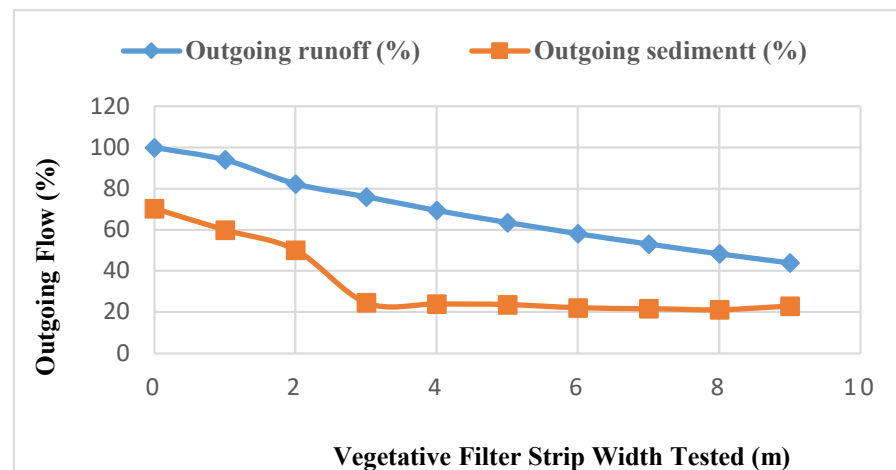


Figure 8. Evolution of outgoing flow as a function of the bandwidth.

With no vegetative strip (0 m), 100% of the runoff is likely to reach the reservoir. However, approximately 70% of the sediment would reach the reservoir. Overall, there is a decrease in flows leaving the band as the width increases. Runoff can drop by up to 56% (44% out) for a 9 m wide strip. The sediments, for their part, drop up to 77% (23% out). At a 3 m width of the strip, there is a reduction of 75% (25% out) in the incoming sediment flows, with the outgoing runoff being 76%, or 24%, retained by the vegetative strip. From 3 m, it is noticed that there is almost no change in the filter efficiency during the ten (10) scenarios tested. For runoff, it is noted that there is a progressive decrease as the width increases. A vegetative strip width of 3 m would allow a reduction of at least 75% of incoming sediments. The results showed that a 3 m wide grassy strip can reduce the incoming water flow by 1119 m³, or a reduction of 24% in the volume (4680 m³) coming from the source of pollution (Figure 9). The estimated sediment load is 132 kg. This gave a sediment concentration of 0.028 kg.m⁻³, or 28 g.m⁻³. The sediment load goes from 132 kg to 33 kg, a reduction of 75% in the quantity of sediment entering the same wide grassy strip (Figure 10).

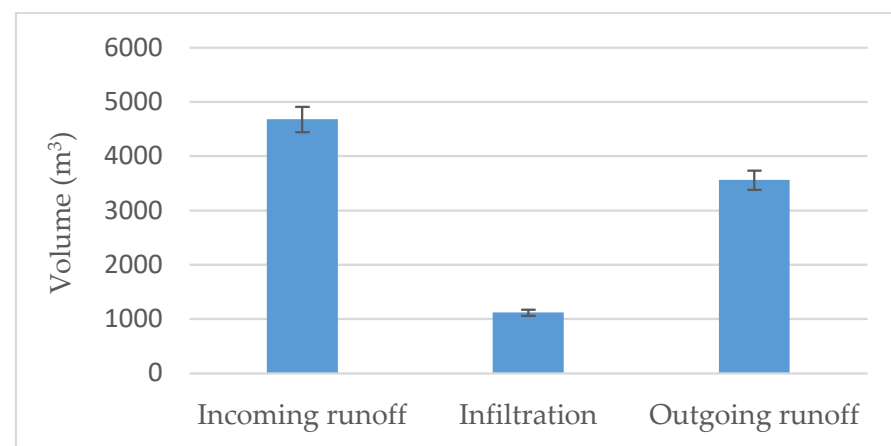


Figure 9. Runoff reduction by the vegetative filter strip was simulated.

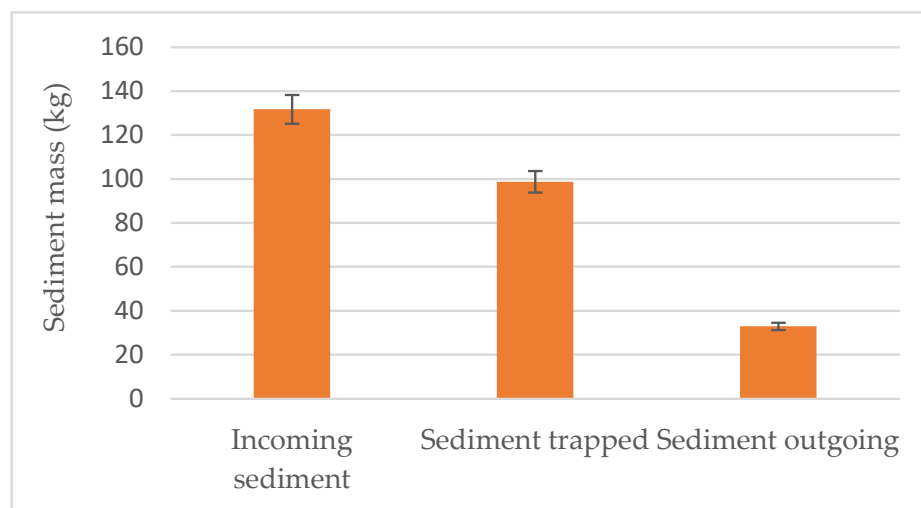


Figure 10. Reduction in sediment load by the vegetative filter strip was simulated.

The mass of sediment entering the strip was 132 kg for a volume of runoff water of 4680 m³, or a sediment concentration of 0.028 kg.m⁻³. After the 3 m wide plant filter strip scenario, the sediment load entering the lake drops to 33 kg for a volume of runoff water reaching the lake of 3557 m³, i.e., a sediment concentration of 0.01 kg.m⁻³.

4. Discussion

This study is carried out with the aim of modeling a grassy strip effective against the transfer of pollutants (sediments) by runoff towards the Lobo reservoir.

The sediments at the study site consist of soil particles. These particles are denser than water. This high density can cause friction on the ground even in the absence of a plant filter strip. This could explain their retention by the soil even before the implementation of the grass strip. Also, the model highlights a linear relationship between the water retention rate and the width of the band in general. However, with regard to sediment retention, the linear relationship remains biased. Indeed, we see that beyond 3 m of bandwidth, the retention rate stabilizes. This could be considered a limitation of the model. Nevertheless, the objective set, which is to reduce the flows by 75% (75% of sediment flows reduced in the case of this study) with a minimum width (optimal width) of 3 m, is achieved.

Of the ten scenarios tested, at least 3 m of vegetation strip width is required to reduce the flow of sediment entering the strip by at least 75%. However, this dimension is not effective for incoming runoff (only a 24% decrease).

The runoff volume and the sediment entering the filter strip loads estimated are, respectively, 4680 m³ and 132 kg, i.e., a sediment concentration of 0.028 kg.m⁻³. This concentration, compared to that estimated by Koffi et al. [20], which was 0.014 kg.m⁻³ using the theory of settling basins, is overestimated. After the 3 m wide filter strip scenario, the sediment load dropped to 33 kg for a volume of runoff water reaching the lake of 3557 m³; this gave a sediment concentration of 0.01 kg.m⁻³. The high efficiency of sediment trapping compared to runoff at a 3 m bandwidth could be explained by the low sediment concentration of runoff water (0.028 kg.m⁻³). With a 3 m wide vegetative filter strip, the flow of sediment entering the strip is reduced by 75%, while the incoming runoff water retained by the strip is reduced by 24%. Certainly, the runoff flow is loaded with sediment. However, the concentration is 0.028 kg.m⁻³, or 28 g.m⁻³. This value remains low. This means that the solid phase of the flow, which is made up of sediments, is in small quantity compared to the liquid phase of the flow, which is made up of water. Indeed, during their transport on the filter strip, it is easier for this strip to retain a greater part of the sediments than the water. This could explain the retention of 75% of sediment and 24% of water in a 3 m wide strip. The high performance of the vegetation strip in reducing the quantities of sediment highlighted in this study has already been demonstrated by Duchemin and

Majdoulé [39]. These authors showed that the performance of plant strips in reducing the mass of sediment from agricultural fields is quite high. Some typical values for sediment retention rates range between 75 and 91% [40]. More recently, the effectiveness of plant filter strips in trapping sediments has also been demonstrated by Bae et al. [41]. Indeed, the authors have shown that plant filter strips can trap up to 90% of incoming sediments.

The sediment concentration overestimated in this study can be explained by the fact that our study was carried out at the plot scale while that of Koffi et al. [20] was carried out at the watershed scale. The result showed that only 3 m of grassy strip width is needed to reduce the runoff volume by 24% and the sediment load by 75%. Dosskey et al. [42] used 4.5 m as a minimum-width vegetative filter to reduce by 60–75% the runoff. This difference in value is normal and can be explained by the parameters taken into account by each of these models. In regions with a cold climate, such as Quebec, which are distinguished by a specific problem linked to the melting of snow in spring, which generates significant water erosion at a time when the vegetation is dormant, their effectiveness is variable [43,44]. It depends on the type of pollutants, local conditions, their location in the hydrographic network, and their width and composition [45,46]. Unlike the tool proposed by Dosskey et al. [42], which is based on only three parameters—notably the slope, the texture of the soil, and the land use type—the VFSMOD model takes into account, in addition to the aforementioned parameters, the plant coverage of the strip. The plant density makes it possible to reduce the speed of runoff [47,48] and, therefore, the energy available for the transport of particles and to limit erosive phenomena on the grassed device itself, in the soil, as well as the sedimentation of particles upstream of the grass strip. The grassy strip allows for a slowdown in the flow of runoff water due to the greater roughness of the cover compared to cultivated soil (an increase in roughness and infiltration implies a reduction in the transport capacity of suspended solids). This increases the sedimentation of solid particles on which polluting substances, in particular phosphorus, can be adsorbed. The grassy strip also promotes the infiltration of water into the soil. This is the main path that the water takes when it reaches the grassy device since at least 70% of the water flow leaves this device, and 24% penetrates into the ground under the grassy strip. Estimates of the surface infiltration capacity of grassy strips are between 50 and 100 mm.h^{−1} (compared to 30 to 60 mm.h^{−1} for soil that has just been plowed) for well-drained soils but much less for beating soil [49].

The reduction in the solid load is much greater than that of the runoff volume, and a wider band is required to reduce the flow of rainwater runoff. These results confirm the experimental results of Borin et al. [50]; these experiments carried out over 4 years using natural rainfall have shown that the performance of grassed devices in reducing the sediment load is 10–15% higher than that allowing runoff to be reduced with the same filtering width.

The different simulation scenarios obtained results from a width range of 3 to 9 m. Runoff retention ranges from 24 to 56%. These results show that the wider the band, the more effective it is. These results are consistent with Schmitt et al. [51]. Indeed, these authors used 7.5 and 15 m wide filter strips downstream to significantly reduce runoff sediment concentrations (76 to 93%) and strongly sediment-associated contaminants (total P, 55 to 79%). Thus, pesticides are transported mainly in dissolved form [6]. Therefore, the greater the width of the grassy strip, the higher the infiltration and adsorption potential. This situation is favored by the root system of plants and by the reduction in flow speed due to the roughness of the plant cover [52].

The VFSMOD model used in this study made it possible to determine the optimal width, allowing an effective reduction in sediment inputs from the Lobo reservoir under ten (10) width variation scenarios. This study was based on data from the site considered and the characteristics of the vegetative filter strip to be implemented on one of the banks of the reservoir in the catchment area of the drinking water distribution company SODECI. This study is an outline for future research work on the implementation of vegetative filter

strips around water bodies in Côte d'Ivoire. These results could be further explored in the future by integrating data from experiments with the vegetative strip installed on the site.

5. Conclusions

The VFSSMOD model has been applied to the Lobo reservoir on one of its banks in the catchment area of the drinking water distribution company SODECI. It has emerged that the contributing surface area is 0.135 km², and the total amount of water runoff is 35 mm with a peak of 13.77.10^{−5} m.s^{−1}.

Without the vegetative filter, approximately 70% of the sediment would reach the reservoir. This could impact the eutrophication conditions of the reservoir. A 9 m wide strip can drop the runoff by up to 56% and the sediments by 77%. The width of 9 m could be recommended to farmers or any other users of the edges of the Lobo reservoir since it would not only effectively reduce runoff (thus capable of filtering water-soluble pollutants, particularly nitrates), but also the sediments, respectively (56% and 77%). However, a 9 m wide buffer zone (free from any activity) could have a disadvantage for agricultural production.

This is why it would be wise to opt for a 3 m vegetated strip, which would allow a reduction in runoff of 24% and a reduction in sediments of 75% and monitor the reservoir over time.

Author Contributions: Conceptualization, T.J.-J.K.; Methodology, T.J.-J.K. and J.J.; Software, T.J.-J.K. and K.A.A.; Validation, T.J.-J.K., K.H.K. and K.L.K.; Writing—original draft, T.J.-J.K.; Writing—review & editing, T.J.-J.K., K.H.K. and K.L.K.; Supervision, T.J.-J.K., K.L.K. and J.J.; Project administration, K.L.K.; Funding acquisition, T.J.-J.K. and J.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by the J. William Fulbright Foreign Scholarship Program, grant number PS00285574.

Data Availability Statement: All the data used in this paper can be traced back to the cited references.

Acknowledgments: The authors would like to thank R. Muñoz-Carpena from the University of Florida in Florida (Gainesville, FL, USA), designer of the VFSSMOD Model, for his availability and coaching, which enabled the effective use of the model.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Koukougnon, W.G. Milieu Urbain et Accès à l'Eau Potable: Cas de Daloa (Centre-Ouest de la Côte d'Ivoire). Ph.D. Thesis, Université Félix Houphouët Boigny Abidjan, Abidjan, Cote d'Ivoire, 2012; 323p.
2. Komelan, Y. Eutrophisation des Retenues d'Eau en Côte d'Ivoire et Gestion Intégrée de leur Bassin Versant: Cas de la Lobo à Daloa. Master's Thesis, École d'Ingénieurs de l'Équipement Rural de Ouagadougou, Ouagadougou, Burkina Faso, 1999; 56p.
3. Floret, C.; (IRD, Dakar, Sénégal); Hien, V.; (INERA, Ouagadougou, Burkina Faso); Pontanier, R.; (INERA, Ouagadougou, Burkina Faso). Personal communication, 1993.
4. Koua, T.J.-J.; Dhanesh, Y.; Jeong, J.; Srinivasan, R.; Anoh, K.A. Implementation of the Semi-Distributed SWAT (Soil and Water Assessment Tool) Model Capacity in the Lobo Watershed at Nibéhibé (Center-West of Côte D'Ivoire). *J. Geosci. Environ. Prot.* **2021**, *9*, 21–38.
5. Maïga, A.; Denyigba, K.; Allorete, J. Eutrophisation des Petites Retenues d'eau en Afrique de l'Ouest: Causes et Conséquences: Cas de la Retenue D'eau de la Lobo en Côte d'Ivoire. *Sud Sci. Technol.* **2001**, *7*, 16–29.
6. Lecomte, V. Transfert de Produits Phytosanitaires par le Ruissellement et l'Érosion de la Parcelle au Bassin Versant. Ph.D. Thesis, École Nationale du Génie Rural des Eaux et des Forêts de Montpellier, Montpellier, France, 1999.
7. Peter, G.V.; Brussaard, C.P.; Nejtgaard, J.C.; Van Leeuwe, M.A.; Lancelot, C.; Medlin, L.K. Current understanding of Phaeocystis ecology and biogeochemistry, and perspectives for future research. *Biogeochemistry* **2007**, *83*, 311–330.
8. Koua, T.J.-J.; Jeong, J.; Alemayehu, T.A.; Dhanesh, Y.; Srinivasan, R. Spatial Distribution of Nutrient Loads Based on Mineral Fertilizers Applied to Crops: Case Study of the Lobo Basin in Côte d'Ivoire (West Africa). *Appl. Sci.* **2023**, *13*, 9437. [[CrossRef](#)]
9. Soro, M.-P.; N'goran, K.M.; Ouattara, A.A.; Yao, K.M.; Kouassi, N.L.; Diaco, T. Nitrogen and phosphorus spatio-temporal distribution and fluxes intensifying eutrophication in three tropical rivers of Côte d'Ivoire (West Africa). *Mar. Pollut. Bull.* **2023**, *186*, 114391. [[CrossRef](#)] [[PubMed](#)]

10. N'goran, K.M.; Soro, M.-P.; Kouassi, N.L.B.; Trokourey, A.; Yao, K.M. Distribution, Speciation and Bioavailability of Nutrients in M'Badon Bay of Ebrie Lagoon, West Africa (Côte d'Ivoire). *Chem. Afr.* **2023**, *6*, 1619–1632. [CrossRef]
11. Traoré, K.; Djaha, K.; Koffi, N.A. Analyse de la flore aquatique envahissante dans les plans d'eau de la ville de Daloa (Centre-ouest de la Côte d'Ivoire). *J. Appl. Biosci.* **2019**, *142*, 14509–14518.
12. Kumwimba, M.N.; Akter, S.; Li, X.; Dzakupasu, M.; Ifon, B.E.; Manirakiza, B.; Muyembe, K.; Zhang, Y.; Huang, J.; Guadie, A. Nutrient and sediment retention by riparian vegetated buffers strips: Impacts of buffer length, vegetation type and season. *Agric. Ecosyst. Environ.* **2024**, *369*, 109050. [CrossRef]
13. Zhang, H.; Meng, Q.; You, Q.; Huang, T.; Zhang, X. Influence of vegetation filter strip on slope Runoff, Sediment Yield and Nutrient loss. *Appl. Sci.* **2022**, *12*, 4129. [CrossRef]
14. Muñoz-Carpena, R.; Parsons, J.E. VFSMOD-W Vegetative Filter Strips Modelling System. MODEL DOCUMENTATION & USER'S MANUAL Version 6.x. 2020. 194p. Available online: https://abe.ufl.edu/faculty/carpena/files/pdf/software/vfsmod/VFSMOD_UsersManual_v6.pdf (accessed on 5 May 2021).
15. Sur, R.; Muñoz-Carpena, R.; Reichenberger, S.; Hammel, K.; Meyer, H.; Kehrein, N. Implementation of Shallow Water Table Effects on Pesticide Runoff Mitigation Efficiency by Vegetative Filter Strips within SWAN-VFSMOD. EGU General Assembly 2021. 19–30 April 2021, EGU21-7829. Available online: <https://meetingorganizer.copernicus.org/EGU21/EGU21-7829.html> (accessed on 1 January 2024).
16. Minwoo, S.; Jisun, B.; Hyun-Dong, Y.; Tae-Hwa, J. A study on trapping efficiency of the non-point source pollution in Cheongmi Stream using VFSMOD-W. *J. Korea Contents Assoc.* **2016**, *16*, 140–150. [CrossRef]
17. Muñoz-Carpena, R.; Reichenberger, S.; Sur, R.; Hammel, K. Fate of pesticide residues in vegetative filter strips in long-term exposure assessments: VFSMOD development and analysis. EGU General Assembly 2021, 19–30 April 2021. EGU21-1735. Available online: <https://doi.org/10.5194/egusphere-egu21-1735> (accessed on 1 January 2024).
18. Koua, T. Apport de la Modélisation Hydrologique et des Systèmes d'Information Géographique (SIG) dans L'étude du Transfert Des Polluants et des Impacts Climatiques sur les Ressources en eau: Cas du bassin Versant du lac de Buyo (Sud-ouest de la Côte d'Ivoire). Ph.D. Thesis, Felix Houphouët Boigny University of Cocody, Abidjan, Côte d'Ivoire, 11 December 2014.
19. Yao, A.B. Evaluation des Potentialités en eau du Bassin Versant de la Lobo en vue d'une Gestion Rationnelle au Centre-Ouest de la Côte d'Ivoire. Ph.D. Thesis, Université Nangui Abrogoua, Abidjan, Côte d'Ivoire, 2015.
20. Koffi, B.; Kouassi, K.L.; Sanchez, M.; Kouadio, Z.A.; Kouassi, K.H.; Yao, A.B. Estimation de la sédimentation dans la retenue d'eau de la rivière Lobo à l'aide de la théorie des bassins de décantation. In Proceedings of the XVIèmes Journées Nationales Génie Côtier—Génie Civil, Daloa, Côte d'Ivoire, 8–10 December 2020.
21. Brou, T.; Akindès, F.; Bigot, S. La variabilité climatique en Côte d'Ivoire: Entre perceptions sociales et réponses agricoles. *Cah. Agric.* **2005**, *14*, 533–540.
22. Delor, C.; Siméon, Y.; Vidal, M.; Zeade, Z.; Koné, Y.; Adou, M.; Dibouahi, M.; Irié, D.B.; N'da, B.D.; Pouclet, D.; et al. *Carte Géologique de la Côte d'Ivoire à 1/200 000, Feuille Nassian*; Mémoire n°9 de la Direction des Mines et de la Géologie; Ivory Coast Ministry of Mines and Energy: Abidjan, Côte d'Ivoire, 1995.
23. Yao, A.B.; Bi Tié, A.G.; Kane, A.; Mangoua, J.O.; Kouamé, A.K. Cartographie du potentiel en eau souterraine du bassin versant de la Lobo (Centre-Ouest, Côte d'Ivoire): Approche par analyse multicritère. *Hydrol. Sci. J.* **2016**, *61*, 856–867.
24. Jean Olivier, K.K.; Brou, D.; Jules, M.O.M.; Georges, E.S.; Frédéric, P.; Didier, G. Estimation of Groundwater Recharge in the Lobo Catchment (Central-Western Region of Côte d'Ivoire). *Hydrology* **2022**, *9*, 23. [CrossRef]
25. Nachtergaele, F.; Velthuisen, H.V.; Verest, L. Harmonized World Soil Database Version1.1. 2009. 20p. Available online: <http://www.fao.org/3/aq361e/aq361e.pdf> (accessed on 1 September 2012).
26. Lighthill, M.J.; Whitham, C.B. On kinematic waves: Flood movement in long rivers. *Proc. R. Soc. Lond. Ser. A* **1955**, *22*, 281–316.
27. Barfield, B.J.; Tollner, E.W.; Hayes, J.C. *The Use of Grass Filters for Sediment Control in Strip Mining Drainage. Vol. I: Theoretical Studies on Artificial Media*; Pub. no. 35-RRR2-78; Institute for Mining and Minerals Research, University of Kentucky: Lexington, Kentucky, 1978.
28. Barfield, B.J.; Tollner, E.W.; Hayes, J.C. Filtration of sediment by simulated vegetation I. Steady-state flow with homogeneous sediment. *Trans. ASAE* **1979**, *22*, 540–545. [CrossRef]
29. Hayes, J.C.; Barfield, B.J.; Barnhisel, R.I. Filtration of sediment by simulated vegetation II. Unsteady flow with non-homogeneous sediment. *Trans. ASAE* **1979**, *22*, 1063–1067. [CrossRef]
30. Jackson, S.; Hendley, P.; Jones, R.; Poletika, N.; Russell, M. Comparison of regulatory method estimated drinking water exposure concentrations with monitoring results from surface drinking water supplies. *J. Agr. Food Chem.* **2005**, *53*, 8840–8847. [CrossRef] [PubMed]
31. Tollner, E.W.; Barfield, B.J.; Haan, C.T.; Kao, T.Y. Suspended sediment filtration capacity of simulated vegetation. *Trans. ASAE* **1976**, *19*, 678–682. [CrossRef]
32. Tollner, E.W.; Barfield, B.J.; Vachirakornwatana, C.; Haan, C.T. Sediment deposition patterns in simulated grass filters. *Trans. ASAE* **1977**, *20*, 940–944. [CrossRef]
33. Wilson, B.N.; Barfield, B.J.; Moore, I.D. *A Hydrology and Sedimentology Watershed Model, Part I: Modeling Techniques*; Technical Report; Department of Agricultural Engineering, University of Kentucky: Lexington, Kentucky, 1981.

34. Catalogne, C.; Lauvernet, C.; Carlier, N. Guide d'Utilisation de l'Outil BUVARD Pour le Dimensionnement des Bandes Tampons Végétalisées Destinées à Limiter les Transferts de Pesticides par Ruissellement. Rapport de Recherche IRSTEA, France. 2018. 66p. Available online: <https://hal.inrae.fr/hal-02607260/document> (accessed on 1 May 2022).
35. USDA-SC. Design hydrographs. In *National Engineering Handbook Hydrology*, 2nd ed.; Vincent, M., William, O., Robert, R., Eds.; Department of Agriculture: Washington, DC, USA, 1972; Section 4; pp. 1–127. Available online: <https://www.hydrocad.net/neh/630ch21.pdf> (accessed on 1 April 2024).
36. Carlier, N.; Fontaine, A.; Lauvernet, C.; Muñoz-Carpena, R. Guide de Dimensionnement des Zones Tampons Enherbées ou Boisées Pour Réduire la Contamination des Cours d'Eau par les Produits Phytosanitaires. Rapport de Recherche IRSTEA, France. 2020. 72p. Available online: <https://hal.inrae.fr/hal-02595578v1/file/pub00032826.pdf> (accessed on 1 May 2022).
37. Chow, V.T.; Maidment, D.R.; Mays, L.W. *Applied Hydrology*; International Edition; Mc-Graw-Hill Book Company: New York, NY, USA, 1988; pp. 153–155. Available online: <https://wecivilengineers.wordpress.com/wp-content/uploads/2017/10/applied-hydrology-ven-te-chow.pdf> (accessed on 1 February 2023).
38. Williams, J.R. Sediment-Yield Prediction with Universal Equation Using Runoff Energy Factor. In Proceedings of the Sediment-Yield Workshop, USDA Sedimentation Laboratory, Oxford, MS, USA, 28–30 November 1972.
39. Duchemin, M.; Majdoulé, R. Les bandes végétales filtrantes: De la parcelle au bassin versant. *Vecteur Environ.* **2004**, *37*, 36–50.
40. The Importance of Wetlands & Uplands Conservation Practices in Watersheds Management: Functions & Values for Water Quality & Quantity. Ducks Unlimited Canada. Available online: <https://www.ducks.ca/news/pdf/pipeshrt.pdf> (accessed on 21 May 2024).
41. Bae, J.H.; Han, J.; Lee, D.; Yang, J.E.; Kim, J.; Lim, K.J.; Neff, J.C.; Jang, W.S. Evaluation of Sediment Trapping Efficiency of Vegetative Filter Strips Using Machine Learning Models. *Sustainability* **2019**, *11*, 7212. [CrossRef]
42. Dosskey, M.G.; Helmers, M.J.; Eisenhauer, D.E. A design aid for sizing filter strips using buffer area ratio. *J. Soil Water Conserv.* **2011**, *66*, 29–39. [CrossRef]
43. Breune, I.; Audet, M.A.; Parent, G. Le Ray-Grass Intercalaire: Essai de Variétés, Essai de Semis à Différents Stades du Maïs. Rapport Final Club Agroenvironnemental de l'Estrie, Québec (Canada). 2015. 60p. Available online: https://www.agrireseau.net/documents/Document_90361.pdf (accessed on 1 February 2019).
44. Kieta, K.A.; Owens, P.N.; Lobb, D.A.; Vanrobaeys, J.A.; Flaten, D.N. Phosphorus dynamics in vegetated buffer strips in cold climates: A review. *Environ. Rev.* **2018**, *26*, 255–272. [CrossRef]
45. Hénault-Ethier, L.; Gomes, M.P.; Lucotte, M.; Smedbol, É.; Maccario, S.; Lepage, L.; Juneau, P.; Labrecque, M. High yields of riparian buffer strips planted with *Salix miyabena* 'SX64' along field crops in Québec, Canada. *Biomass Bioenergy* **2017**, *105*, 219–229. [CrossRef]
46. Lind, L.; Hasselquist, E.M.; Laudona, H. Towards ecologically functional riparian zones: A meta-analysis to develop guidelines for protecting ecosystem functions and biodiversity in agricultural landscapes. *J. Environ. Manag.* **2019**, *249*, 109391. [CrossRef]
47. Zhang, X.; Liu, X.; Zhang, M.; Dahlgren, R.A.; Eitzel, M. A Review of Vegetated Buffers and a Meta-analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution. *J. Environ. Qual.* **2010**, *39*, 76–84. [CrossRef] [PubMed]
48. Remaury, A. Effet de la Densité de Plantation de Peupliers à Croissance Rapide sur L'érosion des Sols Recouvrant des Pentes de Stériles Minières en Région Boréale. Master's Thesis, Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, QC, Canada, 2017. Available online: <https://depositum.uqat.ca/id/eprint/713> (accessed on 1 May 2024).
49. Benoît, P.; Magrinal, I.; Pot, V.; Souiller, C. Fonctions environnementales des dispositifs enherbés en vue de la gestion et de la maîtrise des impacts d'origine agricole. Cas des pesticides. *Etude Gest. Sols* **2003**, *10*, 299–312.
50. Borin, M.; Vianello, M.; Morari, F.; Zanin, G. Effectiveness of buffer strips in removing pollutants in runoff from a cultivated field in North East Italy. *Agric. Ecosyst. Environ.* **2005**, *105*, 101–114. [CrossRef]
51. Schmitt, T.J.; Dosskey, M.G.; Hoagland, K.D. Filter Strip Performance and Processes for Different Vegetation, Widths, and Contaminants. *J. Environ. Qual.* **1999**, *28*, 1479–1489. [CrossRef]
52. Mouisat, A.; Douaïk, A.; Al Faiz, C.; Harrouni, C.; Derradji, A.; Benaouda, N.-E. Suivi De La Cinétique Du Développement Racinaire Des Plantes Destinées A La Stabilisation Des Talus Marneux De L'axe Autoroutier Fès-Taza (Nord Du Maroc). *Eur. Sci. J.* **2020**, *16*, 287–311. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.