Asia Pac. J. Math. 2025 **12**:76

FLOW IN THE MAIN CHANNEL OF A WATERSHED: MODELING AND APPLICATION TO LAKE BAM

SEYDOU SORE[1,*], NESTOR RAMDE[2], YACOUBA SIMPORE[3,4]

[1]Laboratoire de Mathématiques, Informatique et Application (LAMIA), Université Norbert Zongo, Burkina Faso

[2]Laboratoire Analyse Numérique, Informatique et Biomathématiques (LANIBIO), Université Joseph KI-ZERBO, Burkina-Faso

[3]Laboratoire de Mathématiques, Informatique et Application (LAMIA), Université Norbert Zongo, Burkina Faso

[4]Ecole Superieure d'Ingenierie, Université Yembila-Abdoulaye-Toguyeni, Burkina Faso

[*]Corresponding author: seydousore27@gmail.com

Received Jun. 19, 2025

Abstract. The study of water behavior in watershed beds throughout different periods of the year is a central issue in the modeling of natural environments. This study proposes an analytical model based on the physical characteristics of the watershed and the Saint-Venant equations, capable of reproducing flow within the main watercourse. A practical application is carried out on the Lake Bam watershed, the largest natural water reservoir in Burkina Faso. The developed model is calibrated, validated, and used to perform simulations to observe the behavior of the water body at specific locations during determined periods of the year. This model represents a strategic asset for the country, which aims to mobilize its water resources to develop alternative hydro-agricultural systems to achieve food self-sufficiency. The strength of this method lies in its ability to provide accurate predictions of water levels at any point of the water body and for any period of the year. Such an approach also constitutes a valuable tool to address environmental concerns related to water behavior and the sustainable management of water resources.

2020 Mathematics Subject Classification. 35Q35.

Key words and phrases. watershed; flow modeling; watershed bed; Lake Bam.

1. Introduction

Burkina Faso is a landlocked country in West Africa, whose economy relies primarily on the agricultural sector. Despite the agricultural policies adopted and implemented since the 1970s to create the necessary conditions for the development of the rural sector, Burkina Faso struggles to achieve food self-sufficiency. This situation is mainly exacerbated by climate change and water scarcity. Given that water is the primary resource for the sector's growth and considering the country's topography, it is

DOI: 10.28924/APJM/12-76

crucial to have effective policies for the mobilization and management of water resources to support hydro-agricultural developments.

In the context of water resource mobilization and management, modeling flow in watershed beds is essential due to numerous environmental concerns (see Section 2). Thus, finding models to control the flow within these basins is vital for the country.

Over the past decades, numerous models have been developed to represent and predict water flow in rivers or slopes. Some models rely on simple empirical descriptions of flows [4], while others aim to capture the full complexity of hydrological phenomena [9]. The study of flow dynamics can be approached in several ways. The first approach involves a mathematical representation of the processes, aiming to model flows using mathematical equations. For instance, free-surface flow observed in rivers is described by the non-linear differential equation system of Barré de Saint-Venant, which includes a conservation equation and a dynamic equation [3]. Modeling these flows entails solving this system of equations. To achieve this, hydrologists often seek to simplify the equations to make them more practical. These simplified models are frequently used in the "routing" schemes of hydrological models [10, 12]. Thanks to advancements in computing and growing computational capabilities, numerical methods for solving these equations have significantly evolved [1,5].

The second approach, known as the "black-box model analysis," does not directly address the underlying hydrological processes. These models rely on calibrated parameters to replicate observed behaviors, even if those parameters lack a direct physical meaning [6,7].

Overall, hydrological models aim to analyze and predict watershed responses to rainfall events and the dynamics of resulting flows. They seek to reconstruct and anticipate watershed behaviors by modeling the various components of the water cycle. These models generate hydrographs resulting from specific rainfall events using a production function and a transfer function.

In this paper, we propose a model based on the characteristics of the watershed and the Saint-Venant equations, capable of reproducing the flow in the main channel of a watershed. This model can be used to address the environmental concerns detailed in the next section. A concrete application is conducted for the Lake Bam watershed, the largest natural water reservoir in Burkina Faso. The resulting model is calibrated, validated, and utilized to propose simulations that allow observation of the water body's behavior at specific locations during particular periods of the year.

The document is structured as follows: Section 2 discusses the environmental concerns that necessitate modeling the flow in the main channel of a watershed. Section 3 proposes an implementation technique for a model simulating this flow in the main channel of a given watershed. Finally, Section 4 presents a practical application to the Lake Bam watershed.

2. Environmental Concerns

Modeling the flow in the main channel of a watershed is essential due to several environmental concerns, including:

- **Flood management**: Flow models enable the identification of flood-prone areas through simulations, improve flood planning and management, and help mitigate negative impacts on populations and infrastructure.
- **Water quality**: By understanding how water flows within a watershed, it becomes possible to better manage pollution sources and their impacts on aquatic ecosystems. This facilitates the implementation of strategies to maintain or improve water quality.
- **Water resource management**: Modeling helps in sustainably managing water resources by ensuring equitable distribution among various uses, such as agriculture, industry, and domestic needs.
- **Rehabilitation**: Modeling flow helps test the implementation of rehabilitation processes on watercourses.
- **Climate change**: Flow models can be used to simulate the impacts of changes in precipitation and runoff caused by climate change, enabling the planning of adaptation strategies.
- **Habitat conservation**: Models help identify critical areas for flora and fauna and support management measures to preserve or restore these essential habitats.
- **Erosion and sedimentation prediction**: Understanding and predicting erosion and sediment deposition processes helps prevent bank degradation and manage sedimentation in reservoirs and waterways.
- **Sediment management**: Ensuring a balanced sediment flow is crucial to prevent silting of watercourses and habitats, which could lead to biodiversity loss and reduced storage capacity.

Our primary objective is to propose a model based on watershed characteristics and the Saint-Venant equations, capable of reproducing the flow in the main channel of a watershed and addressing the aforementioned environmental concerns.

3. Model Implementation

Optimally, implementing a model involves a complex process that can be divided into six steps: data collection, watershed characterization, mathematical modeling of flow within the watershed bed, parameter estimation (also known as calibration), validation, and finally, model exploitation.

3.1. **Data Collection.** Modeling flow within a watershed requires a thorough understanding of the watershed environment. This includes a digital elevation model (DEM), the coordinates of the outlet, as well as climatic and rainfall data for the region. Collecting and preparing these data is essential to facilitate the characterization of the watershed.

3.2. **Watershed Characterization.** Once the DEM and the outlet coordinates are obtained, the watershed boundary can be delineated using software like QGIS or ArcGIS. This delineation helps identify the watershed's characteristics and the longitudinal profile of the main channel, both of which are critical for mathematical modeling.

3.3. **Mathematical Modeling of Flow Within the Watershed Bed.** In this step, the Saint-Venant equations are employed to derive partial differential equations that accurately model flow within the watershed bed. Depending on the watershed characteristics and base profile, an appropriate variant of the Saint-Venant equations can be selected to describe water behavior in the bed, considering flow discharge Q, cross-sectional area A, height of the water column h in the cross-section, and lateral inflow per unit length q_L.

3.4. **Parameter Estimation (Calibration).** Calibrating a model involves adjusting its unknown parameters to ensure the results closely match real-world observations. Typically, this step primarily focuses on hydrological parameters, while hydraulic parameters are estimated with greater certainty due to the availability of detailed network information. The determined values are then used to simulate events not included in the calibration process or to predict hypothetical future events.

3.5. **Model Validation.** This step aims to evaluate the model's consistency with known events and estimate potential simulation errors. Model validation requires simulations of events that were not used during calibration.

3.6. **Exploitation and Interpretation.** The previous steps constitute a significant portion of the scientific work. Once completed, it is up to the users to leverage the model for their intended studies. The primary challenge before model exploitation lies in selecting input values, initial conditions, and boundary conditions. After simulations are performed, it is important to avoid over-extrapolating the results, consider the errors calculated during validation, and, whenever possible, compare the results with those of other studies.

4. Modeling of Flow in the Main Channel of the Lake Bam Watershed

4.1. **Location and Overview of the Study Area.** Lake Bam, located in Burkina Faso near the city of Kongoussi in Bam Province, is situated approximately 110 km from Ouagadougou. Kongoussi lies between longitudes 1°14′ and 1°58′ West and latitudes 12°46′ and 13°55′ North (see Figure 1).

In the context of surface water resource management, Lake Bam is considered the largest natural surface water reservoir in the country. It is therefore a significant asset for Burkina Faso, particularly for the North-Central region, as water, being the primary resource for agricultural development, plays a critical role. Protecting and managing this resource could contribute significantly to achieving food self-sufficiency. In this perspective, with the support of the West African Development Bank, the government of Burkina Faso launched the Lake Bam Restoration, Protection, and Development Project (PRPVLB) on September 5, 2016.

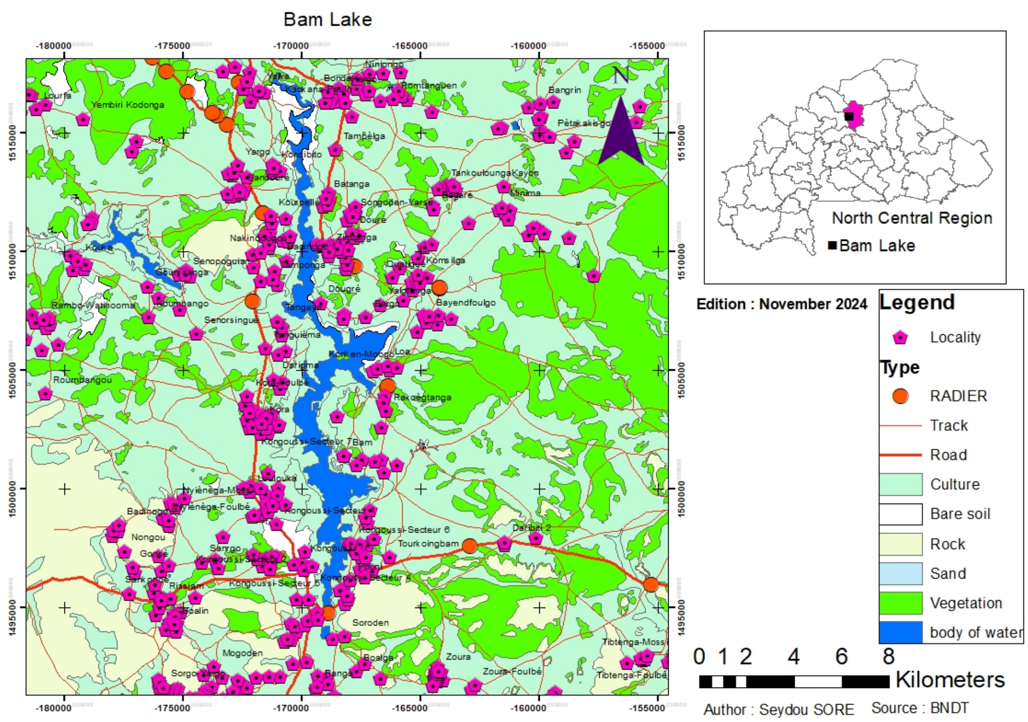

FIGURE 1. Location of Lake Bam

4.2. **Data Collection.**

4.2.1. *Climate of the Study Area.* The climate of the study area is Sudanian-Sahelian, with annual temperatures ranging between 20°C and 43°C and rainfall varying between 600 mm and 750 mm. Precipitation often occurs in the form of heavy downpours, resulting in intense runoff and significant soil erosion. Rainfall data specific to Lake Bam is provided by the Tourcoing Bam station, located nearby. Maximum precipitation generally occurs in August.

4.2.2. *Lake Bam's Water Level-Area-Volume Relationships.* Topographic surveys have been used to establish the Height-Area-Volume relationships for Lake Bam. These data were derived from topographic work conducted in 2011 by the CINTECH firm. The curve representing the Height-Volume relationship is illustrated in Figure 2.

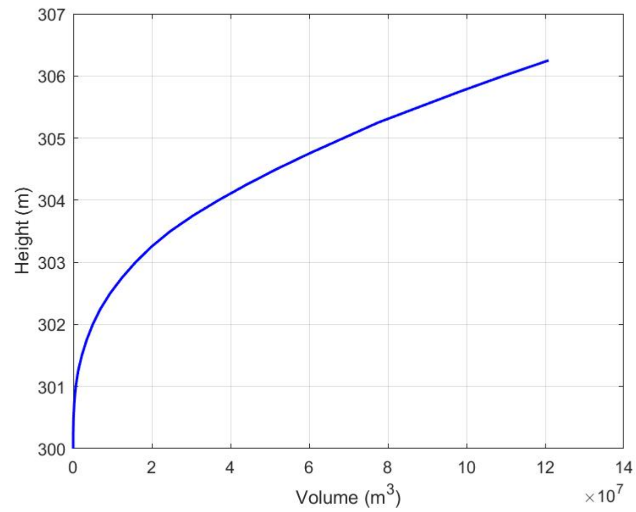

FIGURE 2. Height-Volume Curve.

4.2.3. *Annual Water Inflows and Outflows in Lake Bam.* For optimal modeling, it is essential to consider the balance of various water inputs and outputs in the lake. Outputs include losses due to infiltration, evaporation, and human and livestock consumption. Thanks to work conducted by the Lake Bam Protection and Restoration Project, all these data are available [2].

Annual water inflows into the lake are assessed based on daily water level measurements. These inflows have been determined using the daily minimum and maximum values recorded for each year during the 1966-2010 period. By applying the $H/V/S$ (height/volume/surface) relationship and the annual balance method, the annual inflows for this period have been evaluated. The balance of water inflows and outflows for the lake is illustrated in Figure 3.

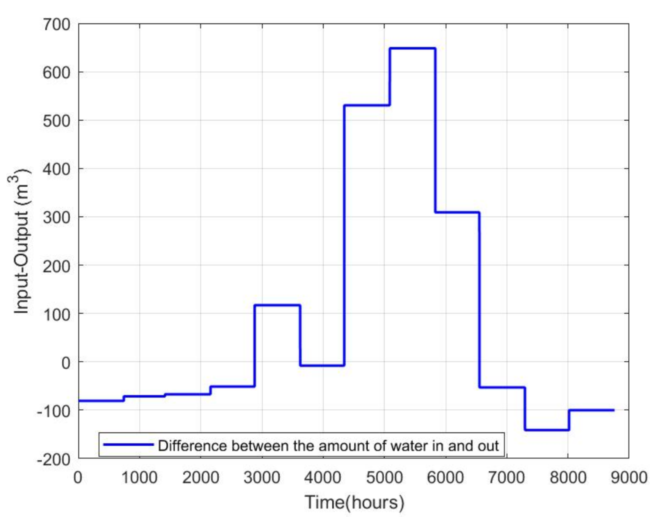

FIGURE 3. Annual balance of water inflows and outflows of the lake.

4.3. **Evolution of Reservoir Water Level Throughout the Year.** Thanks to the work of PRPVLAB, we have an estimate of the annual variations in the water level in the reservoir [2]. This work has allowed us to determine the water level at the end of each month in order to calculate the amount of water available in the lake over the months. We have used this data without considering the amount of water presumed to be consumed by their irrigation project. The obtained water levels are presented in Figure 4.

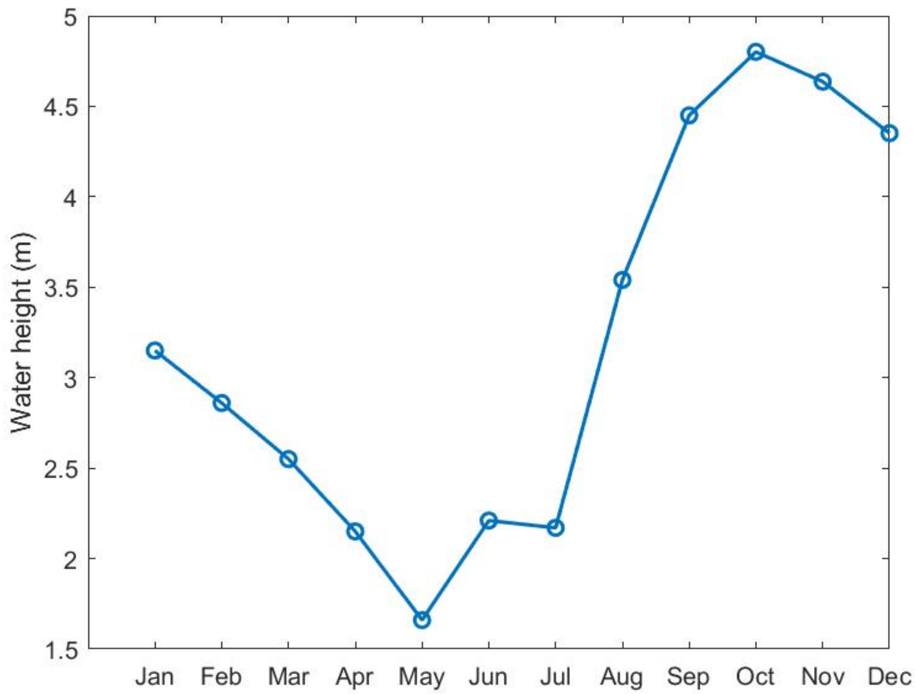

FIGURE 4. Evolution of the water level in the reservoir

4.3.1. *Other Important Data on Lake Bam (see [2]).* The catchment area of Lake Bam is located between the geographic coordinates 01° 18′ and 1° 48′ West longitude and 13° 18′ and 13° 55′ North latitude, representing approximately 70 km as the crow flies from the upstream end to the outlet. Lake Bam has a variable width not exceeding $1,000$ meters from one shore to the other. The flow of Lake Bam is controlled by a sill built in 1963, which ensures its closure at the south of the catchment area, crossed by National Road No. 15 (RN 15) connecting Kaya to Kongoussi. This sill, about 200 meters long, is marked by the following UTM coordinates: $X_1 = 661,119$; $Y_1 = 1,474,164$ and $X_2 = 661,205$; $Y_2 = 1,474,169$. It was recently raised by 0.25 meters by PRPVLAB, bringing the capacity of Lake Bam after raising to about 47.124 million cubic meters. According to [2], the average depth of Lake Bam varies between 2 and 3 meters and remains remarkably constant. The deepest areas, reaching about 6 meters, are located near the town of Kongoussi. When the lake is fully filled, it extends over approximately 25 km in length, with a variable width not exceeding 1,000 meters from one shore to the other. During the flood period, the water expansion allows the lake to establish a connection with the tributaries of the Nakambé and the Bourzanga Lake, forming a continuous water body about 45 km long.

4.4. **Characterization of the Catchment Area of Lake Bam.** The geometric characteristics of the hydrographic network and other morphological aspects of the catchment area are essential for flow modeling.

4.4.1. *Geometric Characteristics.* The geometric characteristics of the catchment area include the following elements:

- **Area S and Perimeter P:** These two very important characteristics of the catchment area are generally measured using digitization techniques with the ArcGIS application.
- **Basin Shape:** To determine the shape of the basin, we use the compactness coefficient of GRAVELIUS:

$$K_G = \frac{P}{\sqrt{2\pi S}} \tag{1}$$

where **S** and **P** represent the surface area in km^2 and the perimeter in km of the basin, respectively.

The compactness index not only characterizes the shape of the catchment area but also evaluates its hydrological behavior. K_G is equal to **1** if the catchment area is circular and greater than **1** for any other shape. Moreover, the more elongated the basin, the higher the Gravelius index and the longer the water convergence time towards the outlet.
- **Equivalent Rectangle:** The rectangle with length **L** and width **l** is defined as a rectangle with the same surface area and perimeter as the studied catchment area. Given the surface area **S** and the perimeter **P** of the catchment area, the length of the rectangle is given by:

$$L = \frac{P + \sqrt{P^2 - 16S}}{4} \tag{2}$$

4.4.2. *Characteristics of the Hydrographic Network.* The hydrographic network consists of all natural drainage channels, permanent or temporary, through which water from runoff or groundwater is conveyed, either through restitution or continuously along the bed of a watercourse.

- **Network Hierarchy:** According to Stralher's classification, any watercourse with no tributaries is said to be of order 1. At the confluence of two watercourses of the same order n, the resulting watercourse is of order $n + 1$. A watercourse receiving a tributary of a lower order retains its order, which is summarized by:

$$n + n = n + 1$$

$$n + m = \max(n, m)$$

- **Length of the Main Watercourse:** The length of the main watercourse is the curvilinear distance from the outlet to the watershed divide, always following the highest order segment when there is a branch and by extension of the last to the topographic limit of the catchment area. If the two segments at the branch are of the same order, the one draining the largest surface area is followed.
- **Longitudinal Profile:** The longitudinal profile is obtained by interpolating the altitudes of the main watercourse according to the distance using the ArcGIS software.

4.4.3. *Results of the Characterization of the Catchment Area of Lake Bam.* The catchment area of Lake Bam, delineated using ArcGIS software, is presented in Figure 5, while the longitudinal profile is illustrated in Figure 6, where we have taken the lowest elevation as a reference. The results of the analysis of its characteristics are summarized in Tables 1 and 2 below. It is important to note that, unlike in previous works, we have taken the entire sub-watershed into account.

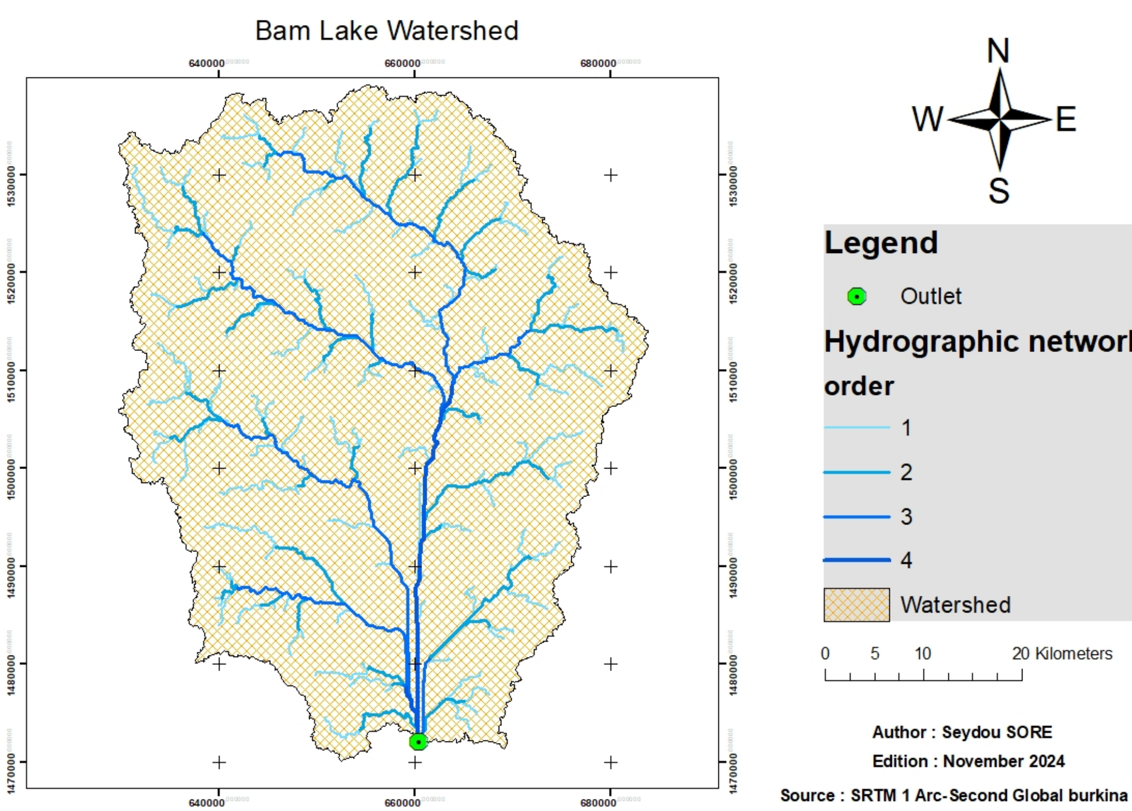

FIGURE 5. Bam Lake Watershed

Table 1. Results of Geometric Characteristics

Geometric Characteristics	Values
Area	2602 km^2
Perimeter	311 Km
Gravelius Compactness Index	2.432
Length of Equivalent Rectangle	136.43 km

Table 2. Results of Hydrographic Network Characteristics

Hydrographic Network Characteristics	Values
Length of the Main Watercourse	38.33 km
Average Slope of the Main Watercourse	0.08 m/km

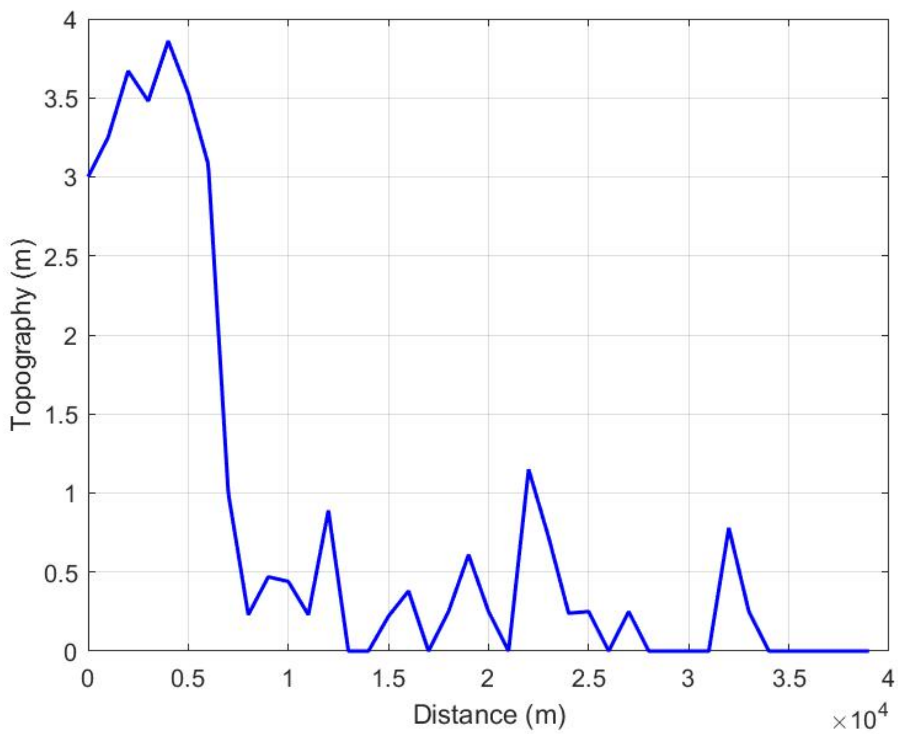

Figure 6. Longitudinal profile of the main channel

It was noted that the Gravelius index obtained is greater than 1. This result confirms the fact that the watershed is not perfectly circular.

4.5. **Mathematical modeling of flows in the main channel of Lake Bam.**

4.5.1. *Description of the Mathematical Model.* This section is dedicated to the modeling of flow in the main channel of the Lake Bam catchment area. The flow in this catchment is free-surface shallow water, so the system we consider is that of the Saint-Venant Equations (CRAS 1871 Adhemar Jean-Claude Barre de Saint-Venant). These shallow water equations are given by the following system:

$$\begin{cases} \partial_t A + \partial_x(Q) = q_L, \qquad x \in \mathbb{R}, \quad t > 0 \\ \\ \partial_t(Q) + \partial_x\big(\dfrac{Q^2}{A}\big) + gA\big(\partial_x h + S_f - S_0\big) = 0. \end{cases} \tag{3}$$

In the system (3), g is the acceleration due to gravity, A is the cross-sectional area, Q is the discharge, x is the distance along the watercourse, t is time, q_L is the lateral inflow per unit length, h is the height of the water column in the cross-section, S_0 is the bed slope of the main channel, and S_f is the friction slope. The first equation represents the continuity of flow, and the second one represents the conservation of momentum.

4.5.2. *Simplification.* We approximate the main channel of the lake as a rectangular river of width b and length L. With this assumption, we have the relations $Q = hV$ and $A = bh$. These relations allow us to rewrite the system (3) as follows:

$$\begin{cases} \partial_t h + \partial_x \left(\dfrac{hV}{b}\right) = \dfrac{q_L}{b}, \qquad x \in [0, L], \quad t > 0 \\ \\ \partial_t(hV) + \partial_x \left(\dfrac{hV^2}{b} + \dfrac{gbh^2}{2}\right) = gbh(S_0 - S_f). \end{cases} \tag{4}$$

Furthermore, we place ourselves within the framework of the wide-channel hypothesis for a rectangular channel. This hypothesis stipulates that the width of the channel is predominant over the height of the water column, so the height is negligible compared to the width. Consequently, the hydraulic radius R_h is approximately equal to the height of the water column h. Indeed, with this assumption:

$$R_h = \frac{S}{P} = \frac{bh}{b + 2h} \sim h. \tag{5}$$

Regarding the friction term S_f, we adopt the popular Manning-Strickler formula given by:

$$S_f = \frac{|Q|Q}{K_s^2 h^2 R_h^{4/3}},$$

where $R_h \sim h$ is the hydraulic radius and K_s is a roughness coefficient.

4.5.3. *Numerical Resolution Scheme.* The system (4) can be written in vector form as follows:

$$\partial_t W + \partial_x F(W) = S(W). \tag{6}$$

where the variable vector W, the flux $F(W)$, and the source term $S(W)$ are defined by:

$$W = \begin{pmatrix} h \\ hV \end{pmatrix}, \qquad F(W) = \begin{pmatrix} hV \\ \dfrac{hV^2}{B} + g\dfrac{bh^2}{2} \end{pmatrix}, \qquad S(W) = \begin{pmatrix} 0 \\ gbh(S_0 - S_f) \end{pmatrix}.$$

By deriving the flux term, it is possible to rewrite (6) in a quasi-linear form,

$$\partial_t W + F'(W)\partial_x W = S(W). \tag{7}$$

thus revealing the Jacobian matrix of the flux $F'(W)$ defined as follows,

$$F'(W) = \begin{pmatrix} 0 & 1/b \\ gbh - V^2/b & 2V/b \end{pmatrix},$$

The matrix $F'(W)$ is diagonalizable and its associated eigenvalues are given by,

$$\lambda_\pm = V/b \pm c,$$

these eigenvalues represent the wave speeds or characteristic speeds of the system, and $c := \sqrt{gh}$ denotes the speed at which information propagates in the flow (for example, the speed of a wave crest) also known as the gravity wave speed.

For the resolution of (7), we will use the well-balanced Godunov-type scheme developed by SORE et al in [11], considering zero sediment transport. The topography is defined by the longitudinal profile of the main channel (see Figure 6), where the minimum elevation is considered as a reference.

4.5.4. *Boundary Conditions.* Regarding the boundary conditions, at the left boundary, both the water depth and the discharge are subject to homogeneous Neumann conditions. At the right boundary, the water depth is prescribed as a fixed value h_0, determined according to the month under consideration, while the discharge also satisfies a homogeneous Neumann condition.

4.5.5. *Initial Conditions.* For our simulations in this article, the initial conditions will be defined by the values h_0 at the beginning of the chosen starting month (see Figure 4) : $h(0,x) = h_0 - B(0,x)$. However, for particular cases, other values can be used. As a reminder, the topography is defined by the longitudinal profile of the main channel (see Figure 6), where the minimum elevation is considered as a reference.

4.6. **Model Calibration and Validation.** We first performed simulations using the initially retained data. To improve the model's performance, an adjustment was made by modifying the parameter K_s, which represents the roughness coefficient of Lake Bam and which, to our knowledge, had not been determined previously. To do this, the annual variations in the water level in the reservoir were divided into 12 months. The water level evolution in January was used for calibration, while the other months served to validate the model. According to the available data (see Figure 4), the water level was $3.15\,m$ at the end of December and $2.86\,m$ at the end of January. Thus, the water level at the end of December was used as the initial condition. After 8 numerical simulations, the retained value of K_s is 45.5, and the set of K_s values used as well as the results obtained for the water level at the end of January are presented in Table 3.

Number	1	2	3	4	5	6	**7**	8
value of Ks used	30	40	42	48	47	46	**45.5**	45
value of h obtained	2.7888	2.8444	2.8510	2.8661	2.8640	2.8617	**2.8605**	2.8593
absolute error	$7{\times}10^{-2}$	$2{\times}10^{-2}$	$9{\times}10^{-3}$	$6{\times}10^{-3}$	$4{\times}10^{-3}$	$2{\times}10^{-3}$	$\mathbf{5 \times 10^{-4}}$	$7{\times}10^{-4}$

TABLE 3. Simulation results

After determining the value of K_s, we conducted a simulation to observe the evolution of the water level in the reservoir over the course of 12 months. The results are presented in Figure 7. It is important to note that, given the available data, only the values at the end of each month are available. Consequently, a comparison was made with the observed solution, which is based on these specific points.

To evaluate the model's performance, we used a widely adopted criterion in hydrology, the Nash-Sutcliffe efficiency criterion (Equation (8)), which ranges from $-\infty$ for very poor fits to 1 [8]. The Nash-Sutcliffe criterion for this simulation is 0.9808. The results demonstrate that the model reproduces the evolution of the water level over time with high accuracy. Therefore, the modeling is validated, and the model can now be utilized.

$$NS = 1 - \frac{\sum_{i=1}^{n}(h_o i - h_p i)^2}{\sum_{i=1}^{n}(h_o i - \overline{h_o})^2}. \tag{8}$$

With $h_o i$ the observed height of the water columns, $h_p i$ the predicted height of the water columns and $\overline{h_o}$ the mean of the observations and n the total number of points.

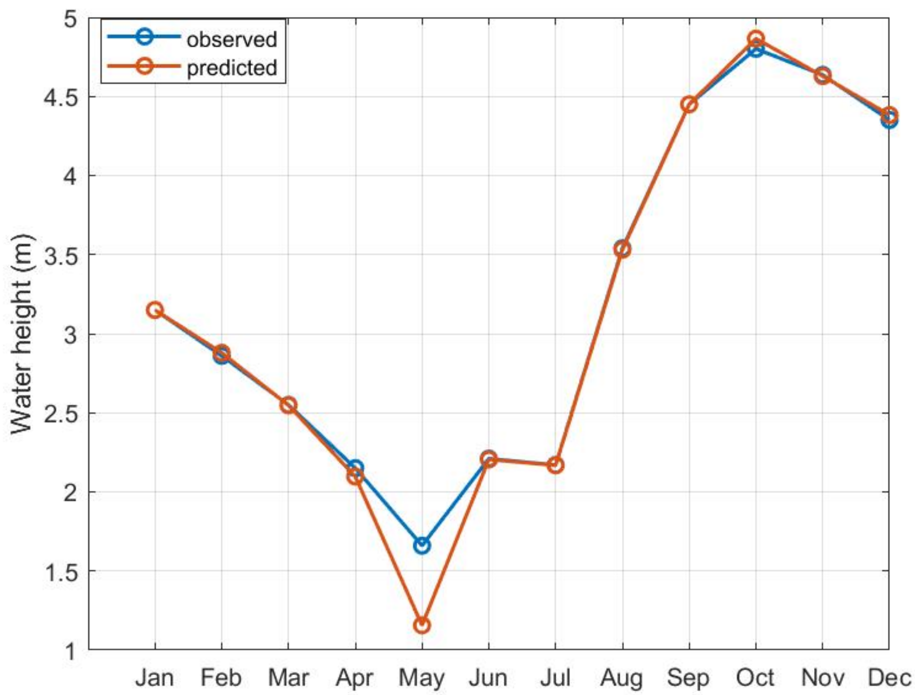

FIGURE 7. Comparison of simulated height of the water column and observed height of the water column.

4.7. **Exploitation and Interpretation.** After validating the model, we conducted simulations to observe the water level in Lake Bam. These simulations are of great significance as they can help address certain environmental concerns mentioned in Section 2. Specifically, they enable the identification of flood-prone areas, the improvement of flood planning and management, and the reduction of negative impacts on populations and infrastructure.

As stated in Section 4.3.1, when the lake is fully filled, it spans approximately 25 km in length, with a variable width not exceeding 1,000 meters from one bank to the other. During flood periods, the water expands to form a continuous water body extending up to about 45 km in length. Therefore, our simulations focus on a distance of 25 km, where the point $x = 25\,\text{km}$, located approximately 400 m upstream of the spillway, acts as a permanent reservoir.

Figure 8 illustrates the behavior of the water level during September and November at four points of the lake, while Figure 9 shows the water level behavior during September exclusively at the point $x = 25\,\text{km}$, and Figure 10 presents the evolution of the free surface throughout November at all points of the lake. These figures reveal a rise in water levels during September, followed by a decline in November. This behavior is explained by water inflows during the rainy season and increased outflows from October onwards, driven by the resumption of human and pastoral activities.

Furthermore, the average depth of Lake Bam ranges between 2 and 3 meters, remaining remarkably stable. The deepest areas, reaching approximately 5 meters, are located near the point $x = 25$ km, about 400 m upstream of the spillway, which is consistent with the data from [2].

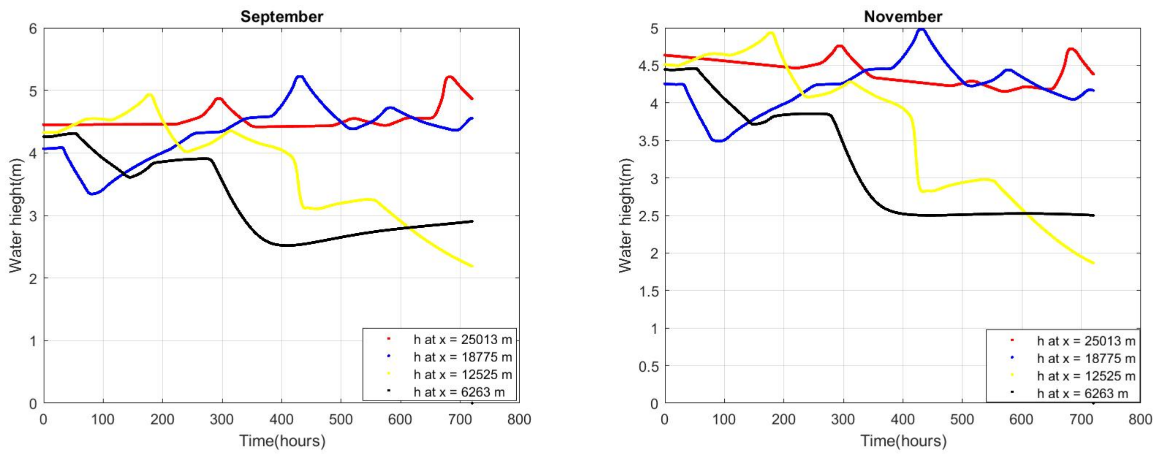

FIGURE 8. Evolution of the height of the water column at four points during the months of September and November.

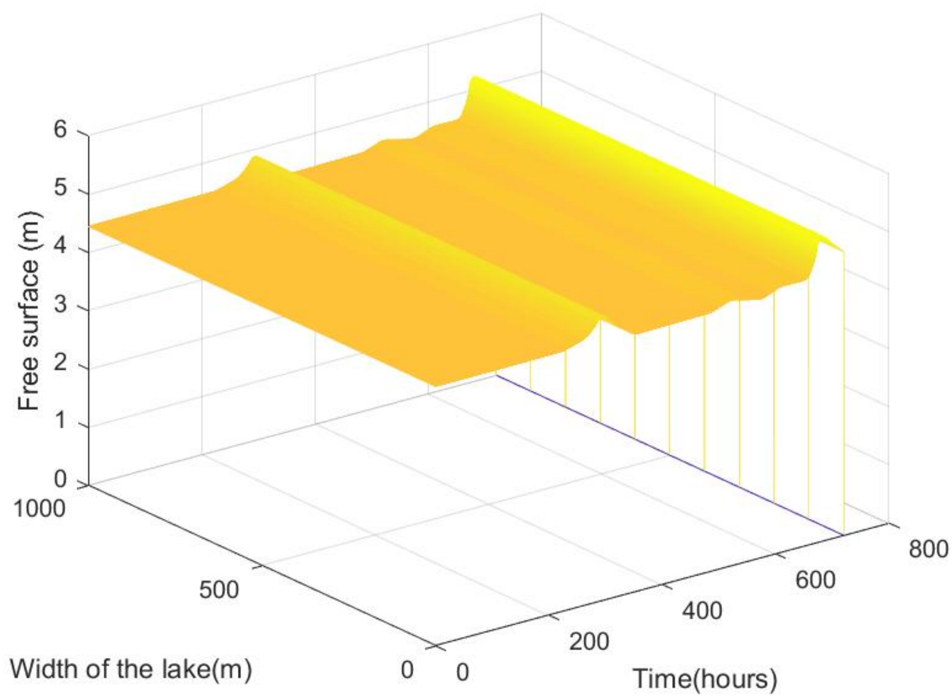

FIGURE 9. Evolution of the height at points $x = 25$ km during the month of September.

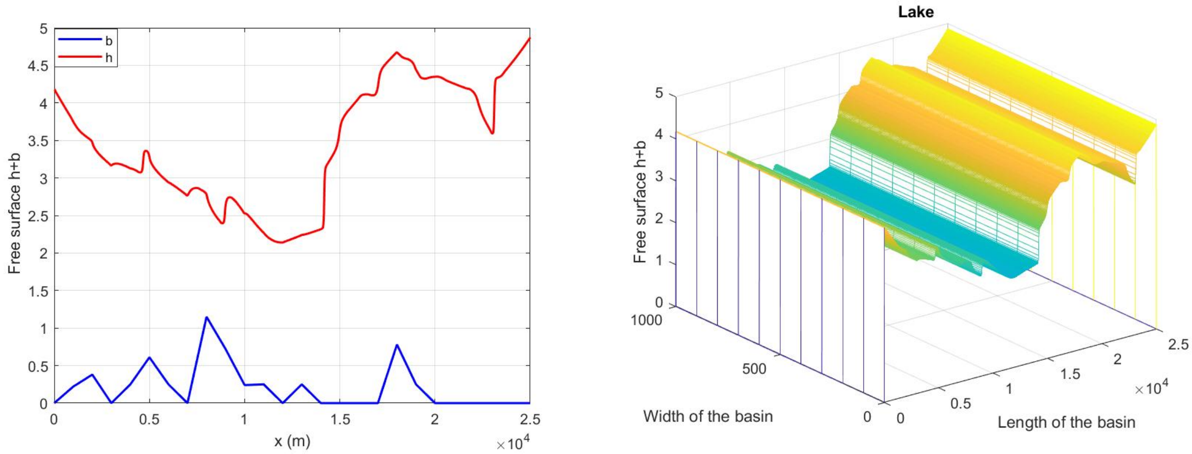

Figure 10. Evolution of the free surface during the month of September.

5. Conclusion

In this paper, we developed a modeling approach for water flow within a watershed bed. A specific application was carried out for the watershed of Lake Bam, the largest natural water reservoir in Burkina Faso. The resulting model was calibrated and validated using data provided by the Project for the Restoration, Protection, and Valorization of Lake Bam (PRPVLB). Once validated, the model was used to conduct simulations addressing key environmental concerns.

These simulations notably help identify flood-prone areas, improve flood planning and management, and minimize negative impacts on populations and infrastructure. Consequently, this model serves as a valuable tool for the integrated and sustainable management of water resources, environmental protection, and population safety.

Availability of data. The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Authors' Contributions. All authors have read and approved the final version of the manuscript. The authors contributed equally to this work.

Conflicts of Interest. The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

[1] T. Chang, H. Kao, K. Chang, M. Hsu, Numerical Simulation of Shallow-Water Dam Break Flows in Open Channels Using Smoothed Particle Hydrodynamics, J. Hydrol. 408 (2011), 78–90. https://doi.org/10.1016/j.jhydrol.2011.07.023.

[2] Groupement CINTECH/BETICO-MALI, Rapport du Volet Hydrologie de l'Études Détaillées du Projet de Restauration, de Protection et de Valorisation du Lac Bam, 2013.

[3] J.A. Cunge, On the Subject of a Flood Propagation Computation Method (Musklngum Method), J. Hydraul. Res. 7 (1969), 205–230. https://doi.org/10.1080/00221686909500264.

[4] Edijatno, C. Michel, Un Modèle Pluie-Débit Journalier à Trois Paramètres, La Houille Blanche 75 (1989), 113–122. https://doi.org/10.1051/lhb/1989007.

[5] F. Padilla, J. Hernández, R. Juncosa, P.R. Vellando, Application of a Numerical Model Designed for Integrated Watershed Management, WIT Trans. Ecol. Environ. 1 (2015), 123–134. https://doi.org/10.2495/ws150111.

[6] A.M. Kalteh, RAinfall-Runoff Modelling Using Artificial Neural Networks (ANNs): Modelling and Understanding, Caspian J. Environ. Sci. 6 (2008), 53–58.

[7] K. Miljan, I. Nenad, D. Tina, M. Ljubo, Application of Artificial Neural Networks for Hydrological Modelling in Karst, J. Croat. Assoc. Civ. Eng. 70 (2018), 1–10. https://doi.org/10.14256/jce.1594.2016.

[8] J.E. Nash, J.V. Sutcliffe, River Flow Forecasting Through Conceptual Models, I: A Discussion of Principles, J. Hydrol. 10 (1970), 282–290.

[9] S.L. Neitsch, J.G. Arnold, J.R. Kiniry, R. Srinivasan, J.R. Williams, Soil and Water Assessment Tool Theoretical Documentation, Version 2005, Agricultural Research Service/Blackland Research Center, Texas, USA, 2005.

[10] J. O'Sullivan, S. Ahilan, M. Bruen, A Modified Muskingum Routing Approach for Floodplain Flows: Theory and Practice, J. Hydrol. 470-471 (2012), 239–254. https://doi.org/10.1016/j.jhydrol.2012.09.007.

[11] S. Sore, Babacar Leye, Yacouba Simpore, A Godunov-Type Scheme for the Saint-Venant-Exner Equations with a Moving Steady States, Gulf J. Math. 17 (2024), 166–189. https://doi.org/10.56947/gjom.v17i2.1937.

[12] G. Wang, C. Yao, C. Okoren, S. Chen, 4-Point FDF of Muskingum Method Based on the Complete St Venant Equations, J. Hydrol. 324 (2006), 339–349. https://doi.org/10.1016/j.jhydrol.2005.10.010.