Approximation of a flood wave

A case study for the black volta river

Bachelor End Project

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by

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Faculty:	Faculty of Civil Engineering, Delft

TU Delft

Preface

For the finalization of the Bachelor's degree in Civil Engineering at TU Delft, it is necessary to complete a final project. The student has the opportunity to choose their own topic. I chose this topic because I am interested in making predictions on real-world system behavior, and this project aligned well with that interest. During these last weeks, I have learned a lot about writing a research paper, finding all the necessary data, and making well-supported predictions. I would like to express my gratitude to my supervisors, Prof. Dr. Ir. Nick van de Giesen and Guus Wiersma. Without their help, this project would not have been possible, and I am very grateful for our collaboration.

T.J. ter Laan
Delft, June 2024

Summary

The Black Volta River, flowing through West Africa, plays a vital role in the region's water supply, agriculture, and transportation. This study focuses on the Lawra District in northwest Ghana, which experiences flash floods. These floods create tidal waves in the river that impact the Bui Dam, which is crucial for electricity generation in the region. The main research question is: "How long does it take for a tidal wave seen at Lawra to reach the Bui dam?" The question is further broken down into sub-questions regarding the river's depth and wave celerity. The main goal is developing a simplified model that can accurately describe the celerity of the wave and as a result predicting the time it takes for the wave to reach the dam. This information can then be used by the dam operators to take measures maximizing electricity generation and minimizing potential damage from flooding.

The study segments the Black Volta River into 65 sections, each 3 to 10 kilometers long. Slopes are determined using satellite images and digital elevation models. Depth calculations use two approaches: Manning's equation, an empirical formula relating flow velocity to roughness, slope, and hydraulic radius; and the Leopold-Maddock method, using an exponential relationship between discharge and hydraulic geometry, suitable for data-scarce regions.

Wave celerity is described using two models: the shallow water wave model, calculating wave speed based on the square root of water depth, and the kinematic wave model, incorporating frictional forces for realistic wave propagation. Results show four combinations: Manning's equation with shallow water wave model, Manning's equation with kinematic wave model, Leopold-Maddock method with shallow water wave model, and Leopold-Maddock method with kinematic wave model. The shallow water wave model with Manning's equation yields high celerity values, while the kinematic wave model offers more moderate and realistic speeds. The Leopold-Maddock method with shallow water wave model indicates depth increases with discharge, but empirical data limitations may affect accuracy. The kinematic wave model, incorporating frictional effects, provides reliable flood wave behavior predictions.

It can be concluded that the Kinematic Wave model is generally recommended for the Black Volta River due to its ability to incorporate frictional resistance and provide more accurate flood wave predictions. Manning's equation is preferred for detailed hydraulic analysis where sufficient data on channel roughness and slope is available, while the Leopold-Maddock method is valuable for broader regional studies and initial assessments in data-scarce areas. Future studies should address the assumptions made in this research, such as constant discharge and Manning's coefficient, by incorporating more detailed field surveys and remote sensing data. Integrating hydrological models to simulate seasonal and event-based discharge fluctuations and using high-resolution topographic and bathymetric data will improve the precision of flood wave predictions. Additionally, considering temporary storage solutions for floodwater can reduce downstream flooding and enhance flood management strategies.

By combining both methods and models, researchers can provide detailed and accurate predictions, ensuring effective flood management and optimal electricity generation at the Bui Dam. This study lays the groundwork for future research, emphasizing the need for comprehensive data collection and advanced modeling techniques to address the complex challenges of flood wave prediction in river systems.

Contents

1 Introduction

1.1. Problem analysis

The Black Volta is a significant river in West Africa. It originates in the western part of Burkina Faso, flows southwest through Ghana, forming part of the border between Burkina Faso and Ghana. Eventually, the river continues southward, also forming part of the border between Ivory Coast and Ghana before it empties into Lake Volta in Ghana [3]. The Black Volta is one of the major rivers in the region and plays a crucial role in water supply, agriculture, and transportation [14].

The focus of this research centers on the Lawra District, situated in the northwest region of Ghana. Characterized by sporadic heavy rainfall, the area has experienced flash floods. The excess water swiftly drains into the Black Volta River, which culminates in the formation of a tidal wave within the river. The tidal wave eventually reaches the Bui dam. The dam generates electricity and is crucial for the region. The influx of water from the tidal wave can lead to dangerously high water levels, prompting the dam operators to release water in controlled amounts to prevent overflow [10].

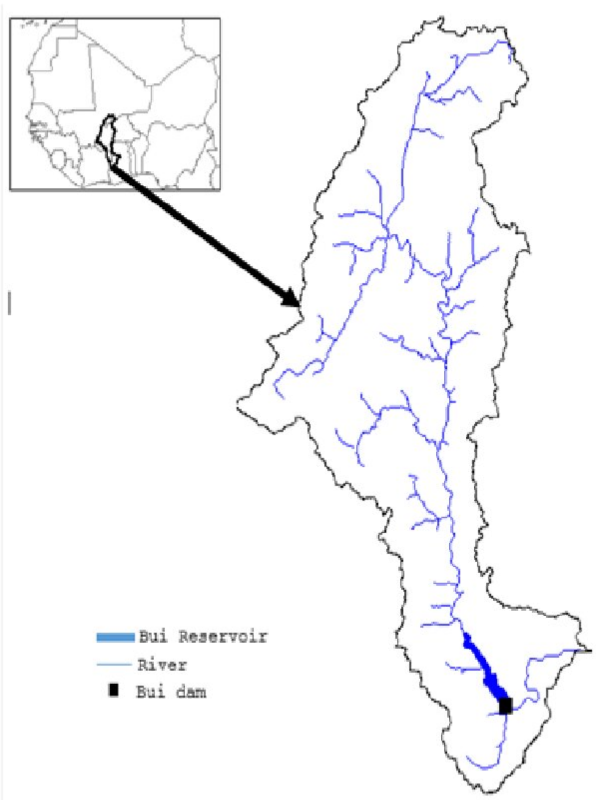


Figure 1.1: Black Volta region [9]

However, this controlled release of water results in a loss of potential power generation, leading to financial losses [10]. Balancing the need for flood control and electricity generation is a complex issue requiring careful management and possibly additional infrastructure or strategies to mitigate the financial losses while ensuring the safety of the dam and surrounding areas.

In the future, it would be beneficial for the dam operators to have more information about how the tidal waves behave in the Black Volta. This would enable better anticipation of such waves and more informed decisions about how much water to release through the dam. As a result, maximum electricity generation could still be achieved.

1.2. Research question

This report focuses on determining the velocity of a tidal wave that occurs in the black volta river during a flash flood. The velocity is examined to determine the time it takes for the flood wave to reach the Bui Dam from the village of Lawra (North West Ghana). The main goal is to create a simplified model that can describe the celerity of the wave. The celerity can then be used to determine how long it takes for the wave to reach the dam. This is useful information for the operators of the dam because action can still be taken to ensure that as much electricity as possible is generated while minimizing damage to surrounding villages. Concluding, the main research question of this research is:

“how long does it take for a tidal wave seen at Lawra to reach the Bui dam”

This main research question can be answered by first answering the following sub-questions:

”what is the depth of different parts of the black Volta river?”

”what is the celerity of a tidal wave in the black Volta river?”

1.3. Approach

This study focuses on determining how long it takes for a tidal wave seen at Lawra to reach the Bui dam. To determine this, the problem will be solved in several steps and the river will be divided into different segments. This is done to simplify the problem. Additionally, the steps can initially be carried out for one segment. Once this is done, the flood wave for this segment will be described, and all the steps will be clear, hence the other segments can be easily described as well. After determining the various variables for all segments and thus knowing the final celerity of the flood wave per segment, the segments can be lined up to provide a simplified version of a flood wave from Lawra to the Bui Dam.

During the first step the geometry of the black Volta river has to be determined. The width of the river can be determined using satellite images. Within each segment, a number of measurements are taken, from which the average width is determined. Then, the depth has to be determined. For this, a method must be found that can estimate the depth with a single cross-section of the river. This will be done by using two different methods. First the Manning’s equation will be used and after that the Leopold’s method. Once the depth is found by these methods, the celerity of a tidal wave can be calculated using the flow in the black Volta river. The celerity is described using again two different simplified formula to give a good indication of the velocity of a tidal wave. This can then be used to determine the time before the tidal wave reaches the dam.

1.4. Structure

In Chapter 2 ”Methodology” the steps to eventually answer the research questions are presented and described. All the steps and the formula used are carefully explained. This is done by first explaining why the river is segmented, then the method of how the slope of the river is found is given and at last the two different ways to find the depth and the two different formula’s to calculate the celerity are presented.

Moving on to Chapter 3 ”Results and Discussion” it presents the newly established celerity of the flood wave and the time it takes to reach the Bui dam. Furthermore, this chapter discusses the findings and the estimations that had to be made to make the calculations. The weight of each variable will be assessed to ultimately make recommendations on which one should be prioritized for an initial measurement.

Finally, Chapter 4 ”Conclusion and recommendations” concludes the study by summarizing the findings and answering the research questions. At last, recommendations are made to improve the approximations and suggestions for future studies are given.

2
Methodology

2.1. Segmenting the Black Volta

To accurately map the Black Volta River, it has been divided into segments. There are a total of 65 segments, with 48 segments being around 3 kilometers long and 17 segments around 10 kilometers long. All segment lengths combined give the length of the river from Lawra to the Bui Dam as approximately 305 kilometers. Approximately 30 measurements of the river's width have been taken per segment.

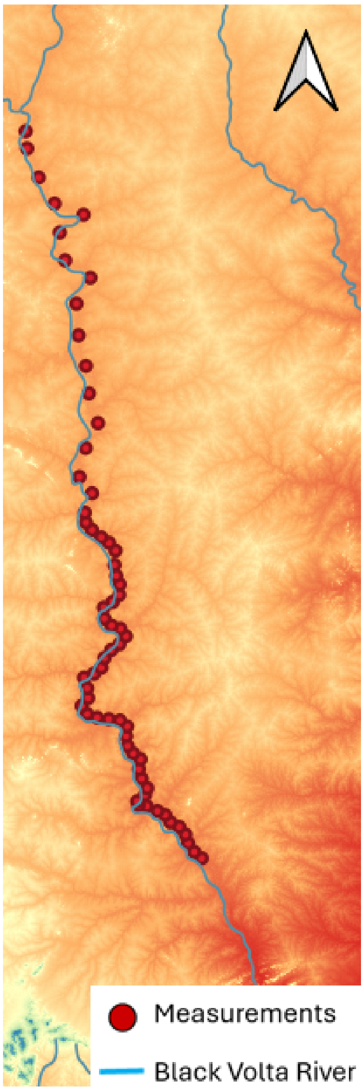


Figure 2.1: Elevation Map with Black Volta and measurement locations

This was done using satellite images retrieved from Google Maps and the measurement tool provided by Google Maps. To use these widths for further calculations, the average width per segment was then determined. This was done by dividing the total sum of widths by the number of measurements. The advantage of dividing the river into different segments is that it allows the research problem to be solved in smaller steps. Initially, the steps to find the ultimate celerity will be carried out through one segment. These steps are as follows:

- finding the slope
- finding the average depth
- Determining a method to describe the celerity

Once the process for determining the celerity for one segment is mapped out, this knowledge can be used to calculate the variables for the other segments. Eventually, an initial description of a flood wave passing through the Black Volta can be made by piecing the segments together. In Figure 2.1 next to this text, the Black Volta River is shown on a digital elevation model (DEM). The begin and end coordinates of the various segments are also visible, indicated by red points.

2.2. Finding the slope

To determine the river's gradient, a digital elevation model (DEM) has to be utilized. A DEM is a representation of the bare ground (bare earth) topographic surface of the Earth excluding trees, buildings, and any other surface objects [18]. The DEMs used are obtained from USGS.gov, an official website of the US government. With the assistance of QGIS, data of the Black Volta can be retrieved and useful maps can be generated. To illustrate the route of the Black Volta River (shown as the blue line in Figure 2.1), data of all the rivers in Ghana were downloaded from the World Bank database [19].

During the process of segmenting the river and measuring the width per segment, the begin and end coordinates of each segment where stored in an excel file. By uploading the file in QGIS, the elevation per coordinate can be established. Subsequently, the slope of each segment can be calculated by subtracting the elevation of the endpoint from that of the starting point and dividing this by the length of the segment. Knowing the slope is important because it will ultimately be needed to determine the average depth of the various segments. This will be done, among other things, using the Manning equation.

The segment that is used to make the first calculations with is the most northern segment. In table 2.1 the elevation of the begin and end coordinates can be seen. A similar table is created from QGIS containing all the coordinates and their corresponding elevations. The slope is then calculated as described above:

$$\frac{235-234}{6140} = 1.629 \times 10^{-4}$$

The length of this first segment is 6.14 kilometers, as used in the calculation above. Eventually this calculation will be made for all segments. For now, all the further calculations will first be made with this most Northern segment.

Longitude	Latitude	Elevation
-2,93036664	10,60066509	234
-2,93412676	10,64818318	235

Table 2.1: Elevation of the most northern segment

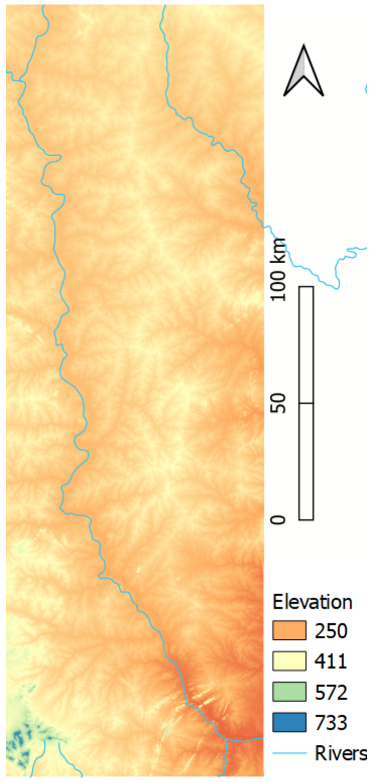


Figure 2.2: Elevation Map of Black Volta area

2.3. finding the average depth

The research will continue as explained by first making an estimation of the depth, this will be done in two different ways. The first method with help of the Manning's equation and the Continuity equation and the second with the Leopold-Maddock theory. Then the celerity will be described with the shallow water wave model and the kinematic wave model for both.

2.3.1. Finding the average depth with Manning's equation

The continuity equation links the flow (Q) with the width (w), the average depth (h) and the velocity (v) [6]. This equation is fundamental in hydraulic engineering as it represents the conservation of mass principle, ensuring that the rate of flow into a section of the river equals the rate of flow out:

$$Q = w * h * v$$

The Manning equation relates the velocity of the water to the hydraulic radius (R), the slope and the Gauckler–Manning coefficient (n) and is widely used in river hydraulics [1]. With its empirical basis and applicability to natural channels, the Manning equation has been extensively validated and applied in various hydrological studies [5]:

$$v = \frac{1}{n} * R^{\frac{2}{3}} * S^{\frac{1}{2}}$$

The Gauckler–Manning coefficient can differ significantly per river. For now the value that has been determined for the Black Volta River by the MDP study [7] will be used for the equation and is 0.045. In the previous section the method of how the slopes where determined is explained. The hydraulic radius will be determined by assuming the river is a rectangular channel, for a rectangular channel the hydraulic radius is almost the same as the water depth [2]:

$$R \approx h$$

To calculate the depth with the known variables the equations have to be rewritten. First the Manning Equation is used to express the velocity in terms of the water depth. Next the velocity of the continuity equation will be replaced by the expression found in the manning equation. Finally, the equation will be reformulated to solve for the depth. This gives the following equation:

$$h = \frac{Q * n}{w * S^{1/2}}^{3/5}$$

So for the first segment, the average depth will become:

$$h = \frac{840 * 0.045}{57.875 * 1.12 * 10^{-4^{1/2}}}^{3/5} = 10.6$$

In the result and discussion the impact of different Manning's coefficients and discharges will be discussed. This because the Manning's coefficient can very between 0.02 and 0.1. The coefficient varies depending on several factors, for example the channel roughness, channel geometry, flow conditions, vegetation and sediment transport [11]. Furthermore, the discharge can also vary and the effect will also be evaluated.

2.3.2. Finding the average depth with Leopold and Maddock

Finding the depth is a very important step to calculate the celerity. Without the depth the average surface of a cross-section can't be determined. Another method to estimate the depth is by assuming an exponential relationship between the discharge of a river and their hydraulic geometry. This relationship is described in the Leopold and Maddock method [12]. In the thesis of Le Poole [15] the Leopold equation for data scarce areas is completely explained. This highlights that the Leopold equation is a suitable method to use for areas with limited data. The area under investigation in this study is one such data-scarce area. There is only one cross-section of the river available, obtained from another study's [7] bathymetry. The location of the bathymetry is at 'Chache' and the bathymetry is depicted below.

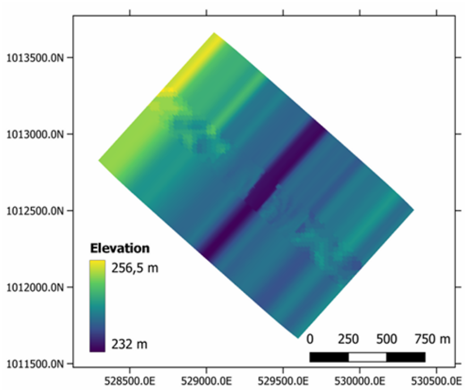


Figure 2.3: Bathymetry of the main channel and floodplain of the Black Volta in Chache [7]

From this Bathymetry the depth of the river at Chache can be determined. The width of the river at the time the width measurements for this study where made at Chache is 150 meters. By evaluating the Bathemetry the depth is determined to be 12.25 meters.

Now a method to determine the depth at other segments has to be found. Here fore the Leopold and Maddock hypotheses is used. They derived the following power law relationships with six different parameters to define the hydraulic geometry of rivers:

$$w = a * Q^b$$
$$d = c * Q^f$$
$$v = k * Q^m$$

These six parameters have to fit the following two constrains:

$$b + f + m = 1 \pm 0.1$$
$$a * c * k = 1 \pm 0.1$$

The parameters can be obtained by using the data found at Chache. Once the parameters are found the depth of the other segments can be determined by using the average width of each segment. These parameters can be found by taking atypical set used in hydraulic geometry for the empirical exponents, which include:

- Width exponent (b): 0.5
- Depth exponent (f): 0.4
- Velocity exponent (m): 0.1

These exponents have been validated through numerous studies and are considered standard for many river systems [16] [4].

Using the known width (w) and depth (h), the coefficients where calculated first by rewriting the equations above:

$$a = \frac{w}{Q^b}$$
$$c = \frac{h}{Q^f}$$

Substituting the given data and exponents:

$$a = \frac{150}{840^{0.5}} \approx 5.17$$
$$c = \frac{12.25}{840^{0.4}} \approx 1.07$$

With the coefficients a and c calculated, the depths for other river segments can be determined using their respective widths. The relationship used for calculating depth is derived from the Leopold-Maddock power-law equations:

$$d_i = c * \frac{w_i}{a}^{f/b}$$

Here, w_i represents the width of the segment and this formula allows the predictions of the depths of each segment based on the width and the previously calculated coefficients.

2.4. Describing the celerity with the Shallow Water Wave model

Now that the depth for each segment can be calculated using the continuity and Manning equation and the Leopold-Maddock theory, a model will be described to calculate the celerity of the flood wave. This is with the shallow water wave equation. The equation is one of the fundamental concepts applied in hydraulic engineering, which formulates the movement of shallow water waves across open channels or rivers [13]:

$$c = \sqrt{g * h}$$

This relationship implies that the speed of a wave is directly proportional to the square root of the water depth. As the depth increases, the wave speed increases, and vice versa. This equation is derived from the linear theory of shallow water waves, which assumes that the wave height is small compared to the depth of the water and that the flow is primarily horizontal [8]. The shallow water wave formula can be derived from the fundamental principles of fluid mechanics. The derivation typically begins with the Navier-Stokes equations, which describe the motion of fluid substances. By making the assumption of incompressible and inviscid flow and applying the continuity equation and momentum conservation, the linearized shallow water wave equation can be obtained.

2.5. Describing the celerity with the kinematic Wave model

An other model to describe the celerity is with the use of the kinematic wave model. The model is particularly significant for the fact that it has the ability to simplify complex fluid dynamics into more manageable calculations. The celerity is now described as:

$$c = \frac{dQ}{dA}$$

Where Q denotes the discharge and A represents the cross-section area of the flow. For the first calculations the discharge will remain the same and the cross-sectional area is calculated by multiplying the width with the depth. The model operates under several assumptions. It presumes that the flow is primarily influenced by friction and gravitational forces and the effects of inertia and pressure gradients are neglected [17].

3 Results and discussion

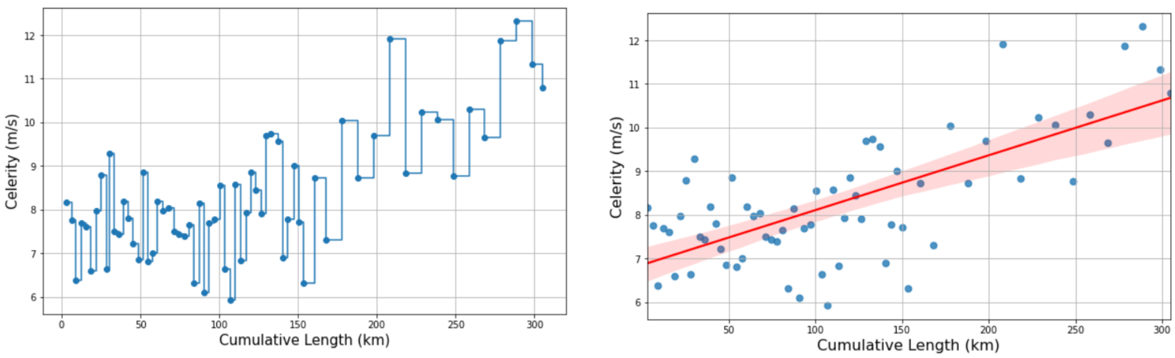
In this chapter, the results of the findings from Chapter 2 will be presented. All the data collected and the calculations made have been compiled into a database. Using Python, graphs have been generated to illustrate the various findings. First, the results found with the Manning's equation will be displayed, followed by an analysis of the effects of using different values for the parameters and variables. The travel times are also calculated and because the goal of the study is to give an indication on when a flood wave in the Black Volta will reach the Bui dam the 'worst-case scenario' time for each method will be presented as this will show how much time the dam operators at least have to take measure. After all the results are presented the different results for the combinations of the depth and celerity methods are discussed.

3.1. Results Manning's equation

First the results found with the Manning's equation will be shown and thereafter the influence of different values for the discharge and Manning's coefficient will be given.

3.1.1. Results shallow water wave model

For the shallow water wave model the values from the MDP [7] have been taken first. All the celerity's for the different segments have been calculated and (as explained) put after each other. This gives a graph showing the celerity for every given location from the Bui dam to Lawra. So left side is the Bui dam and right side is Lawra. In figure 3.1.b a graph with the linear regression can be seen. One can see that the celerity decreases from Lawra to the Bui dam. The reason for this is because the width gradually increases from Lawra to the dam, which gives a smaller depth and a smaller depth results in a lower celerity.



(a) Celerity over the length of the Black Volta

(b) Celerity Over the Length of the River with Regression Line

Figure 3.1: Results for the black Volta river with shallow water wave model and Manning's equation

Because for each segment the celerity is found, the total time needed for the flood wave to reach the dam can be approximated. this is done by making a summation of the division of the length of each segment with the celerity for each segment. For the first parameters used this is a total of 9.82 hours, or 9 hours and 49 minutes.

The width and the slope measurements where fairly accurately made. However, in reality the Manning's coefficient and the discharge can vary quite a bit. Up until now an assumption of these values were used but in this section the effect of different values of these variables will be discussed, starting with the Manning's coefficient. In the previous chapter it was concluded that the coefficient can vary between 0.02 and 0.1. For comparison the linear regression's of a couple of different values for the coefficient have been plotted. In the figure below it can be seen that a higher Manning's coefficient results in a higher celerity.

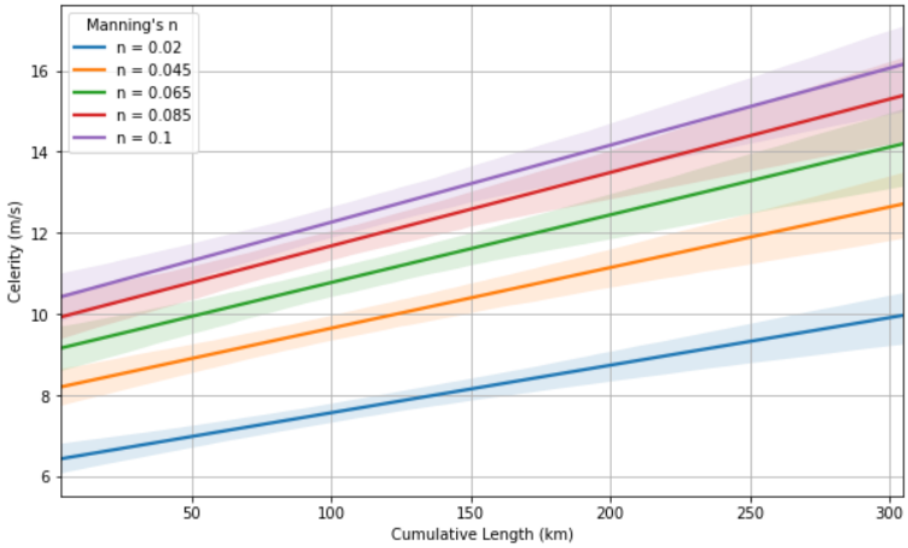


Figure 3.2: Linear Regression of Celerity vs Length for Different Manning's Coefficients

The different celerity's of the different Manning's coefficients also give different travel times for the flood wave. This has been put in the table below:

Manning's coefficient (n)	Total travel time (hours)
0.020	12.53
0.045	9.82
0.065	8.80
0.085	8.12
0.100	7.73

Table 3.1: different travel times for the different values of the Manning coefficient

For these calculations the discharge was assumed to be constant. In chapter 2 a value of 840 m^3/s was used, however the discharge in the black Volta river has a large variation and this has to be taken into account. The discharge can actually vary between 500 to 1500 m^3/s. In the graph below the relationship between the discharge (flow rate, Q) and the total travel time for the river segments is illustrated, while considering different values of Manning's coefficient (n). There are two trends which can be concluded from the graph. The first one being that for all values of n, the travel time decreases as the discharge increases. This is because higher discharge typically results in higher water velocities, reducing the travel time for water to flow through the river segments. The second trend is that higher values of the Manning's coefficient result in longer travel times for the same discharge. This is because higher *n* values indicate rougher channels, which slow down the flow of water. In typical hydraulic analysis, a higher Manning's n (rougher channel) would decrease the flow velocity due to increased resistance. However, the derived formula shows that an increase in *n* leads to an increase in celerity. This unusual result stems from the specific derivation and assumptions involved in the formula, particularly the relationship between discharge, depth, and roughness.

It is an useful figure because it shows a lot of different scenarios for the variables which are not measured that well. A worst case scenario can be found. The worst-case scenario, which maximizes travel time, occurs under conditions of high discharge and high Manning's coefficient. the combination of a discharge of 1500 m^3/s and a Manning's coefficient of 0.1 results in the shortest travel time, reaching approximately 6.5 hours. For now, this is useful for the dam operators as they have at least this amount of time to take measures and, for example, make a controlled spillage.

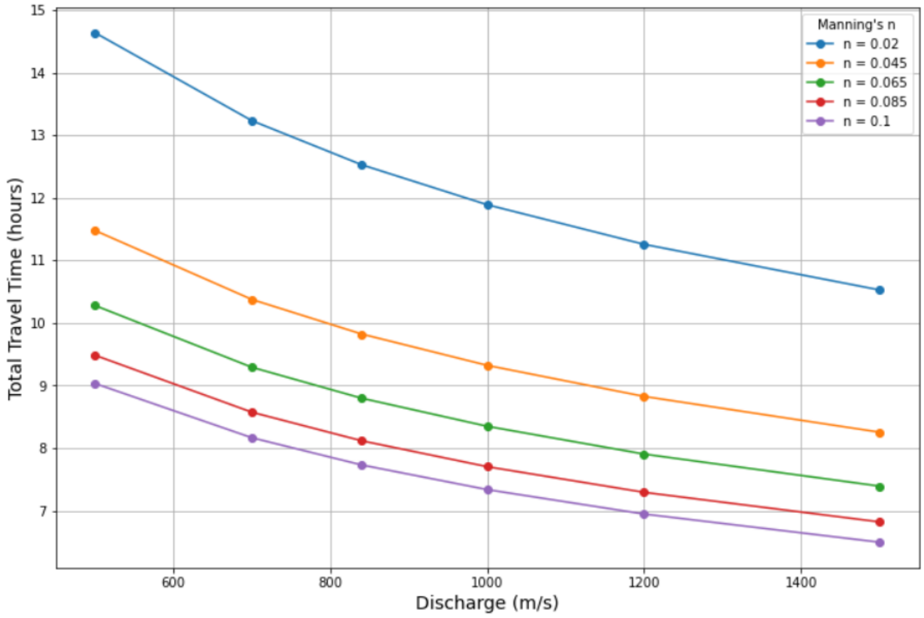
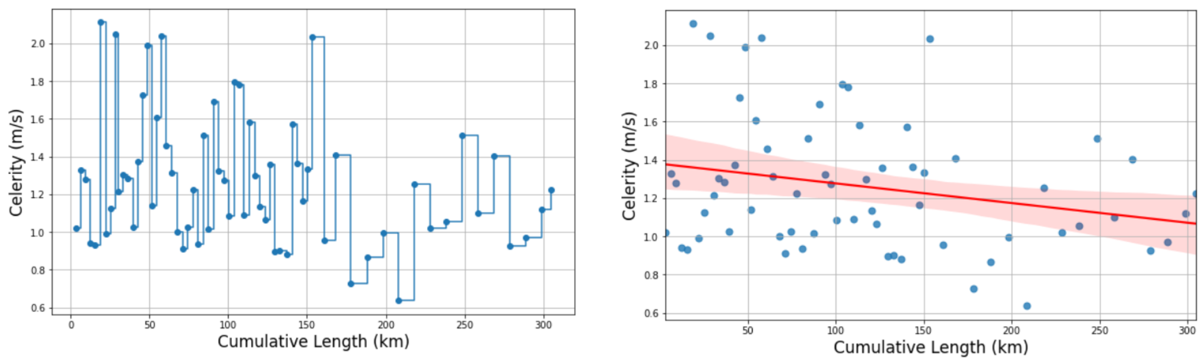


Figure 3.3: Effect of Discharge (Q) on Total Travel Time for Different Manning's Coefficients

3.1.2. Results kinematic wave model

The celerity has also been described with the kinematic wave model. The same steps will be followed as for the shallow water wave model giving two graphs, the celerity over the cumulative length of the river and the corresponding linear regression. The graph shows how the flood wave will behave if it will flow with the assumptions for the kinematic wave model.



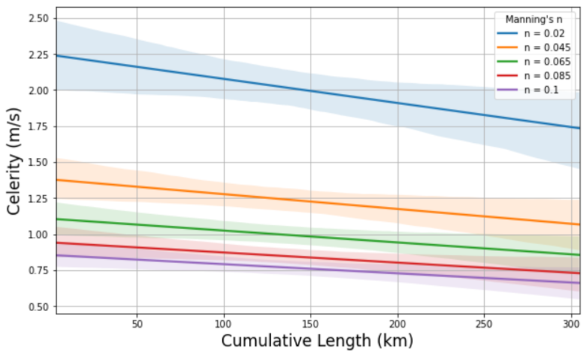
(a) Celerity over the length of the Black Volta

(b) Celerity Over the Length of the River with Regression Line

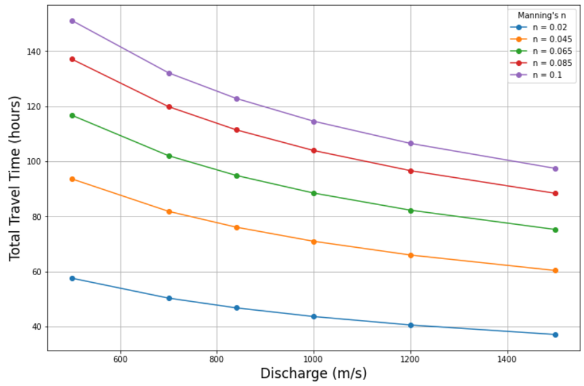
Figure 3.4: Results for the black Volta river with kinematic wave model and Manning's equation

As can be seen from the linear regression line the celerity remains fairly steady over the length of the river with the kinematic wave model. This happens because the model assumes that frictional forces dominate the flow, which will dampen the rapid changes in velocity, resulting in a more stable wave speed. It also neglects inertial effects, such as acceleration and declaration, which contribute further to the consistency of wave celerity.

The method to evaluate the contribution of the variables described for the shallow water wave model will also be used for the kinematic wave model, giving similar looking graphs. Again, the celerity and travel time where calculated for different combinations of discharge and Manning's coefficient. Giving the two graphs below:



(a) Linear Regression of Celerity vs Length for Different Manning's Coefficients



(b) Effect of Discharge (Q) on Total Travel Time for Different Manning's Coefficients

Figure 3.5: Results for the black Volta river with kinematic wave model and Manning's equation

In figure 3.5.b the travel time for the corresponding discharge and Manning's coefficient can be seen. It differs quite a lot with the travel times of the shallow water wave function. For the initial discharge taken the total amount of travel time for the different Manning's coefficient can be seen in table 3.2.

Manning's coefficient (n)	Total travel time (hours)
0.020	46.78
0.045	76.09
0.065	94.88
0.085	111.45
0.100	122.86

Table 3.2: different travel times for the different values of the Manning coefficient, kinematic wave model

What is even more important to conclude than the fact that the travel times are longer, is that the celerity decreases when the Manning's coefficient increases. This is hydraulically correct because a higher Manning's coefficient indicates more friction, resulting in slower celerity. The difference between the results for the two wave models will further be analyzed in the discussion.

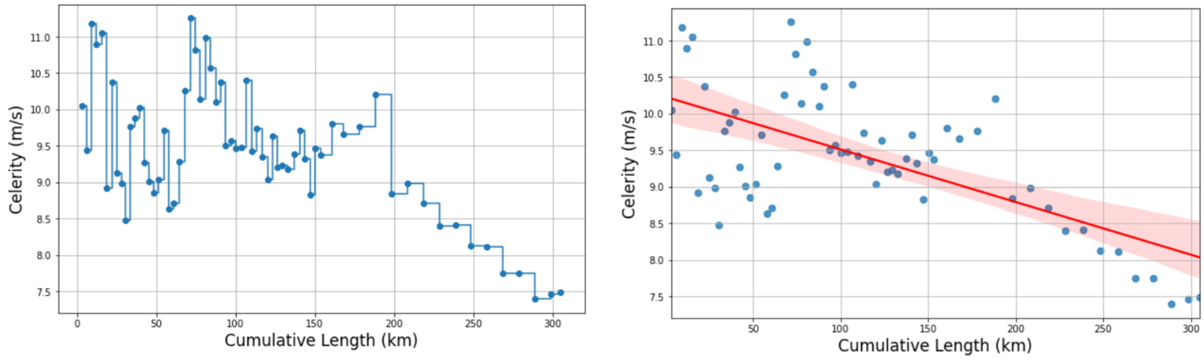
3.2. Results Leopold and Maddock

Now the results found with the Leopold-Maddock theory will be presented. Again the celerity has been found with the two different models and they will first be shown and thereafter also discussed.

3.2.1. Results shallow water wave model

The calculations were implemented using Python, iterating through each segment width to compute the corresponding depth. The code, which can be seen in appendix A, reads the provided data, prepossesses it, calculates the coefficients, and computes the depths for each segment based on the provided widths. The results show a non-linear increase in depth with an increase in width, consistent with the power-law relationships predicted by the Leopold-Maddock theory.

Once the depths of all the segments are found. A plot of the celerity over the length of the Black Volta (again from the Bui dam to Lawra) can be made. Again, the celerity is calculated with the shallow water wave equation first. Looking at the regression line, it can be seen in that the celerity increases from Lawra to the Bui dam. This is because the width of the river steadily increases from Lawra to Bui and with the Leopold-Maddock theory the depth also increases when the width increases. The total travel time for this situation is 9.40 hours and as the discharge and Manning's coefficient have no influence this will be the worst case scenario.



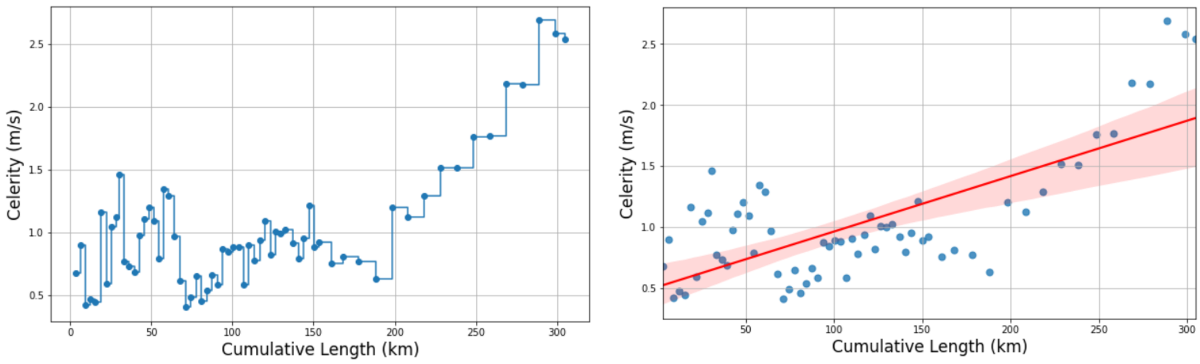
(a) Celerity over the length of the Black Volta with Leopold-Maddock

(b) Celerity Over the Length of the River with Regression Line

Figure 3.6: Results for the black Volta river with Leopold-Maddock

3.2.2. Results kinematic wave model

The celerity can also be calculated with the depths found with the Leopold-Maddock method and with the kinematic wave model. Using the depth found as described in the previous subsection the celerity over the length of the river is determined. Giving the following two graphs:



(a) Celerity over the length of the Black Volta with Leopold-Maddock

(b) Celerity Over the Length of the River with Regression Line

Figure 3.7: Results for the black Volta river with Leopold-Maddock and kinematic wave model

As the celerity is significantly less then for the shallow water wave function it shouldn't come as a surprise that the total travel time for the flood wave with the kinematic wave model is a lot longer, which is 88.09 hours.

3.3. Discussion

Now that the depths, celerity's and total travel times are known for the different methods/models and the combination of those it is time to discuss the findings. This will be done by first discussing the difference for the two wave models for the Manning's equation and after that for the Leopold-Maddock. At last the results belonging to the two different methods of finding the depth will be discussed.

3.3.1. Manning's equation: Shallow water wave vs kinematic water

The first difference between the results of the shallow water wave and kinematic water models that can be seen is the difference in celerity, resulting in a difference in total travel time. This significant difference in celerity is due to their differing emphasis on the gravitational forces and the frictional resistance. Gravitational acceleration is prioritized by the shallow wave model. This results that the wave speed is heavily dependent on the water depth and predicting much higher wave speeds in the deeper segments. The kinematic wave model however also incorporates the effects of friction, giving more moderate and realistic celerity values.

The second difference that can be seen is the fact that for a shallow water wave a higher Manning's coefficient results in a higher celerity and for the kinematic wave model a higher *n* results in a lower celerity. This is an interesting difference as in hydraulic theory, it is generally accepted that a higher Manning's coefficient results in lower flow velocity and, consequently, lower celerity. By substituting the rewritten Manning's equation into the shallow water wave equation the following formula is found:

$$c = \sqrt{g \cdot h} = \sqrt{g \cdot \left(\frac{Q \cdot n}{w \cdot S^{1/2}}\right)^{3/5}}$$

This formula gives a better overview of the relationship between *n* and the celerity. As *n* increases, the depth increases, and thus, the celerity increases. This relationship is direct because a greater depth leads to faster wave propagation in the shallow water wave model. Rewriting the kinematic wave eqaution with manning's equation gives:

$$c = \frac{d}{dA}\left(\frac{A^{5/3}S^{1/2}}{w^{2/3}n}\right) = \frac{5}{3} \cdot \frac{A^{2/3}S^{1/2}}{w^{2/3}n}$$

In this formula, *n* is in the denominator, so as *n* increases, the celerity decreases. This reflects the increased frictional resistance slowing down the flow, which is consistent with the physical expectation that rougher channels (higher *n*) reduce flow velocity and celerity.

Understanding the differences between the shallow water wave model and the kinematic wave model is crucial for accurately predicting flood wave behavior and implementing effective flood management strategies for the Black Volta River in Ghana. Each method has its advantages and limitations, making them suitable for different scenarios. The advantage of the shallow water wave model is the simplicity and directness, the model uses a straightforward relationship between wave speed and water depth. It is easy to implement and can provide quick estimates of wave celerity based on the depths. The simplicity also has a downside as it assumes a constant wave height relative to depth, which might not hold true in all real-world scenarios, particularly in complex or heavily vegetated channels. The kinematic wave model on the other hand explicitly includes frictional effects, making it more accurate for channels with significant roughness and variable flow conditions. By considering the balance between gravitational forces and friction, it also provides a more realistic representation of wave propagation in natural channels. A limitation of the model is that it assumes that inertial effects are negligible, which might not be accurate in rapidly changing flow conditions.

3.3.2. Leopold and Maddock: Shallow water wave vs kinematic water

The Leopold and Maddock method provides a valuable empirical approach to estimate river depth and, consequently, celerity of flood waves. Applying this method with both the shallow water wave model and the kinematic wave model reveals distinct differences in the predicted behavior of flood waves in the Black Volta River. Again the celerity values for the shallow water wave model are much higher then for the kinematic wave model. The advantages and limitations of the two methods for the celerity where already described in the previous subsection. Using the Leopold-Maddock means there are no other variables to discuss as it relies heavily on the measurements of the observed location, in this case only Chache. To apply this method accurately, having well-placed observation spots along the river is crucial. Adding more than one observation location will increase the reliability of the method significantly.

3.3.3. Manning's equation vs Leopold and Maddock

The Leopold and Maddock method and Manning's equation are two distinct approaches used to estimate river depth and, consequently, the celerity of flood waves. Each method has its unique principles and applications, leading to differences in the results obtained for the Black Volta River.

As described in chapter 2 Manning's equation is an empirical formula used to estimate the velocity of water flow in open channels based on the channel's roughness, hydraulic radius, and slope. The depth is calculated by rearranging the continuity equation and this approach directly relates the depth to discharge, width, slope and Manning's coefficient. The advantages of the Manning's equation are the fact that it is widely validated and used in hydraulic engineering and that it directly incorporates the channel's roughness and slope, providing a practical estimation of flow velocity and depth. The limitations are the fact that it assumes a simplified channel shape and uniform flow, which might not capture all the complexities of natural rivers and it is sensitive to the accuracy of the Manning's coefficient, which can vary significantly.

The Leopold and Maddock method on the other hand uses empirical relationships to define hydraulic geometry, linking river discharge to channel width, depth, and velocity through power-law equations. The coefficients are calculated from the observed data at Chache. The advantages of this method are the fact that it provides a detailed empirical relationship between discharge and channel geometry and that it is suitable for data-scarce regions, as it relies on a few key measurements to estimate depths for other segments. For the case of this study the disadvantage however is that there is only one observed data location. Furthermore, an other limitation is that it may not account for local variations in channel roughness and slope as effectively as Manning's equation.

To summarize, for the Manning's equation the depth estimates are derived from a combination of discharge, channel width, slope, and roughness. This method is sensitive to variations in these parameters, particularly the Manning's n. For the Leopold and Maddock Method the depth estimates are based on empirical relationships with discharge. This method is less sensitive to local variations in channel roughness and slope but relies on the accuracy of the empirical coefficients. The combination of methods has been summarized in the table below.

Model	**With Manning's Depths**	**With Leopold and Maddock Depths**
Shallow Water Wave Model	Higher celerity values as depth increases with higher n.	Depth increases with discharge, leading to varying celerity depending on segment-specific widths and empirical coefficients.
Kinematic Wave Model	Lower celerity with higher n due to increased friction.	Celerity varies based on empirical depth estimates, generally resulting in lower values compared to the shallow water wave model due to the emphasis on frictional effects.

Table 3.3: Comparison of Wave Models with Different Depth Estimates

4 Conclusion and recommendations

4.1. conclusion

This study conducted on the Black Volta River in Ghana aimed to develop a simplified model to predict the celerity of flood waves and determine the time it takes for this wave to travel from the town of Lawra to the Bui dam. Through the application of Manning's equation and the Leopold-Maddock method, combined with the shallow water wave model and the kinematic wave model, various scenarios were analyzed to provide insights into the behavior of a flood wave through this river.

The results demonstrated that the kinematic wave model is generally recommended for the Black Volta River due to its ability to incorporate frictional resistance and provide more accurate predictions of flood wave behavior. This model's consideration of channel roughness and other real-world conditions makes it well-suited for the detailed and variable nature of the river. Although the shallow water wave model can be useful for initial assessments and theoretical insights, the kinematic wave model offers a more reliable basis for developing effective flood management strategies. This ensures that dam operators and other stakeholders can make well-informed decisions to mitigate flood risks and optimize water resource management.

Manning's equation is preferred for detailed and precise hydraulic analysis when sufficient data on channel roughness and slope is available. It offers more direct control over input parameters, making it suitable for engineering applications. On the other hand, the Leopold and Maddock method is valuable for data-scarce regions, providing a practical way to estimate river depth and flow characteristics based on empirical relationships. It is useful for broader regional studies and initial assessments.

Combining both methods may offer the best results for the Black Volta River. Manning's equation can be applied where detailed data is available, while the Leopold and Maddock method can fill gaps in data-scarce areas. This approach ensures detailed and accurate flood wave predictions, ultimately helping in effective flood management and optimal electricity generation at the Bui Dam.

In summary, the study uses a combination of different methods and models to approximate the behaviour of a tidal wave. By doing so the study tries to answer various questions. The depth of of different parts of the black Volta river has been calculated using the Manning's equation and the Leopold-Maddock method. In addition, the celerity of a tidal wave in the black Volta has been found by implementing the Kinematic wave model and the shallow water wave model. These findings ultimately gave the opportunity to answer the main research question:

"how long does it take for a tidal wave seen at Lawra to reach the Bui dam"

The time was found for the combination of the different models/methods and different scenario's. These combinations give a lot of different values for the total travel time. So, per combination a 'worst case scenario' was introduced which gives an indication of how long the Dam operators at least have before the flood wave will reach the Bui dam.

4.2. recommendations

This study can be improved quite a lot as assumptions had to be made to give a first indication of the travel time of a flood wave in the Black Volta river. These assumptions include assuming the Discharge to be constant. However, discharge can fluctuate due to seasonal variations, rainfall events, and upstream water usage. The Manning's coefficient was also assumed to be constant throughout the river segments. In reality, channel roughness can vary significantly along different sections of the river. Furthermore, the river was segmented and assumed to have a rectangular cross-section, which simplifies the actual river geometry. At last,

To improve the precision of the study future studies could check if the assumptions are correct or improve the uncertainty of the assumptions. This can be done by for example measuring and using segment-specific Manning's coefficients to account for variations in channel roughness. This can be achieved through detailed field surveys and remote sensing data. The discharge can be more precise by incorporating a variable discharge model that accounts for seasonal and event-based fluctuations. This can be done by integrating hydrological models that simulate rainfall-runoff processes and upstream water usage. Using a more detailed river geometry will also improve the study, geometry data can be obtained from high-resolution topographic maps and bathymetric surveys. Especially for the Leopold-Maddock method using more data points will improve the depth estimations and as a result the reliability of the flood wave warning system.

Future studies should also consider the impact the temporary storage of floodwater in designated areas to reduce downstream flooding. Incorporating storage into flood wave models can improve predictions and management strategies. An effect of storage is that it reduces the peak flow of the flood wave by temporarily storing a portion of the floodwater. This can lower the risk of over topping riverbanks and reduce the likelihood of downstream flooding. Researchers should explore methods to include storage by integrating hydrodynamic models and identifying potential storage sites along the river, this will improve reality of the flood wave model.

As for the different methods of enquiring the data of the depth a recommendation, in the context of the Black Volta River, is combining both methods to offer the best results. Manning's equation can be used where detailed data is available, while the Leopold and Maddock method can fill gaps in data-scarce areas, ensuring comprehensive and accurate flood wave predictions.

When deciding between the kinematic wave model and the shallow water wave model for future flood wave studies, it's essential to match the model to the specific characteristics and needs of the study area. the kinematic wave model is ideal for areas with gentle slopes and channels that have significant roughness or vegetation. It is also suitable for floodplain studies and overland flow scenarios where frictional resistance is the dominant factor. The shallow water wave model should be used for regions with steeper slopes and complex flow dynamics, such as those found near dams, reservoirs or sections of the river with sudden drops. A recommendation would again be using a combination of both models, for the Black Volta river the kinematic wave model will be used in most segments as the river mostly has a gentle slope. Some parts of the river however have sudden drops or lots of rocks in the water, changing the flow of the water. Then it could be better to use the shallow water wave model.

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A
Source Code

Listing A.1: Manning's equation and shallow water wave code

```
# Load the Excel file
file_path = 'gegevensBEP.xlsx'  # Update with your actual file path
spreadsheet = pd.ExcelFile(file_path)

# Load the data from the first sheet
data = pd.read_excel(file_path, sheet_name='Blad1')

# Convert the gradient column to its actual value by multiplying with 10^-4
data['verhang␣(10*-4)'] = data['verhang␣(10*-4)'] * 10**-4

# Rename the column to reflect the conversion
data.rename(columns={'verhang␣(10*-4)': 'verhang'}, inplace=True)

# Convert 'Lengte (km)' to meters
data['Lengte␣(m)'] = pd.to_numeric(data['Lengte␣(km)'], errors='coerce') * 1000

# Drop the original 'Lengte (km)' column
data.drop(columns=['Lengte␣(km)'], inplace=True)

Q = 840  # Flow rate in cubic meters per second (example value)
n = 0.045  # Manning's roughness coefficient (example value)

# Calculate depth h for each segment
data['depth␣(m)'] = ((Q * n) / (data['gem␣breedte␣(m)'] * np.sqrt(data['verhang']))) ** (3/5)

g = 9.81  # Acceleration due to gravity in m/s^2
data['celerity␣(m/s)'] = np.sqrt(g * data['depth␣(m)'])

# Calculate travel time for each segment
data['travel_time␣(s)'] = data['Lengte␣(m)'] / data['celerity␣(m/s)']

# Create a cumulative length column in kilometers
data['Cumulative␣Length␣(m)'] = data['Lengte␣(m)'].cumsum()
data['Cumulative␣Length␣(km)'] = data['Cumulative␣Length␣(m)'] / 1000

# Reverse the order to start from the highest length
data = data.iloc[::-1].reset_index(drop=True)

# Plot celerity over the length of the river
plt.figure(figsize=(10, 6))
plt.step(data['Cumulative␣Length␣(km)'], data['celerity␣(m/s)'], where='pre', marker='o')
#plt.title('Celerity Over the Length of the River')
plt.xlabel('Cumulative␣Length␣(km)')
plt.ylabel('Celerity␣(m/s)')
plt.grid(True)
plt.show()

import seaborn as sns

# Plot celerity over the length of the river with a regression line
```

```python
plt.figure(figsize=(10, 6))
sns.regplot(x=data['Cumulative Length (km)'], y=data['celerity (m/s)'], marker='o', scatter_kws={'s':50}, line_kws={'color':'red'})
#plt.title('Celerity Over the Length of the River with Regression Line')
plt.xlabel('Cumulative Length (km)')
plt.ylabel('Celerity (m/s)')
plt.grid(True)
plt.show()

# Define the different values of Manning's coefficient
n_values = [0.02, 0.045, 0.065, 0.085, 0.1]

# Create a plot to show the regression lines for different values of n
plt.figure(figsize=(10, 6))

# Plot the regression lines for each value of n
for n in n_values:
    # Calculate depth h for each segment
    data['depth (m)'] = ((Q * n) / (data['gem breedte (m)'] * np.sqrt(data['verhang']))) ** (3/5)

    # Calculate celerity for each segment
    data['celerity (m/s)'] = np.sqrt(g * data['depth (m)'])

    # Plot the regression line
    sns.regplot(x=data['Cumulative Length (km)'], y=data['celerity (m/s)'], label=f'n = {n}', scatter=False, line_kws={'label':f'n = {n}'})

# Add titles and labels
#plt.title('Regression Lines for Different Values of Manning\'s Coefficient')
plt.xlabel('Cumulative Length (km)')
plt.ylabel('Celerity (m/s)')
plt.grid(True)
plt.legend(title="Manning's n")
plt.show()

# Calculate the total travel time for each Manning's coefficient
travel_times = []

for n in n_values:
    # Calculate depth h for each segment
    data['depth (m)'] = ((Q * n) / (data['gem breedte (m)'] * np.sqrt(data['verhang']))) ** (3/5)

    # Calculate celerity for each segment
    data['celerity (m/s)'] = np.sqrt(g * data['depth (m)'])

    # Calculate travel time for each segment
    data['travel_time (s)'] = data['Lengte (m)'] / data['celerity (m/s)']

    # Calculate total travel time in hours
    total_travel_time_hours = data['travel_time (s)'].sum() / 3600
    travel_times.append(total_travel_time_hours)

# Create a DataFrame to display the results
travel_time_df = pd.DataFrame({
    "Manning's Coefficient (n)": n_values,
    "Total Travel Time (hours)": travel_times
})

# Define the different values of flow rate Q
Q_values = [500, 700, 840, 1000, 1200, 1500]

# Prepare a dictionary to store travel times for each n and Q
travel_time_dict = {n: [] for n in n_values}

# Calculate the travel time for each combination of n and Q
for n in n_values:
    for Q in Q_values:
        # Calculate depth h for each segment
        data['depth (m)'] = ((Q * n) / (data['gem breedte (m)'] * np.sqrt(data['verhang']))) ** (3/5)

```

```
        # Calculate celerity for each segment
        data['celerity␣(m/s)'] = np.sqrt(g * data['depth␣(m)'])

        # Calculate travel time for each segment
        data['travel_time␣(s)'] = data['Lengte␣(m)'] / data['celerity␣(m/s)']

        # Calculate total travel time in hours
        total_travel_time_hours = data['travel_time␣(s)'].sum() / 3600
        travel_time_dict[n].append(total_travel_time_hours)

# Plot the travel time vs discharge for different Manning's coefficients
plt.figure(figsize=(12, 8))

for n in n_values:
    plt.plot(Q_values, travel_time_dict[n], marker='o', label=f'n␣=␣{n}')

#plt.title('Total Travel Time vs Discharge for Different Manning\'s Coefficients')
plt.xlabel('Discharge␣(m/s)')
plt.ylabel('Total␣Travel␣Time␣(hours)')
plt.grid(True)
plt.legend(title="Manning's␣n")
plt.show()
```

Listing A.2: Manning's equation and dynamic wave model

```

#calculating area
data['area␣(m2)'] =  data['depth␣(m)'] * data['gem␣breedte␣(m)']

#calculating celerity
data['celerity␣(m/s)'] = Q / data['area␣(m2)']

# Create a cumulative length column in kilometers
data['Cumulative␣Length␣(m)'] = data['Lengte␣(m)'].cumsum()
data['Cumulative␣Length␣(km)'] = data['Cumulative␣Length␣(m)'] / 1000

# Reverse the order to start from the highest length
data = data.iloc[::-1].reset_index(drop=True)

# Plot celerity over the length of the river
plt.figure(figsize=(10, 6))
plt.step(data['Cumulative␣Length␣(km)'], data['celerity␣(m/s)'], where='pre', marker='o')
#plt.title('Celerity Over the Length of the River')
plt.xlabel('Cumulative␣Length␣(km)')
plt.ylabel('Celerity␣(m/s)')
plt.grid(True)
plt.show()

import seaborn as sns

# Plot celerity over the length of the river with a regression line
plt.figure(figsize=(10, 6))
sns.regplot(x=data['Cumulative␣Length␣(km)'], y=data['celerity␣(m/s)'], marker='o',
    scatter_kws={'s':50}, line_kws={'color':'red'})
#plt.title('Celerity Over the Length of the River with Regression Line')
plt.xlabel('Cumulative␣Length␣(km)')
plt.ylabel('Celerity␣(m/s)')
plt.grid(True)
plt.show()

# Define the different values of Manning's coefficient
n_values = [0.02, 0.045, 0.065, 0.085, 0.1]

# Create a plot to show the regression lines for different values of n
plt.figure(figsize=(10, 6))

# Plot the regression lines for each value of n
for n in n_values:
    # Calculate depth h for each segment
    data['depth␣(m)'] = ((Q * n) / (data['gem␣breedte␣(m)'] * np.sqrt(data['verhang']))) **
        (3/5)

    data['area␣(m2)'] =  data['depth␣(m)'] * data['gem␣breedte␣(m)']

```

```
    # Calculate celerity for each segment
    data['celerity (m/s)'] = Q / data['area (m2)']

    # Plot the regression line
    sns.regplot(x=data['Cumulative Length (km)'], y=data['celerity (m/s)'], label=f'n = {n}',
        scatter=False, line_kws={'label':f'n = {n}'})

# Add titles and labels
#plt.title('Regression Lines for Different Values of Manning\'s Coefficient')
plt.xlabel('Cumulative Length (km)')
plt.ylabel('Celerity (m/s)')
plt.grid(True)
plt.legend(title="Manning's n")
plt.show()

# Calculate the total travel time for each Manning's coefficient
travel_times = []

for n in n_values:
    # Calculate depth h for each segment
    data['depth (m)'] = ((Q * n) / (data['gem breedte (m)'] * np.sqrt(data['verhang']))) **
        (3/5)

    data['area (m2)'] =  data['depth (m)'] * data['gem breedte (m)']

    # Calculate celerity for each segment
    data['celerity (m/s)'] = Q / data['area (m2)']

    # Calculate travel time for each segment
    data['travel_time (s)'] = data['Lengte (m)'] / data['celerity (m/s)']

    # Calculate total travel time in hours
    total_travel_time_hours = data['travel_time (s)'].sum() / 3600
    travel_times.append(total_travel_time_hours)

# Create a DataFrame to display the results
travel_time_df = pd.DataFrame({
    "Manning's Coefficient (n)": n_values,
    "Total Travel Time (hours)": travel_times
})

# Define the different values of flow rate Q
Q_values = [500, 700, 840, 1000, 1200, 1500]

# Prepare a dictionary to store travel times for each n and Q
travel_time_dict = {n: [] for n in n_values}

# Calculate the travel time for each combination of n and Q
for n in n_values:
    for Q in Q_values:
        # Calculate depth h for each segment
        data['depth (m)'] = ((Q * n) / (data['gem breedte (m)'] * np.sqrt(data['verhang'])))
            ** (3/5)

        data['area (m2)'] =  data['depth (m)'] * data['gem breedte (m)']

        # Calculate celerity for each segment
        data['celerity (m/s)'] = Q / data['area (m2)']

        # Calculate travel time for each segment
        data['travel_time (s)'] = data['Lengte (m)'] / data['celerity (m/s)']

        # Calculate total travel time in hours
        total_travel_time_hours = data['travel_time (s)'].sum() / 3600
        travel_time_dict[n].append(total_travel_time_hours)

# Plot the travel time vs discharge for different Manning's coefficients
plt.figure(figsize=(12, 8))

for n in n_values:
    plt.plot(Q_values, travel_time_dict[n], marker='o', label=f'n = {n}')

#plt.title('Total Travel Time vs Discharge for Different Manning\'s Coefficients')
```

```python
plt.xlabel('Discharge␣(m/s)')
plt.ylabel('Total␣Travel␣Time␣(hours)')
plt.grid(True)
plt.legend(title="Manning's␣n")
plt.show()
```

Listing A.3: Leopold and Maddock and shallow water wave

```python
import pandas as pd
import matplotlib.pyplot as plt
import numpy as np

# Load the Excel file
file_path = 'gegevensBEP.xlsx'  # Update with your actual file path
spreadsheet = pd.ExcelFile(file_path)

# Load the data from the first sheet
data = pd.read_excel(file_path, sheet_name='Blad1')

# Convert the gradient column to its actual value by multiplying with 10^-4
data['verhang␣(10*-4)'] = data['verhang␣(10*-4)'] * 10**-4

# Rename the column to reflect the conversion
data.rename(columns={'verhang␣(10*-4)': 'verhang'}, inplace=True)

# Convert 'Lengte (km)' to meters
data['Lengte␣(m)'] = pd.to_numeric(data['Lengte␣(km)'], errors='coerce') * 1000

# Drop the original 'Lengte (km)' column
data.drop(columns=['Lengte␣(km)'], inplace=True)

Q = 840  # Constant discharge in m³/s
d_1 = 12.25  # Known depth in meters
w_1 = 150  # Known width in meters

# Widths for other segments
widths = data['gem␣breedte␣(m)']  # widths in meters

# Empirical exponents
b = 0.5
f = 0.4

# Calculate coefficients a and c
a = w_1 / Q**b
c = d_1 / Q**f

# Calculate depths for other segments
depths = []
for w_i in widths:
    d_i = c * (w_i / a)**(f/b)
    depths.append(d_i)
    #print(f"Segment with width {w_i} m has a calculated depth of {d_i:.2f} m")

data['depth␣(m)'] = depths

g = 9.81  # Acceleration due to gravity in m/s^2
data['celerity␣(m/s)'] = np.sqrt(g * data['depth␣(m)'])

# Calculate travel time for each segment
data['travel_time␣(s)'] = data['Lengte␣(m)'] / data['celerity␣(m/s)']

# Create a cumulative length column in kilometers
data['Cumulative␣Length␣(m)'] = data['Lengte␣(m)'].cumsum()
data['Cumulative␣Length␣(km)'] = data['Cumulative␣Length␣(m)'] / 1000

# Reverse the order to start from the highest length
data = data.iloc[::-1].reset_index(drop=True)

# Plot celerity over the length of the river
plt.figure(figsize=(10, 6))
plt.step(data['Cumulative␣Length␣(km)'], data['celerity␣(m/s)'], where='pre', marker='o')
#plt.title('Celerity Over the Length of the River')
plt.xlabel('Cumulative␣Length␣(km)')
plt.ylabel('Celerity␣(m/s)')
```

```
plt.grid(True)
plt.show()

import seaborn as sns

# Plot celerity over the length of the river with a regression line
plt.figure(figsize=(10, 6))
sns.regplot(x=data['Cumulative Length (km)'], y=data['celerity (m/s)'], marker='o',
    scatter_kws={'s':50}, line_kws={'color':'red'})
#plt.title('Celerity Over the Length of the River with Regression Line')
plt.xlabel('Cumulative Length (km)')
plt.ylabel('Celerity (m/s)')
plt.grid(True)
plt.show()

#total travel time
data['travel_time (s)'].sum() / 3600
```

Listing A.4: Leopold and maddock and kinematic wave model

```

# Load the Excel file
file_path = 'gegevensBEP.xlsx'  # Update with your actual file path
spreadsheet = pd.ExcelFile(file_path)

# Load the data from the first sheet
data = pd.read_excel(file_path, sheet_name='Blad1')

# Convert the gradient column to its actual value by multiplying with 10^-4
data['verhang (10*-4)'] = data['verhang (10*-4)'] * 10**-4

# Rename the column to reflect the conversion
data.rename(columns={'verhang (10*-4)': 'verhang'}, inplace=True)

# Convert 'Lengte (km)' to meters
data['Lengte (m)'] = pd.to_numeric(data['Lengte (km)'], errors='coerce') * 1000

# Drop the original 'Lengte (km)' column
data.drop(columns=['Lengte (km)'], inplace=True)

Q = 840  # Constant discharge in m³/s
d_1 = 12.25  # Known depth in meters
w_1 = 150  # Known width in meters

# Widths for other segments
widths = data['gem breedte (m)']  # widths in meters

# Empirical exponents
b = 0.5
f = 0.4

# Calculate coefficients a and c
a = w_1 / Q**b
c = d_1 / Q**f

# Calculate depths for other segments
depths = []
for w_i in widths:
    d_i = c * (w_i / a)**(f/b)
    depths.append(d_i)
    #print(f"Segment with width {w_i} m has a calculated depth of {d_i:.2f} m")

data['depth (m)'] = depths

#calculating the area
data['area (m2)'] =  data['depth (m)'] * data['gem breedte (m)']

#calculating the celerity
data['celerity (m/s)'] = Q / data['area (m2)']

# Create a cumulative length column in kilometers
data['Cumulative Length (m)'] = data['Lengte (m)'].cumsum()
data['Cumulative Length (km)'] = data['Cumulative Length (m)'] / 1000

```

```
# Reverse the order to start from the highest length
data = data.iloc[::-1].reset_index(drop=True)

# Plot celerity over the length of the river
plt.figure(figsize=(10, 6))
plt.step(data['Cumulative Length (km)'], data['celerity (m/s)'], where='pre', marker='o')
#plt.title('Celerity Over the Length of the River')
plt.xlabel('Cumulative Length (km)')
plt.ylabel('Celerity (m/s)')
plt.grid(True)
plt.show()

import seaborn as sns

# Plot celerity over the length of the river with a regression line
plt.figure(figsize=(10, 6))
sns.regplot(x=data['Cumulative Length (km)'], y=data['celerity (m/s)'], marker='o',
    scatter_kws={'s':50}, line_kws={'color':'red'})
#plt.title('Celerity Over the Length of the River with Regression Line')
plt.xlabel('Cumulative Length (km)')
plt.ylabel('Celerity (m/s)')
plt.grid(True)
plt.show()

# Calculate travel time for each segment
data['travel_time (s)'] = data['Lengte (m)'] / data['celerity (m/s)']
data['travel_time (s)'].sum() / 3600
```