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Simulation of Flood Propagation from the Niandouba Dam Outlet (Kayanga River, Senegal) to the Waïma Lake Inlet Using HEC RAS for Water Resource Management in the Anambé Irrigated Perimeters

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Abstract: Dams are designed for water storage intended to compensate downstream fluctuations that are stabilizing water supply and hydropower production. Hydraulic modelling tools and schemes allow understanding the hydraulic characteristics of the irrigation systems and mitigating uncertainty inherent to dam removals. The construction of the Niandouba dam at the confluence of the Kayanga and Anambé rivers (Senegal) has perturbed the natural flow of the Anambé River to feed the Waïma Lake and irrigated perimeters. The flow gauges at the Kayanga and Anambé Rivers are no longer operational. In this study, the HEC-RAS (Hydrological Engineering Centre River Analysis System) and the RAS Mapper is used to simulate the flow propagation of the Kayanga-Anambé hydraulic system ranging from the Niandouba dam to the entry of Waïma lake. The HEC-RAS modelling enables the estimating of, among other variables, water levels, depths and flow velocities for the different flow configurations and different cross-sectional zones. This study presents a flood mapping of the Kayanga-Anambé hydro system using the RAS Mapper and HEC-RAS hydraulic modelling tools. The study has exhibited the depths at the inlet of the supply channels where the pumping stations are located.

Key words: HEC-RAS, RAS Mapper, hydraulic models, irrigation, Kayanga/Anambé, dams.

1. Introduction

Competition among different water practices has been enhanced more than twice according to the increasing of the population over the last century. Then, frequent conflicts are noticed in the precedence of water practices. Water use for irrigation is about 70% of the worldwide available freshwater and has retained in many countries, as one of the activities using the more important part of the available freshwater. Molden [1] found that, at soon, the water available for agricultural production will be considerably reduced because of the competition in the water uses. Consequently, food production will have to be increased to feed the all the population in the world that is estimated at 81 million per year [2]. It has been estimated that the world will need to feed 1.5 to 2 billion extra people by 2025 [3]. Considering the hard decrease of the availability for irrigation and the ever-increasing population, the agricultural sector will indubitably face serious challenges in producing enough food with the available freshwater [4, 5]. Since water from rainfall is not available during all periods in a year, dams appear as an interesting alternative to control the available water. A dam is a massive barrier built across rivers and streams to confine the water and for specific applications in the duration. There are many reasons to build a dam: hydropower production, control of flooding either to stop or to reduce the amount of water in a river system,

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irrigation support by deviating the natural course towards the different irrigation channels. In irrigation channels, water needs to be controlled and hydrodynamic models appear as well-used tools. In these models, the program solves the conservation laws of the fluid mechanics to simulate flood events for planning, and risk assessment [6]. The Saint-Venant fundamental equations (or Saint-Tenant's principle), first presented in 1871, represent a complete approach for modelling the flow in the hydrodynamic models. Analytic resolving of Saint-Venant equations, especially in canals network or in open channels with irregular sections is very complex so it is compulsory to use computer programs and software [7] and HEC-RAS (Hydrological Engineering Centre River Analysis System) is one of them. The HEC-RAS model is a software widely used around the world in many hydraulic and hydrological studies. Mohamad Faudzi [8] applied a 2D (Two-Dimensional) resolution to simulate the water discharge, downstream the SAB (Sultan Abu Bakar) dam and found that HEC-RAS is more convenient for simulating the SAB dam release in 2D according to all of the related criteria. Logah [6] used version 5.0 of the HEC-RAS model (U.S. Army Corps of Engineers, 2016) for the hydrodynamic modelling of the Lower Volta River and its floodplain to assess the extent of flooding that could occur from dam releases under various scenarios relevant to dam manipulation. In this paper, the HEC-RAS is applied in the Kayanga/Anambe river system, downstream the Niandouba Dam to simulate the steady behaviour of flow released from the Niandouba Dam. This dam is designed to supply water for the Anambe irrigated perimeters. The results from this study are intended to help authorities in the management of the Katanga Anambe Hydro system.

2. Material and Methods

2.1 Area of Study

2.1.1 Kayanga Anambé River Basin

The area of study is the part of the Kayanga-Anambé watershed located upstream of the Confluent dam (Fig.1) covering an area of 6,596 km^2. It extends between latitudes 12°31′ and 13°09′ North and longitudes 13°20′ and 14°26′ West [9]. The Kayanga-Anambé hydraulic system consists of the Niandouba dam, the Confluent dam, the Kounkané bridge, and the irrigated perimeters of Anambé [10].

2.1.2 The Kayanga Anambe Hydro System

The river system consists of two main rivers, the Kayanga River and the Anambe one. The system accumulates water flows by gravity towards the ocean in Guinea Bissau. Waïma Lake is a freshwater reservoir that flows naturally to the Anambe [11]. To supply water to irrigation of the rice-growing areas of the Anambé valley, a dam has been built at the confluence of the Anambé and Kayanga rivers. This dam is so-called the Confluent dam. This dam impedes the flow to run towards Guinea Bissau by gravity. Another dam referred to as the Niandouba dam, has also been built on the Kayanga river. The aforesaid dam stores the runoff from Kayanga [12]. The Kounkané bridge completes the hydraulic system (Fig. 2). Thus, this bridge causes a deviation of the natural course of the Anambé river for supplying the Lake Waïma on the one hand, and on the other hand, water for the irrigation of the Anambé rice-growing areas.

The hydrological behaviour of the Kayanga-Anambé system is relatively simple and purely gravitational: the confluence reservoir, which receives the water from the Niandouba dam, fills upon gravity by the Lake Waïma which also receives the runoff from the surrounding basin. In the period of low flows, a part of the water is trapped in Lake Waïma according to the threshold of the Kounkané Bridge which deviates the downstream flow towards the Kayanga [13].

2.1.3 Irrigation Network

The total irrigated area covering the various perimeters of the Anambé valley (Fig. 3) is supplied by a hydraulic system which consists of the Confluent (available volume of about 48 millionm^3) and the

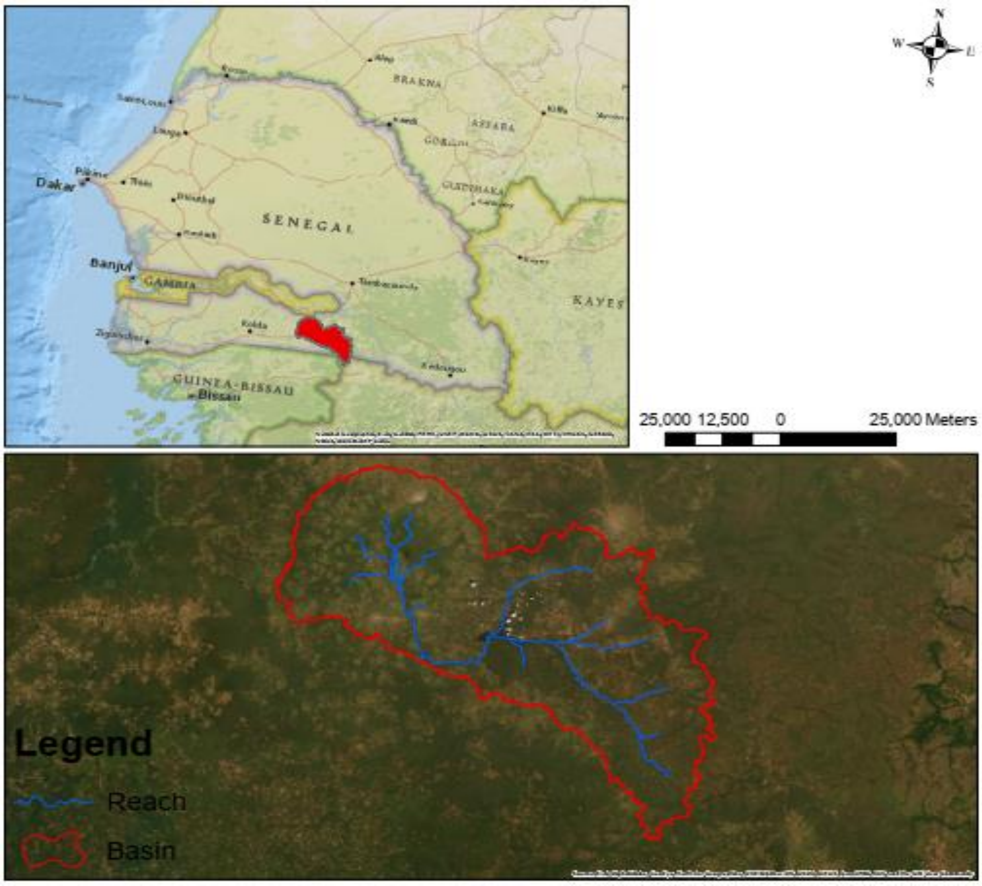


Fig. 1 Study area of the Kayanga-Anambé river basin.

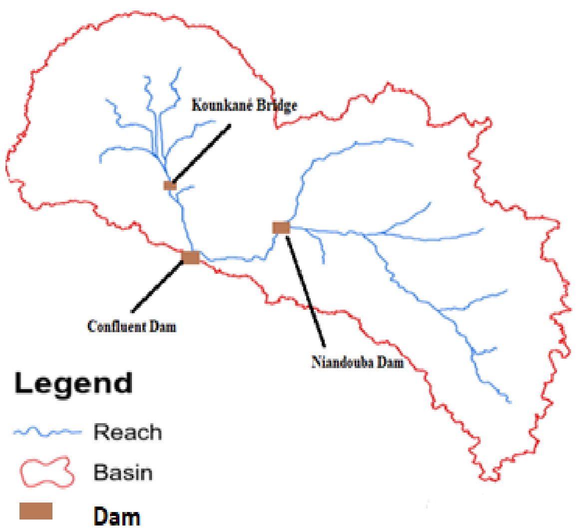


Fig. 2 Kayanga-Anambe basin hydro system.

Niandouba dams (available volume of about 75 million m^3), respectively built in 1984 and 1997 [14]. The irrigation area covers a spread of 4,170 hectares divided into 6 sectors and 5 pumping stations. Each of the pumping stations (pumping station A, pumping station 4, pumping station 5, and pumping station G operates with 2 submerged electro-pumps, run by soundproof enclosure generators. The SP3 station is composed of 2 motor pumps with 4-cylinder diesel engines, installed on a concrete platform without shelter or handling equipment [15]. The development plan is almost identical for all sectors, although each of them has some variations according to the topographical characteristics of the considered sector. The above scheme ensures the linearity of the involved channels. It has been noticed that the linear ratios of the secondary and tertiary channels surfaces vary little from one sector to another [16].

2.1.4 HEC-RAS Model

The HEC-RAS is a numerical software used in the calculation of river flow, developed by the U.S. Army Corps of Engineers Centre in 1995 [17, 18]. It is run

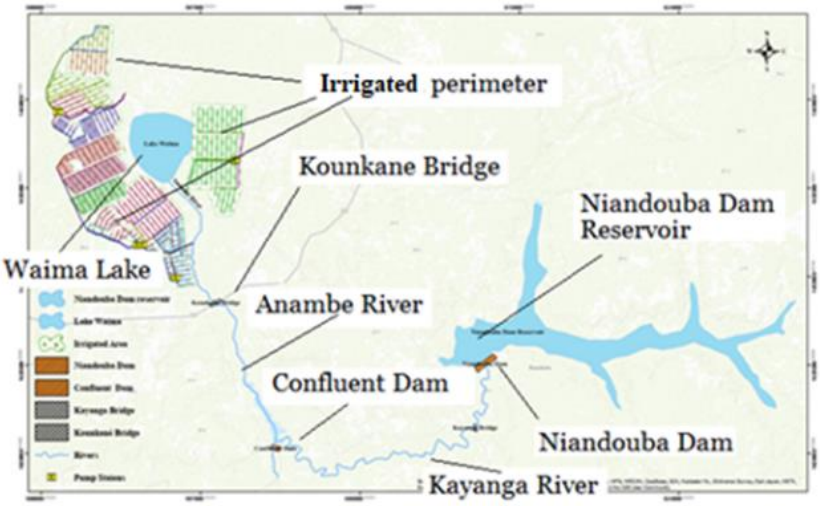


Fig. 3 An irrigated network of the Kayanga-Anambé hydraulic system.

either in one or two dimensions, at transitory or permanent fluvial laws in natural channels or channel network [19]. It calculates subcritical, supercritical, and mixed regime law, water surface profiles from one cross-section to a follower using the equation of energy [20]. The equation of energy is numerically computed through a well-known standard discrete method. Between two given cross-sections, the equation given the energy balance (Eq.(1)) is defined as following [21-24]:

$$Y_2 + Z_2 + \alpha_2 \frac{V_2^2}{2g} = Y_1 + Z_1 + \alpha_1 \frac{V_1^2}{2g} + H_L \qquad (1)$$

where, Y_1, Y_2: cross-section's water depths; Z_1, Z_2: cross-section's bed elevations; V_1; V_2: the mean velocity on the level of the sections; α_1, α_2: weighting coefficient of the velocity and H_L: energy head loss.

The method used to calculate the longitudinal profile of the waterline between two control sections of a river is called the Standard Step Backwater Method (Fig. 4). If, in a river, the flow is fluvial, there is always a univocal relationship between the elevation of the water line in the downstream control section and the elevation of any other intermediate section of the reach. If the section is in torrential regime (Froude number greater than 1), the relation exists between the upstream control section and the intermediate sections.

The characteristics A and h of the control section can be calculated, for a determined flow, independently of the rest of the section with the critical flow condition equation (Eq. (2)):

$$Q = A\sqrt{gh} \qquad (2)$$

Where,

A = section area, $A = bh$,

b = mirror width,

h = average depth Therefore.

The control section will be the starting point for the calculation of the backwater method, the progression of the calculations will be upstream or downstream, depending on whether the flow regime of the reach will be fluvial or torrential.

The Standard Step Method uses the Energy Balance Equation (Eq.(1)) to calculate the water surface. This approach allows getting information of water surface elevation of an upper section (upstream) using the one from a preceding section (downstream). in this procedure, discharge, roughness of these cross sections is assumed to be already set. Generally, the assumption of subcritical flow is very useful for engaging the simulation process [27]. It is important to notice that subsequent tasks are involved in the process:

we determine the elevation of a target starting water surface and for subcritical flow start with the most downstream cross-section.

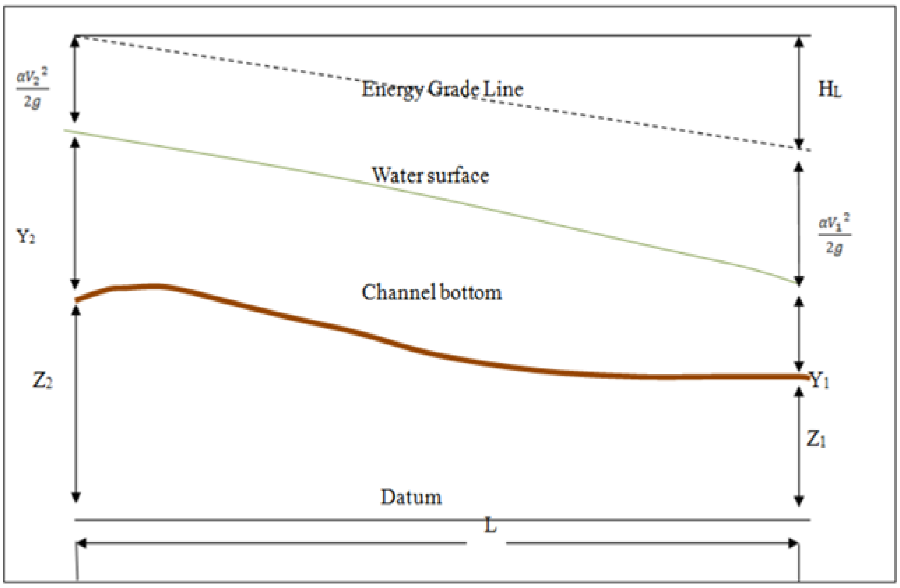


Fig.4 Illustration of water surface profiles and energy lines between two points.

Considering Eq. (1) and Fig. 4, we use the downstream water surface and the first section to calculate the related variables: Y_1, Z_1, α_1 and V_1.

After the energy head loss $H_L$is calculate using the following equation (Eq.(3)):

$$H_L = L\bar{S}_f + C\left|\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right| \quad (3)$$

The energy balance is assessed using the following equations.

$$L = Y_2 + Z_2 + \alpha_2 \frac{V_2^2}{2g} \quad (4)$$

$$R = Y_1 + Z_1 + \alpha_1 \frac{V_1^2}{2g} + H_L \quad (5)$$

Eqs. (4) and (5) are used under the following considerations: if $L = R$ within a reasonable tolerance, then the assumed depth of the upstream section is assigned to be the calculated water surface depth of the considering section. if $L \neq R$, go back to the step of calculation of Y_1, Z_1, α_1 and V_1 and use another estimated depth.

Last, we determine the critical depth of the cross-section and calculate the uniform depth using Eq. (2). However, when running a supercritical simulation, profile leads to a critical depth greater than the uniform one. For subcritical flow, the procedure is similar but the calculations must begin at the upstream section and propagate towards the downstream section.

The process is repeated until all of the sections are covered along a considered reach.

2.1.5 Model Setup

RAS Mapper in HEC-RAS is used to set a 1D (One Dimensional) hydraulic modelling of the Kayanga-Anambé river Hydro system. The free software HEC-RAS, version 5.0.7 (https://www.hec.isace.army.mil/software/hec-ras/) has been used. The HEC-RAS runs using terrain in format TIN (Triangulated irregular network) or DEM (Digital Elevation Model) to implement the hydraulic model [19]. In addition, we can add the land-use information. Torun model, a project has to be created after starting HEC-RAS. The system coordinates are set by the RAS Mapper involving an ESRI (Environmental Systems Research Institute) projection file. Then, the DEM is imported into the RAS Mapper. The range of information describing the river and its floodplains are inserted into different datasets needed to perform the HEC-RAS hydraulic simulation. The central line of the river is digitized to establish the river reach network for the HEC-RAS running [28]. On the screen, the river centerline is aligned according to the flow direction. The bank lines are digitized to separate the main channel from the overbank flood plain areas. The flow paths are represented by lines towards the river reaches, along the left overbank, the main channel, and the right overbank. The line of the reach along the main channel nearly corresponds to the river centerline. The required number of cross-sections needed to create a good representation of the main channel and floodplain is defined. The intersection of the cross-sections with the centerline and flow path lines allows computing the HEC-RAS attributes such as the bank stations and the manning coefficient. Cross-sections are drawn perpendicularly to the flow direction. They also must span over the entire flood river extent in modelling. Cross-sections are designed from the left to the right (forward the downstream) and must intersect on one hand both the centerline and the bank lines and on other hand the flow paths [29].

3. Results and Discussion

3.1 DEM Terrain

The raster data are structured as a rectangular mesh of points joined by lines, creating a grid of square uniform grids. A representation of the earth surface in the raster is referred to as the DEM [28]. The digital elevation models of the area of study have been extracted from the website https://earthexplorer.usgs.gov/ of the USGS (United States Geological Survey). The USGS has developed research-quality, steady scientific applications (Level 2, and Level 3) using Landsat data of Level1. It important to notice that the Scientific Products of Landsat Available provided by the Landsat 4-5 TM (Thematic Mapper) and the range of Landsat Water Surface Dynamics are generated by the U.S. Landsat ARD (Analysis Ready Data) and the Surface Reflectance data. The DEM allows the analysis of the drainage profiles upon the land [30]. The DEM of the studied area from the RAS Mapper is shown in Fig. 5. In practice, it is important to define the coordinate system in the RAS Mapper before joining the DEM. For implementing process, all datasets should be in the same coordinate system. Further, the DEM of the zone is imported into the RAS Mapper. The hydro system DEM through the RAS Mapper is shown in Fig. 5.

3.2 River Centerline, Bank Lines, Flow Paths

The centerline, bank lines, flow paths of the river are very important hydraulic characteristics. For the Kayanga-Anambe river ranging from Niandouba Dam

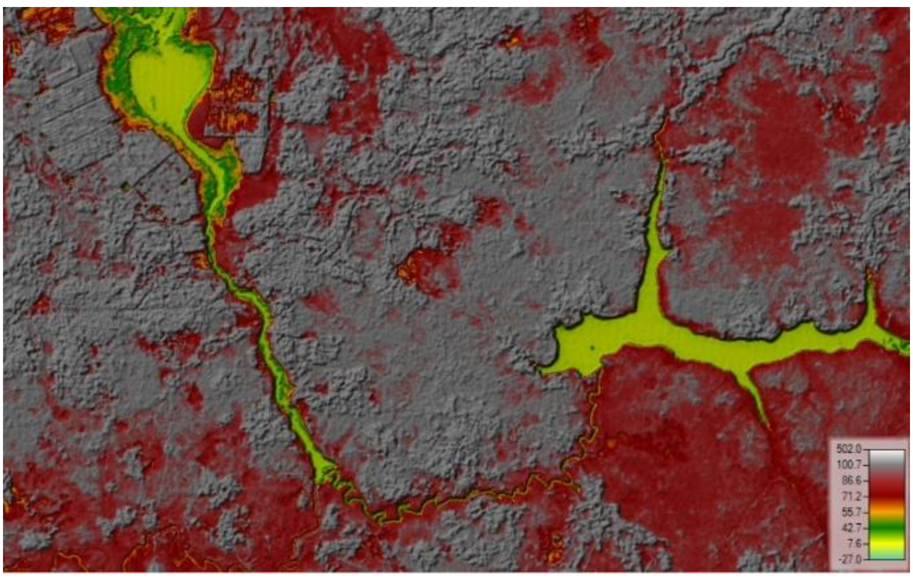


Fig. 5 DEM of the area of study.

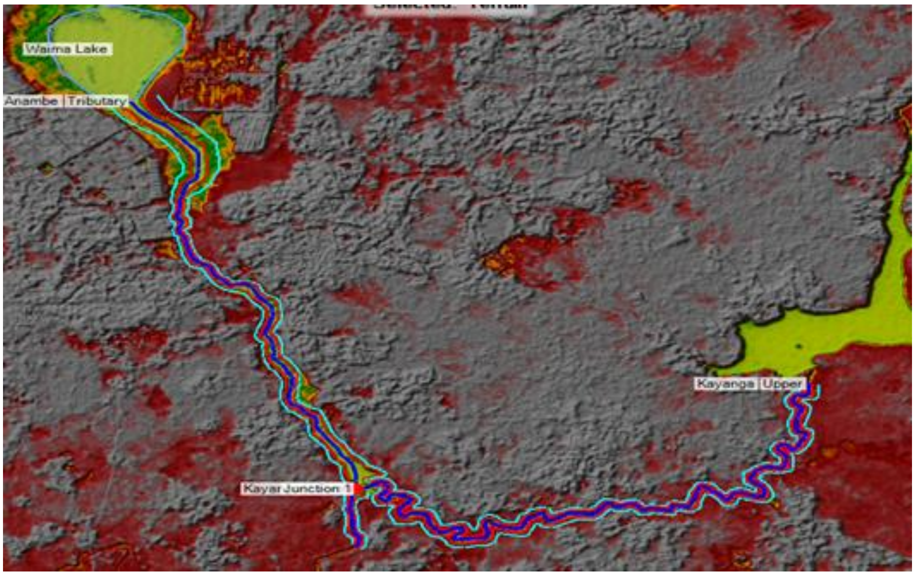


Fig. 6 Centerline, bank line, flow paths.

to Confluent Dam on one hand and from Confluent Dam to the Waïma Lake, hydraulic characteristics are shown in Fig. 6. It has been obtained using the digitalizing methods. Centerlines are represented in blue lines, bank lines in red and flow paths in green.

Centerline digitized one feature of each reach. It approximately fits the center of the river and oriented towards the flow direction [29]. When digitizing the river centerline, we start from the upstream extremity of the upper Kayanga River reach, towards the downstream until we reach the intersection/junction with the Anambe River. After we start the digitizing of the Anambe River (Tributary) from its upstream extremity towards the junction with the Upper Kayanga River reach. Finally, we digitize the lower Kayanga River reach from junction with the Anambe River (Tributary) to the lower downstream extremity point of the Kayanga River. Note that the HEC-RAS automatically creates a junction by connecting the three reach centerlines.

The bank lines are used to distinguish the main channel of the overbank floodplain areas [19]. Information related to the bank locations gives different properties for cross-sections. For example, in comparison to the main channel, higher Manning's *n* values, accounting for more roughness caused by vegetation, are attributed to the overbank areas. The bank lines digitizing process are the same as channel centerline. In this case of study, the left bank is first digitized, then the right bank.

The flow paths are used to determine the downstream reach along the left overbank, the main channel, and the right overbank [31]. For the left and right overbanks, the digitizing follows the left and right flow paths respectively. All the digitizing lines of the area are presented in the Fig. 6.

3.3 Creating Cross-Sections

Cross-sections are one of the key inputs of the HEC-RAS. They are used to extract the data of the terrain elevations to create a ground profile across channel flow [32]. The cross-sections are generated perpendicularly to the flow direction. They must be extended over the entire width of the flood to be modelled. They are always plotted from left to right and downwards. Finally, each cross-section should intersect the centerline, bank lines, and flow paths. The intersection of the cross-sections with other RAS layers is used to compute HEC-RAS attributes such as bank stations, lengths of downstream reach, and Manning's *n*. Fig. 7 indicates cross-sections from the Niandouba Dam to the Waïma Lake.

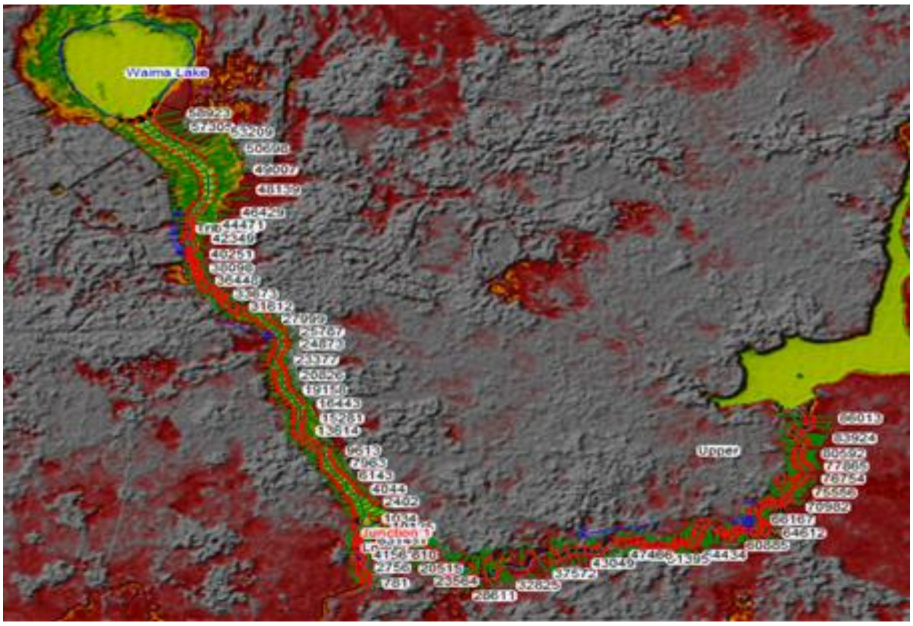


Fig. 7 Cross-sections from Niandouba Dam to the Waïma Lake.

3.4 Simulation of the Steady Flow

3.4.1 Manning Coefficient and Slope Setting

In practice, the Manning coefficients are based on observed flows. In this work, no measured data has been used. However, some values found in the literature were choose [20]: 0.06 for the left bank, 0.035 for the minor bed, and 0.05 for the right bank. To define downstream boundary conditions before engaging the HEC-RAS model, a normal depth of about 0.01 has been chosen. Normal depth is directly obtained through the geometric section of the associated DEM.

3.4.2 Steady Flow Characteristics

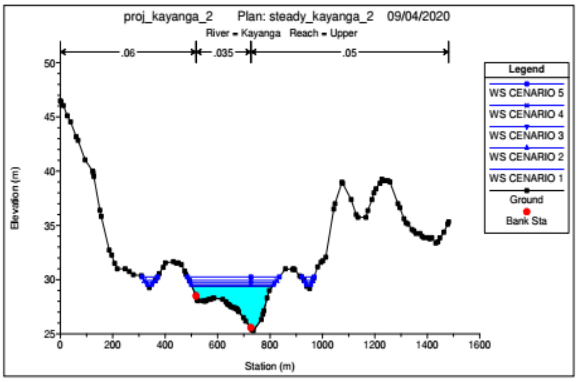
The operational releases from Niandouba Dam are about 8 m^3/s. In this study, the propagation of four other releases from the Niandouba dam (4 m^3/s, 16 m^3/s, 32 m^3/s, 64 m^3/s) is done, in addition to the operational. The parameters have been calculated from the downstream, determining the choice of the boundary condition. In this study about a natural stream, the hydraulic depth of cross-sections, the longitudinal of water surface elevations, the velocity, and the flood per area were studied for the different flow releases.

3.4.2.1 Cross-Section and Longitudinal Surface Water Profile

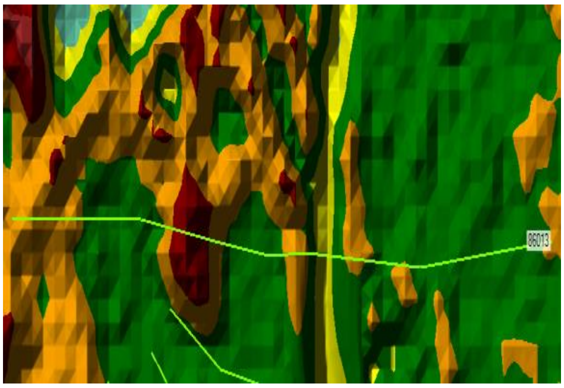
Cross-section elevation profiles are extracted from the DEM. Other cross-section properties are extracted based on their intersection with the other layers.

The cross-sections XS-86013 and XS-9400 of the Upper Kayanga are presented in Fig. 8 (Niandouba dam). In Fig. 9, longitudinal surface water profiles between the cross-sections XS-86013 and XS-9400 of the Upper Kayanga river are shown. Figs. 10 and 11 illustrate the cross-sections XS-58854 (at the entrance of Lake Waïma) and XS-1034 and longitudinal surface water profiles of the Anambe river (tributary). Further, the design of the Lower Kayanga river cross-sections (XS-7356 (Confluent dam) and XS-162) and longitudinal surface water profiles are represented in Figs. 12 and 13. The above cross-sections correspond to ones of the upstream and downstream rivers (Upper and lower Kayanga, Anambe), respectively.

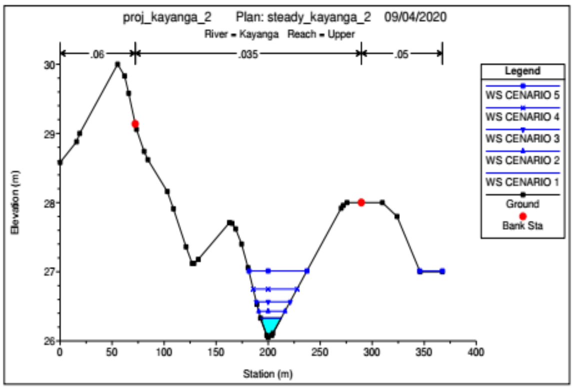
It is important to notice that the flow regimes of longitudinal profiles of the surface water are different from a river to another. For the Upper Kayanga river, the regime varies gradually with the presence of alternative torrential and fluvial regimes. However, the lower Kayanga river shows a torrential regime.



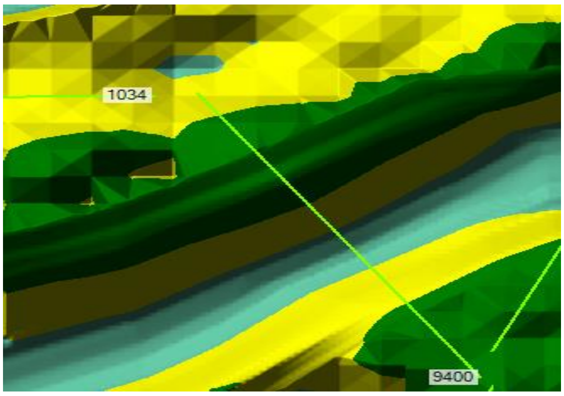
(a) Cross section XS-86013



(a') Cross section XS-86013



(b) Cross section XS-9400



(b') Cross section XS-9400

Fig. 8 Cross-section of the upstream ((a) and (a')) and downstream ((b) and (b')) of Upper Kayanga River.

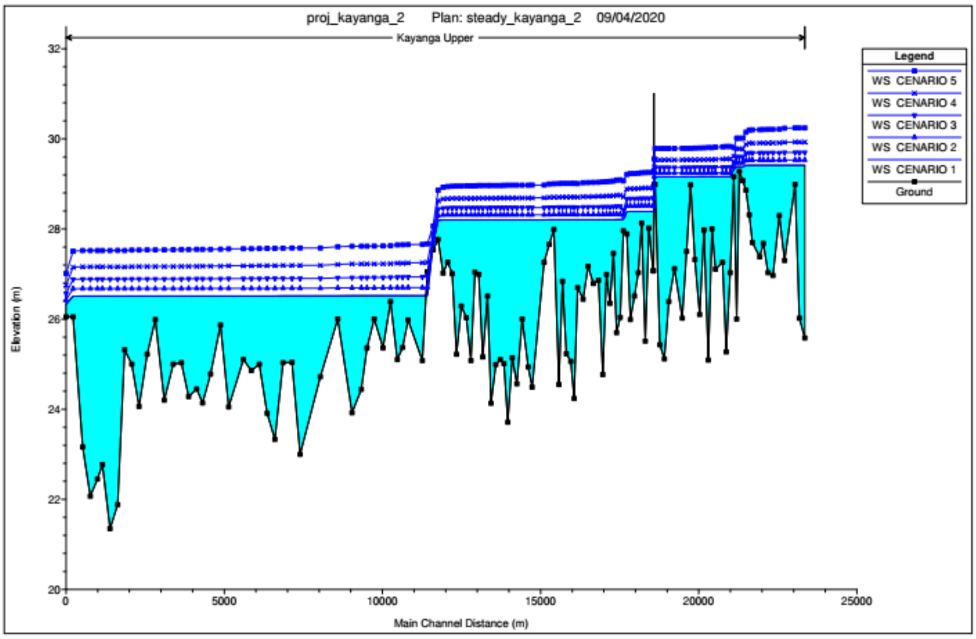
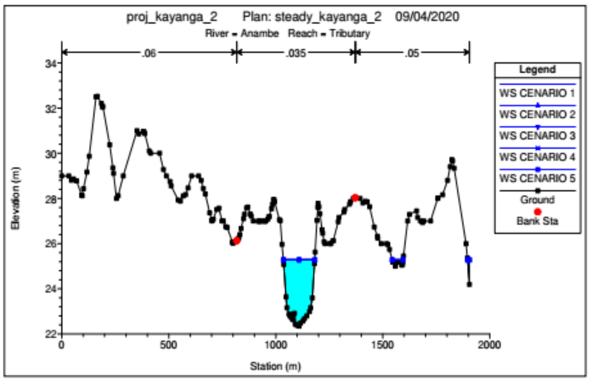
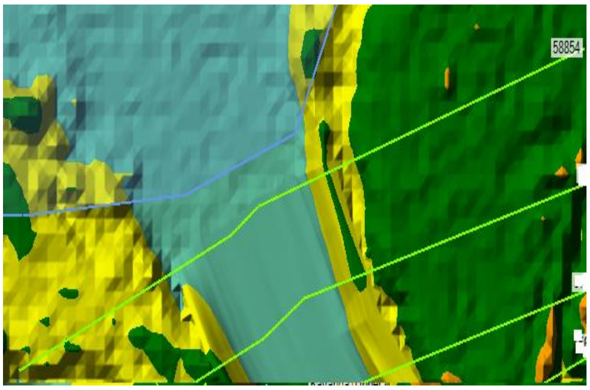
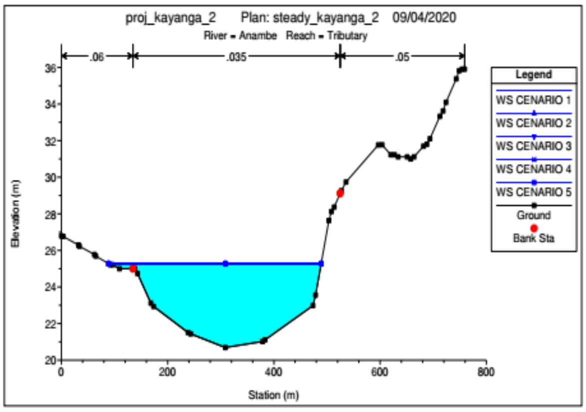


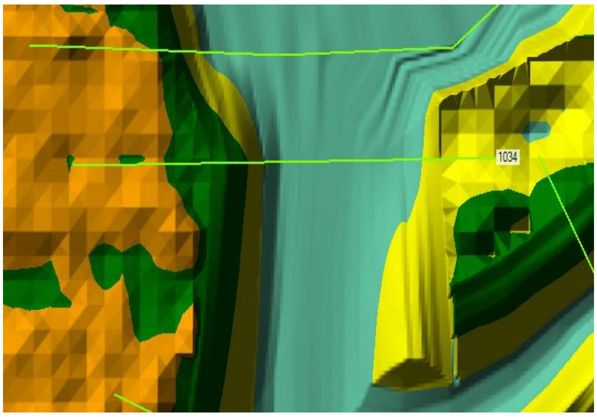
Fig. 9 Longitudinal surface water profile of the Upper Kayanga River.





(a) Cross sections XS-58854 *(a') Cross sections XS-58854*





(b) Cross sections XS-1034 *(b') Cross sections XS-1034*

Fig. 10 Cross-section of the upstream ((a) and (a')) and downstream ((b) and (b')) of Anambé tributary River.

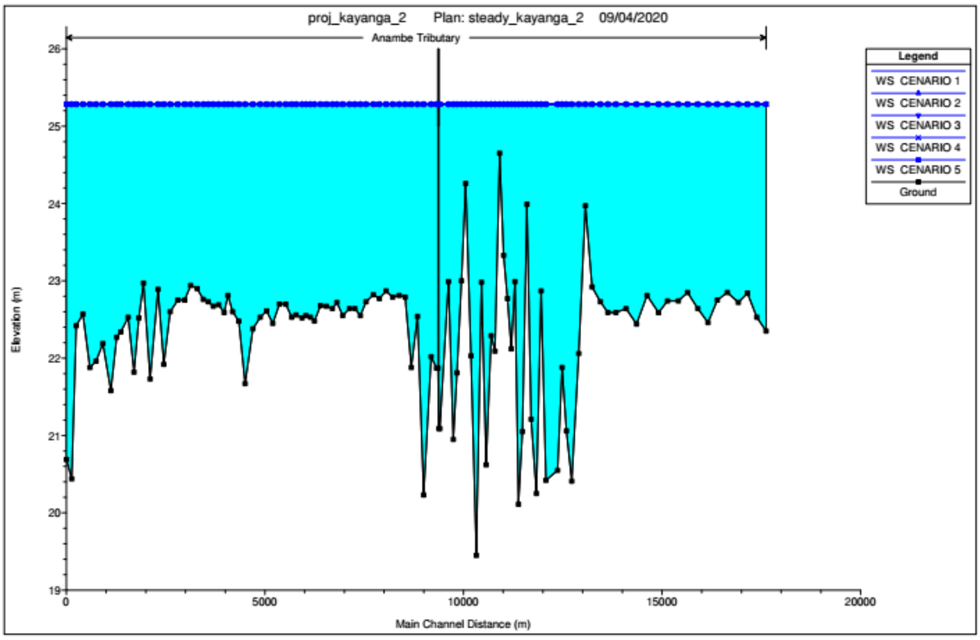
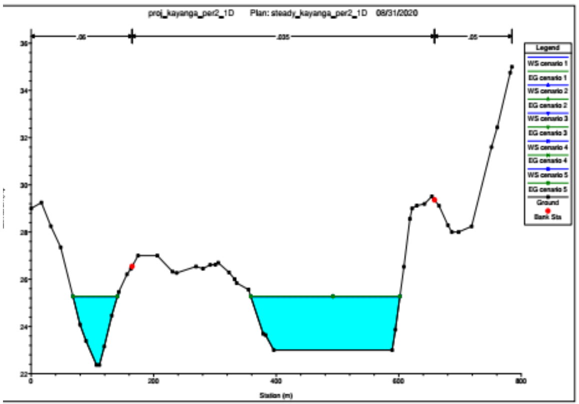
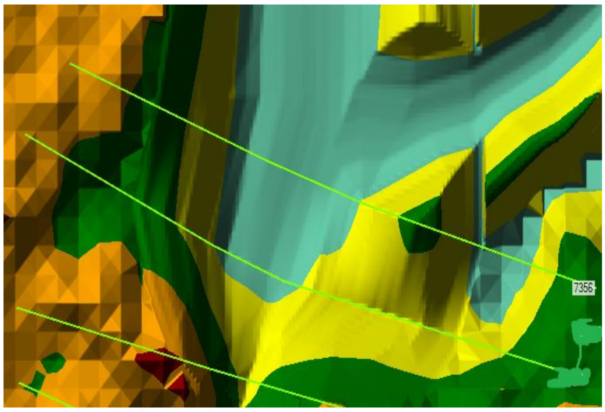


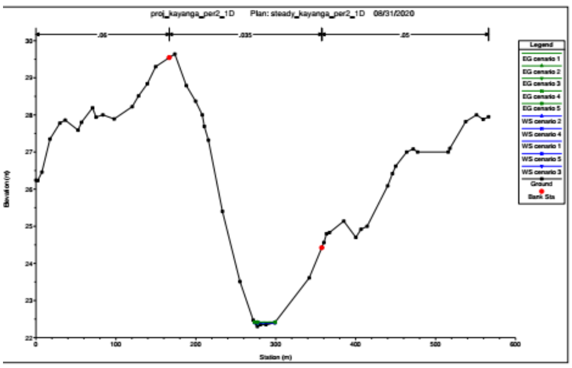
Fig. 11 Longitudinal surface water profile of the Anambé tributary River.



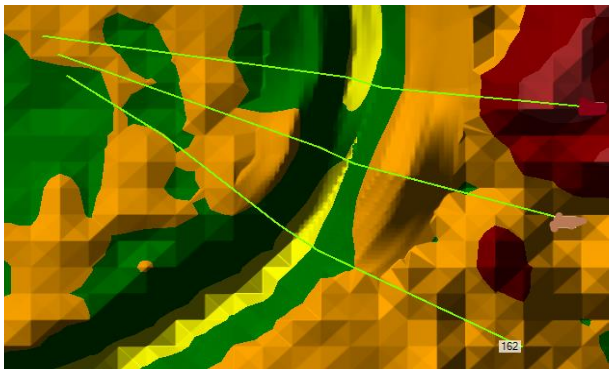
(a) Cross sections XS-7356



(a') Cross sections XS-7356



(b) Cross sections XS-162



(b') Cross sections XS-162

Fig. 12 Cross-section of the upstream ((a) and (a')) and downstream ((b) and (b')) of Lower Kayanga River.

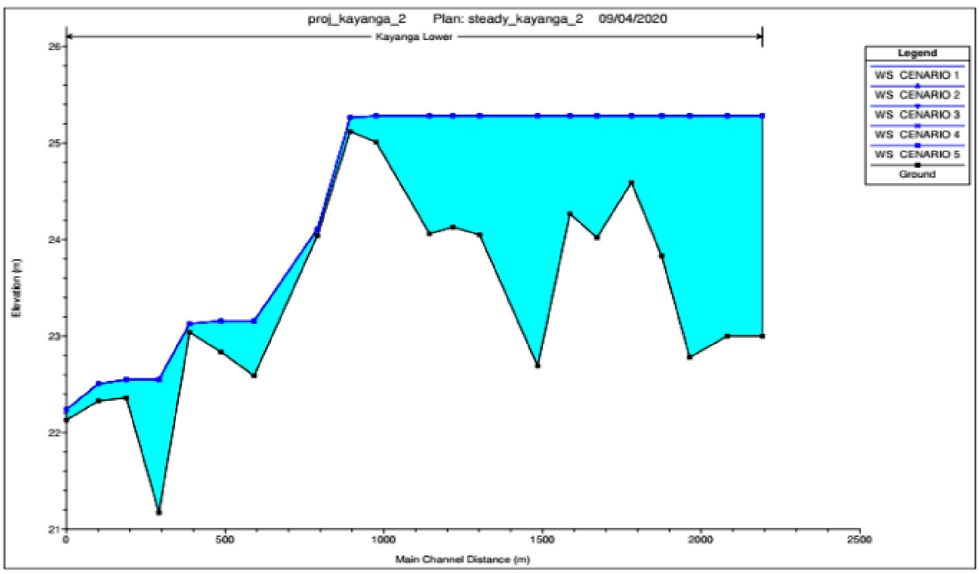


Fig. 13 Longitudinal surface water profile of the Lower Kayanga River.

According to the Anambe River (tributary), a permanent and uniform regime has been observed.

3.4.2.2 Velocities Profile

The velocity profiles simulated along the tree rivers are presented: Upper Kayanga (Figs. 14 and 15), Anambé tributary (Figs. 16 and 17), Lower Kayanga (Figs. 18 and 19). We observe velocity peaks along the rivers corresponding to the cross-sections XS-78662, XS-67203, XS-47466 (Upper Kayanga), XS-57305, XS-39084, XS-35332, XS-12754 (Anambé tributary) and XS-2756, XS-1434 (Lower Kayanga). Inthe Upper Kayanga river, the velocity average is ranging between 0.00 and 1.18 m/s for the first scenario, between 0.01 and 1.36 m/s for the second scenario, between 0.01 and 1.58 m/s for the third scenario, between 0.02 and 1.78 m/s for the fourth scenario and between 0.03 and 2.03 m/s for the last scenario. For the Anambé tributary, the velocity average is between 0.0002 and 0.0025 m/s for all the considered scenarios. It is between 0.00 and 0.83 m/s for the lower Kayanga for all scenarios.

3.4.2.3 Flooding Areas

The XYZ perspective view of the HEC-RAS model for the five release scenarios is represented in 2D and

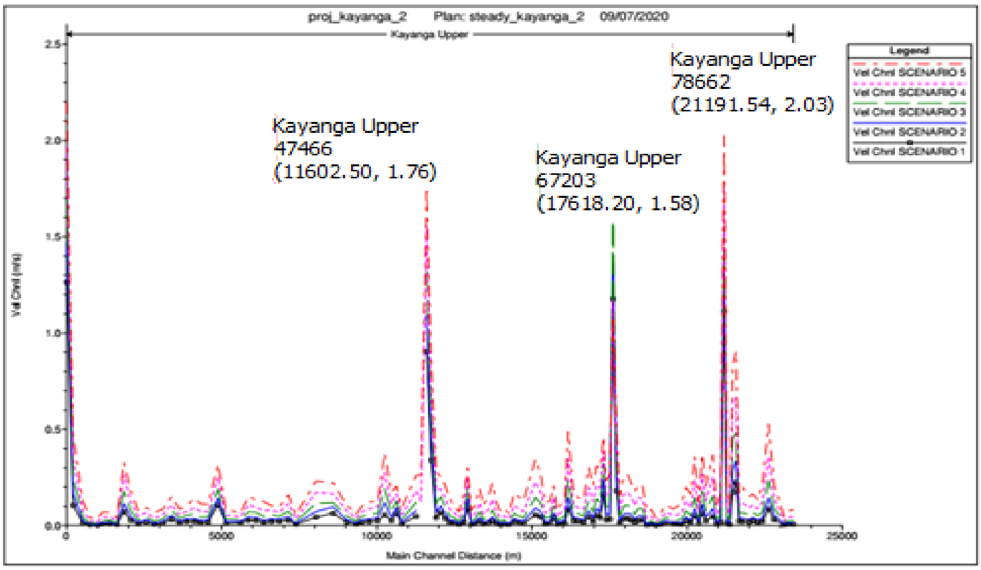


Fig. 14 Computed velocities along the Upper Kayanga River (Main Channel).

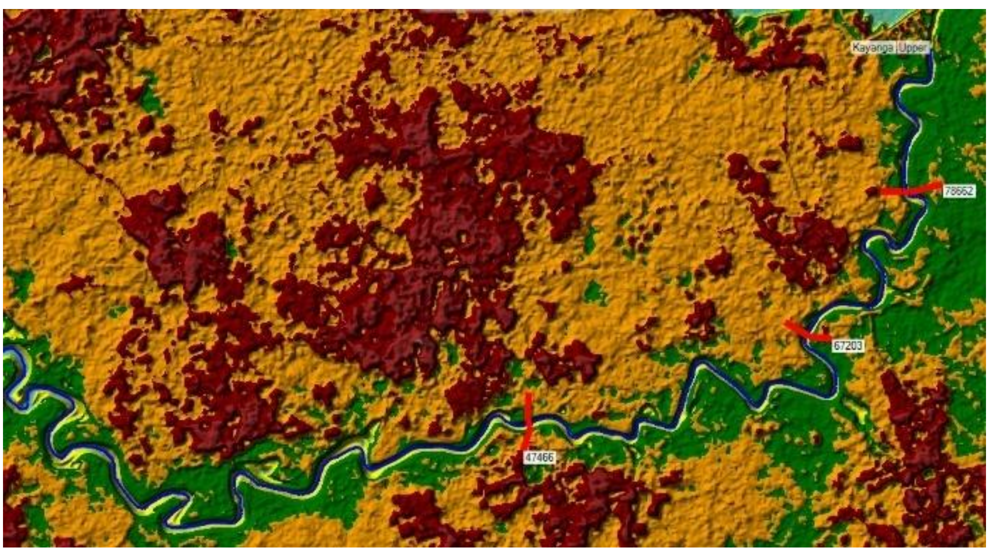


Fig. 15 Velocity peaks of cross-sections along the Upper Kayanga River (Main Channel).

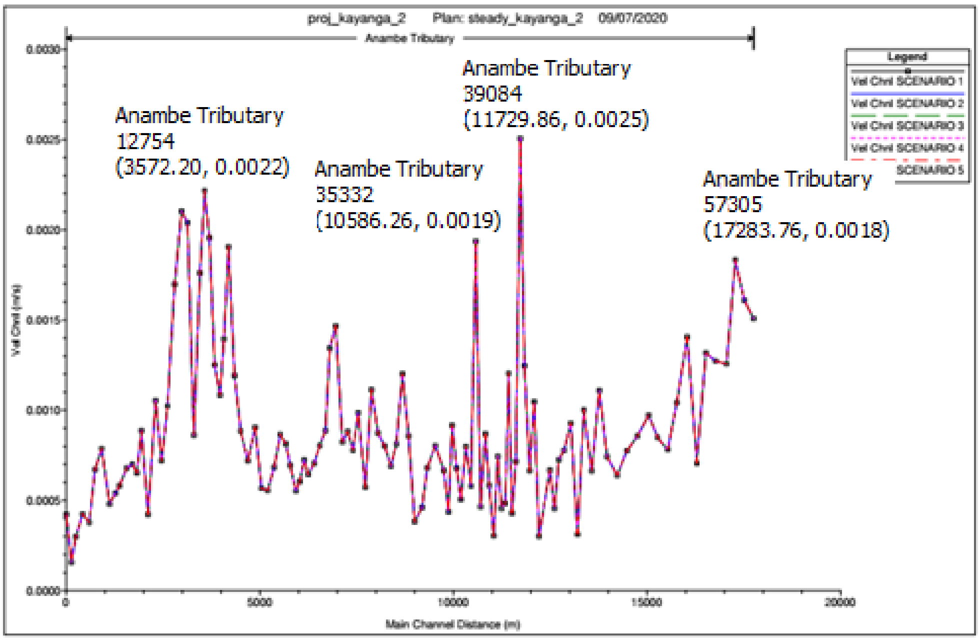


Fig. 16 Computed velocities along the Anambé tributary River (Main Channel).

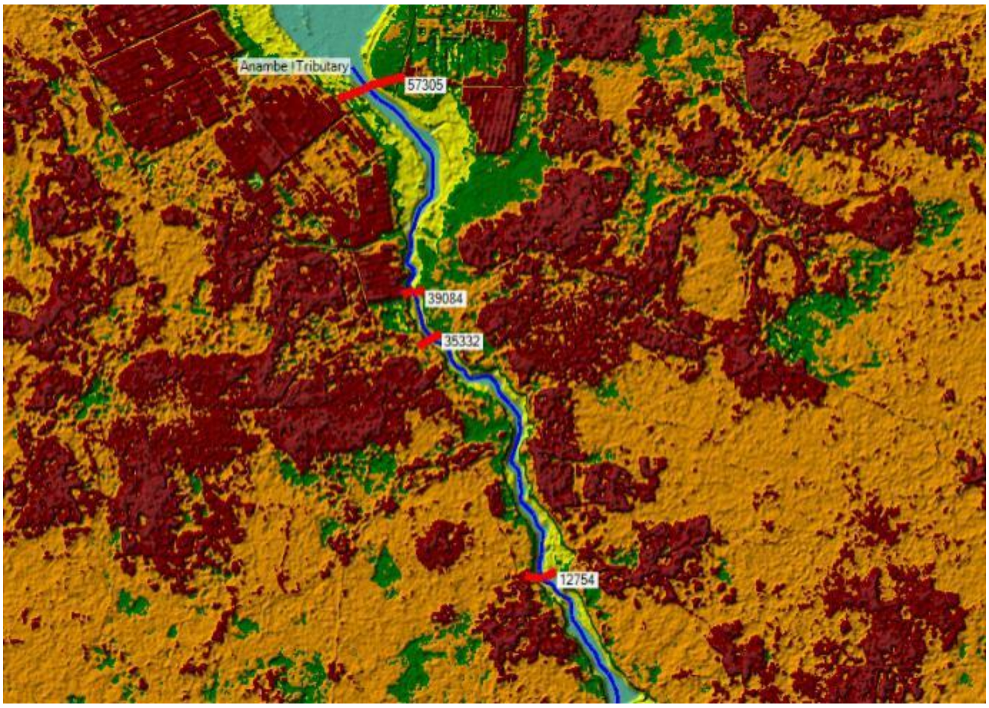


Fig. 17 Velocity peaks of cross-sections along the Anambé tributary River (Main Channel).

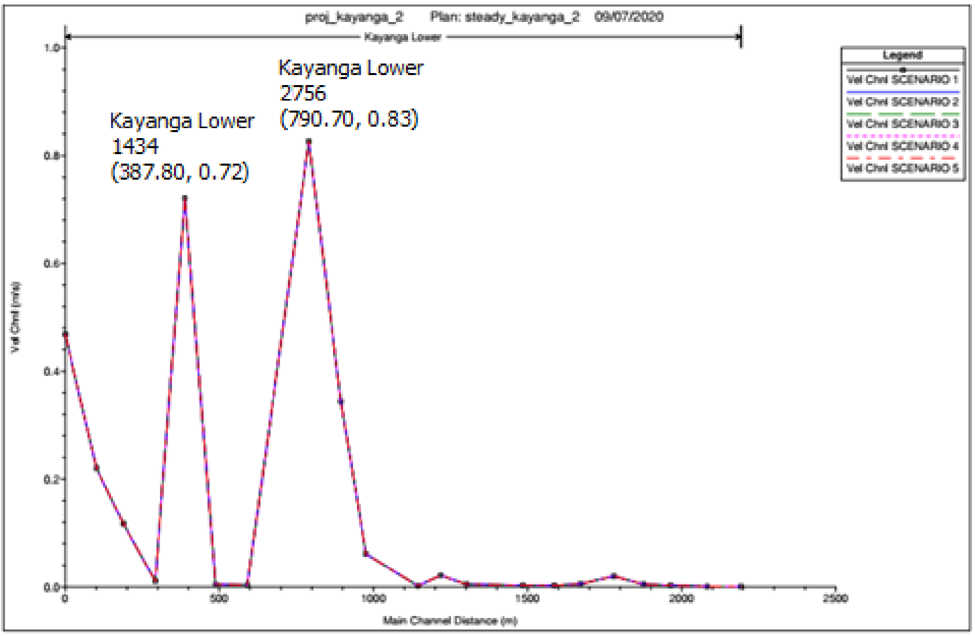


Fig. 18 Computed velocities along the Lower Kayanga River (Main Channel).

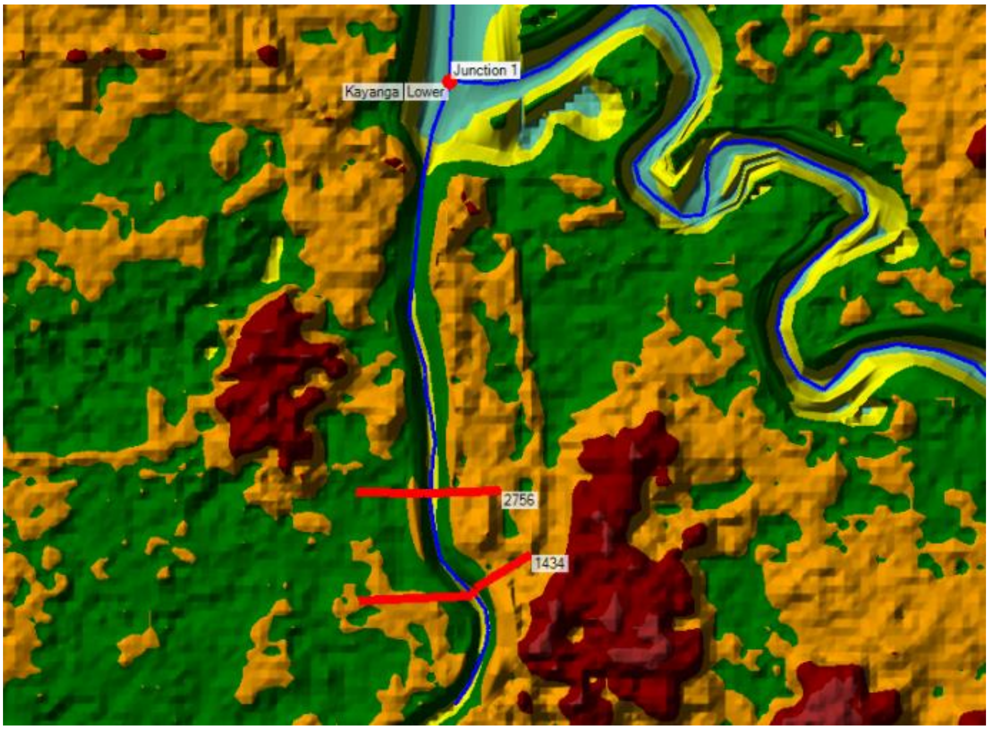


Fig. 19 Velocity peaks of cross-sections along the Lower Kayanga River (Main Channel).

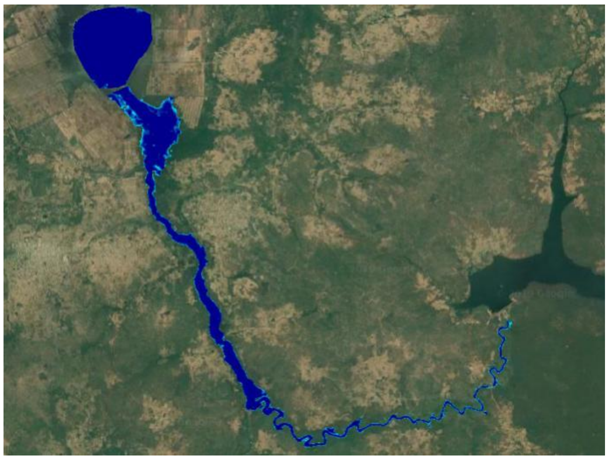
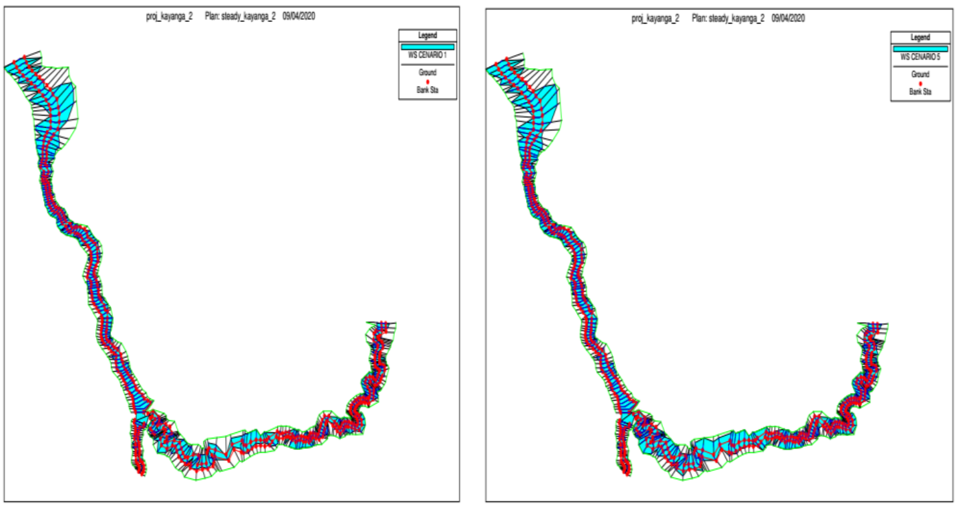


Fig. 20 2D representation of flood area.



Scenario 1 ***Scenario 5***

Fig. 21 3D representation of flood hazard.

3D. The water surface profiles in 2D and 3D show irregularity of the river flow behavior as shown in Figs. 20 and 21.

4. Conclusions

Traditional rainfed agriculture systems suffer from climate change and climate variability. Irrigation seems to be a good alternative. However well-suited water management tools are needed to increase the network irrigation efficiency. The main objective of this study was to assess the relevance of the HEC-RAS model in the simulation of the water surface profiles of the Anambé river, which is the main river responsible for the development of irrigated rice cultivation in southern Senegal (lower Casamance). The HEC-RAS model was used to calculate the main flow characteristics along the Kayanga-Anambé hydro-system to better understand their hydraulic behavior. In the different scenarios of the flow release, we can find in the model the hydraulic depth profiles, the water surface profiles, the flow velocity profiles, the spatial evolution in 2D and 3D in the hydraulic system. Analysis of the results shows that the water profiles remain constant for the different flow rates on the Anambé tributary. These results are predictable because we have a dam (Confluent Dam) that controls the flow in the tributary and the HEC-RAS model can predict this situation.

This means that HEC-RAS is a good tool to simulate the Kayanga-Anambé hydro-system and to be able to ensure efficient management of water for the irrigation system.

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