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Using of Hec-ras Model for Hydraulic Analysis of a River with Agricultural Vocation: A Case Study of the Kayanga River Basin, Senegal

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Abstract In West Africa, there is serious asymmetry on food safety between consumers and food producers. This made that the management system of food safety in many developing countries became a top priority for authorities and decision makers. In Senegal, the government has selected the flood plain of Kayanga River to develop irrigated agriculture through rice cultivation to promote the food safety. For this, two dams (Niandouba and Confluent) have been built to reinforce water availability .The management of this hydraulic system required the better knowledge of its water resources through the dynamic of the flow. In this paper, we used Hec-ras model to compute the flow characteristics to analyze the hydraulic behavior of this system. The river reach selected, is located between the Niandouba dam and Kounkane threshold. From the DEM of this area, we have divided the river reach into 78 cross sections perpendicular to flow direction and numbered from 1 to 78. Arcgis software is used to extract the bathymetry for each cross section and the distance between two adjacent cross sections. This step allows creating the river geometry with Hec-ras. Four stream flows have successively fixed at Niandouba dam outlet as upstream boundaries. For each stream flow, Hec-ras calculate flow characteristics including: water surface profiles, energy grade line, water surface elevation, flow velocity, flow area, total surface area, volume, wetted perimeter, Froude number, top width, specif force, shear total, power total ,friction loss, head loss, conveyance total, and slope. The high, low and constant flow characteristics areas have been located. The large and narrow section sectors have also been identified allowing estimating floodplain. Certain of these flow characteristics such as the volume**,** total surface area…decrease from upstream to downstream. Flow velocities are substantially higher in the main channel than in the floodway. This study provides an opportunity for stakeholders to identify important elements of irrigated agriculture for investment plans in this area.

Keywords: *hec-ras, hydraulic analysis, kayanga river basin, hydraulic behavior, water resources knowledge, food safety*

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1. Introduction

Water is considered as the most vital item in the world due to reduction of water resources in most area [32,34-41]. The most water consumption is related to the agricultural sector and irrigation has the maximum water withdrawal in agriculture [32,34-41]. Irrigated agriculture is certainly, a vital component of sustainable development but it is not a unique sector, since it faces challenges similar to those confronting other public and private sector economic activities [32-43]. The world population is growing day to day and need to provide the food according to meet sustainable development distinguises necessity of accurate decision in the agricultural management [32,34-41]. For this, agricultural water management must be necessarily taken into account. The role of macroeconomic policies in agricultural water management is there vital and undeniable due to limitation of water resources [33,42,43]. The agricultural water management plays a role to reduce poverty in the world as three pathways. Those are improvement of production, enhancement of employment opportunities and stabilization of income and consumption using access to reliable water, increasing high-value products, and finally its role to nutritional status, health, societal equity and environment [32,34-41]. Therefore, due to its role on water resources, studying agricultural water management is still reasonable in the world in general and developing countries in particular [32,34-41]. In this condition, role of water science researchers and irrigation experts is important more than ever [32,34-41]. The first concern of these researchers and irrigation experts is the satisfaction of water demand because of a central place that water resources occupy on economic and social human activities [28,46]. However, Due to the climate change and variability, water resources are nowadays insufficient in many rivers systems. This penalizes development projects related to water, such as agriculture [17,27]. Thus, the analysis of the dynamics of the rivers flow became an important step towards the better understanding of hydraulic behavior of the river [1]. This can be done by the optimal design of rivers and hydraulic structures for water resources management [16]. An appropriate modeling to monitor the spatial evolution of the flow main characteristics is then required. The use of hydraulics models as decision support has become essential [13]. These models use mathematics to represent a system in order to analyze the dynamic of river system flows .There are many hydraulic models for river system flows analysis [8]. However, the choice of the model must be made by identifying an appropriate model structure which is able to represent accurately the real system [45]. This representation passes by the computation of the most important hydraulic parameters of flow such as water surface, Froude number, water flow velocity, slopes, flow area, wetted perimeter, head loss, and volume [23,29-32,34-41]. In this paper, we focus on the Kayanga-Anambe river system located in the southern part of Senegal. Due to the climate change and variability whose effects are the decline in rainfall, in piezometric level and the fall of the flows of rivers, this system has been selected by the government to develop irrigated agriculture in the research of food safety. Food is the first necessity for human's life and economic development. Food safety is directly related to people's lives, health, stability and other human rights, therefore the management system of food safety is a major issue [24]. This is why; food safety has recently attracted significant attention from Senegalese authorities. Thus, with a vast flood plain and favorable climatic conditions, the authorities have made Kayanga-Anambe river system into an agricultural hub. The main objectives of these authorities are to promote the food safety to consumers through irrigated agriculture. To implement this project, two dams (Niandouba and Confluent) have then been built to reinforce water availability. This hydraulic system aims at water allocation for irrigated perimeters of the Anambe area through Waïma Storage Lake. An efficient management of this river system for water allocation and for hydraulic structures implementation such as pumping stations needs an appropriated tool for hydraulic system analysis based on flow calculation. This research analyses the dynamic of the flows of Kayanga river basin for an application to the irrigation of lands suitable for rice cultivation; therefore, a better understanding of the hydraulic behavior of this basin is required. Use of the mathematical models for simulation of surface irrigation is necessary for reducing costs and decrease of time in analysis of indexes including application efficiency and distribution uniformity [17,44]. Thus, Hec-ras model based on hydraulic routing is selected to describe the hydraulic behavior of this river basin by calculating the main flow hydraulic parameters that are essential to the analysis of a hydraulic system. This software is widely recommended for this purpose because of its useful information for water management and planning [4,23,26]. This model is very little demanding in data, it is very easy to provide results [20]. Its applications on many basins in the world indicate that Hec-ras model is suitable for investigation and simulation of hydraulic flows in irrigation network of River system. This is a main reason we have used it in this study. First, it is useful to note that no hydraulic study based on serious mathematical models have been conducted in this area. Secondly, the few studies that were done there were rather geographical order. The authors were content with a simple description of the system through land survey and often by GIS. This seems necessary but not sufficient to have a clear idea of how the system for possible hydraulic improvements. However, in this study, recognizing that good water management requires above all the knowledge of the water itself, we used the Hec-ras model to calculate the flow characteristics. This is necessary to analyze the flow dynamics of the system. The goal was to show the relationship between these parameters and the special evolution of the water resource of the system. The work offer an opportunity to provide useful information for many hydraulic engineering problems, including five specific applications: 1) the determination of the effect of hydraulic structures on the upstream and downstream ; 2) the estimation of flood plain; 3) the determination of the safe and optimum operation of hydraulic structures; 4) the corrections of the rivers in order to avoid a possible overflow in the event of rising and 5) the choice of implantations sites of hydraulic structures (such as dams, pumping stations,…). Finally, this study provides an opportunity for decision makers to identify many necessary element of irrigated agriculture for investment plans in the area that have not been investigated by previous researchers.

2. Materials and Methods

2.1. Study Area

Kayanga River originates in the Fouta Djallon Mountains in the Republic of Guinea Figure 1. It is a transboundary basin shared by three countries, Guinea, Senegal and Guinea-Bissau. It is located in the south of

Senegal and the north of Guinea-Bissau, between latitude 12° 31N and 13° 09 N and longitude 13° 20 and 14 ° 26W. The climate is Sudano Guinean in the southern part and Sudano Sahelian in the northern part. There are two seasons, a rainy one from June to September and a dry one from October to May. The temperature is minimum in December to February and maximum from May to November. The relative humidity reaches its maximum in September and minimum in January. The average annual rainfall decreases regularly from south (985mm) to north (790mm) [6,19].

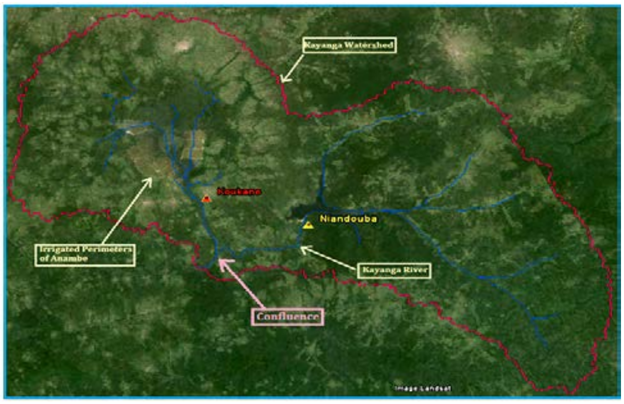

Figure 1. Kayanga river basin

2.2. Hydraulic System

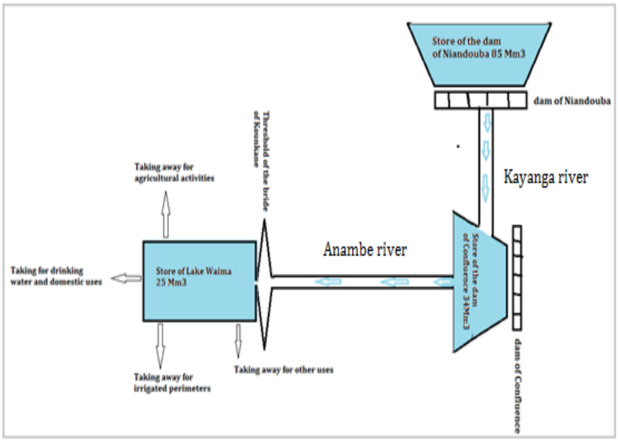

Figure 2. Hydraulic system in influenced regime

The main economical activity in Kayanga river basin was rain agriculture. However, since 1970, this basin has been facing the decrease of the rainfall due to climate change and variability [5]. That has encouraged the government of Senegal to select it to develop irrigated agriculture through rice cultivation to reduce the cereal deficit and promote the food safety to consumers. Its vast flood plain and favorable climatic conditions have made Kayanga river basin into an agricultural hub [7]. To reinforce water availability and allow an irrigation of lands suitable for rice cultivation, two dams (Niandouba and Confluent) have been built: the first, Confluence dam, has been builtin 1983 with a capacity of 34.10^6m3and the 2nd, Niandouba dam, in 1994 with a capacity of 85.10^6 $m^3$to reinforce water resources of the Confluence dam [6]. The last element of the hydraulic system is the Waïma lake, whose capacity is 25.10^6 m^3. This lake is filled by Niandouba dam through Confluent Dam and by overland flow from the lake basin. A threshold is realized at the outlet of this lake, at the Kounkane Bridge to store water to be used for agricultural activities in the Anambe flood plain during low flow [7]. See the diagram below of the general device of the Hydraulic system in influenced regime Figure 2.

2.3. Hec-ras Model

Hec-rasis a computer program that models the hydraulics of water flow through natural rivers and other channels. It was developed by the US Department of Defense, Army Corps of Engineers in order to manage the rivers (Robert et al., 2012). This software contains four one-dimensional hydraulic components for: steady flow computations; unsteady flow simulation; movable boundary sediment transport computations and water quality analysis using a common geometric data representation and common geometric and hydraulic computation routines. [3,11,13]. It is widely used in one-dimensional flow main parameters calculations in case of steady and unsteady river flow regimes [12,21]. These parameters are essential in the analysis of various hydraulic engineering problems including the determination of the effect of hydraulic structures on the upstream and downstream channels; the estimation of flood plain; the analysis of the capacity of river; the monitoring of the depth at any point in river; the choice of implantations sites of hydraulic structures (such as dams, pumping stations,) [2,14]. In this paper, we focus on the steady flow component of Hec-ras to perform and analyze flow parameters of the Kayanga River. The basic data requirements for simulation are included: geometric data, cross section geometry, reach lengths, Manning's roughness coefficients, contraction and expansion coefficients, steady flow data, boundary condition, flow regime [10,13].

2.3.1. Computation of Hydraulic Parameters

Computation from one cross section to the next was based on the solution of the one-dimensional energy equation (1) with an interactive procedure called the standard step method [9]

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

Where Z_1, Z_2 are elevations of the main channel inverts (m), Y_1, Y_2 are depths of water at cross sections (m), V_1, V_2 are averages velocities (total discharge/total flow area) (m/s), α_1, α_2 are velocity weighting coefficients, g is gravitational acceleration (m/s^2),he is energy head loss (m) Energy losses due to friction are evaluated by Manning's equation (2) [18,29,30,31]

$$h_e = L\overline{S_f} + C\left|\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right| \qquad (2)$$

Where: L is discharge weighted reach length (m), $\overline{S_f}$ is representative friction slope between two adjacent sections, C is contraction / expansion loss coefficient.

2.3.2. Boundaries Conditions

Boundary conditions are necessary to define the starting water depth at upstream and downstream [14,25]. In a sub critical flow regime, boundary conditions are only required at the downstream ends of the river system and the computation starts from downstream to upstream. If a supercritical flow regime is going to be calculated, boundary conditions are only necessary at the upstream ends of the river system and the computation starts from upstream to downstream. If a mixed flow regime calculation is going to be made, both downstream and upstream boundaries conditions are required at all open ends of the river system [13]. There are three kinds of boundaries conditions (critical depth, normal flow depth, or a given depth downstream of the channel), but only one is needed [18].

In this study, the flow regime is supposed subcritical. The depth at Kounkane is then fixed as downstream boundary condition.

3. Application

3.1. Kayanga River Geometry

From the DEM of the basin, we have judiciously divided the river reach into 78 cross sections perpendicular to flow direction from Niandouba Dam outlet to Kounkane threshold. These cross sections have been numbered from 1 corresponding to Kounkane threshold cross section (downstream) to 78 corresponding to Niandouba Dam outlet cross section (upstream). ArcGIS software has been used to extract the bathymetry of each cross section the distance between two adjacent cross sections. Each section is represented by the coordinates (X, Y) where X (corresponding to station value),is the abscissa measured starting from a point chosen on one of banks and Y (Corresponding to elevation value), is the ordinate measured starting from a horizontal plane of reference. To increase the stability of calculations and have a step of space even finer, we add by interpolation(using Hec-ras), additional cross sections between two existing consecutive sections. Coefficient values of Manning roughness used are fixed to 0.06 for left overbank, 0.035 for main channel and 0.05 for right over bank. The contraction coefficient is fixed to 0.1 and the coefficient of expansion is fixed to 0.3. Application of Hec-ras has allowed creating River Cross-section before and after interpolation. We present for example cross sections plots after interpolation in Figure 3.a; Figure 3.b and Figure 3.c respectively between river station (78 and 77); (46 and 45) and (2 and 1). We can see in these examples that, cross sections have not the same width. Figure 3.a is narrow whereas the Figure 3.b and Figure 3.c are larger. This is due to the significant change in the topography of Kayangariver bed.

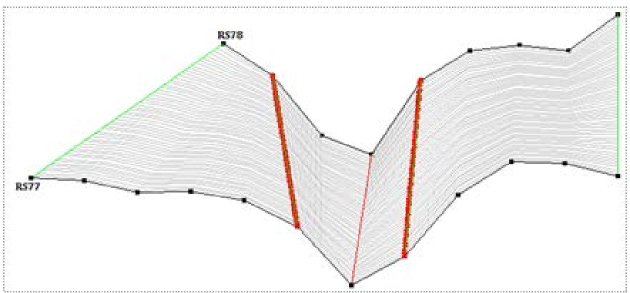

Figure 3.a. Interpolated cross-sections plots Between RS78 and RS77

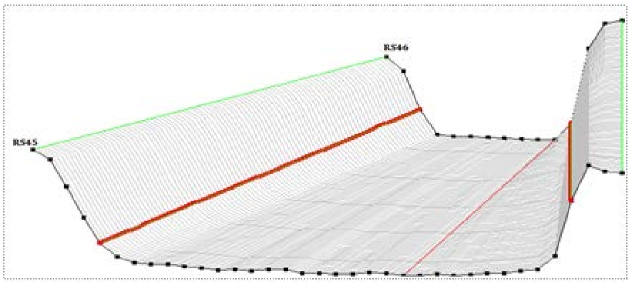

Figure 3.b.Interpolated cross-sections plots Between RS46 and RS45

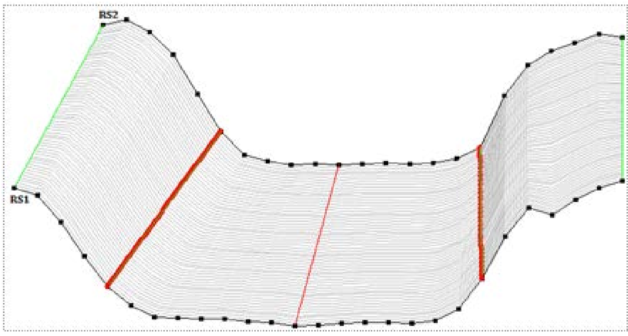

Figure 3.c.Interpolated cross-sections plots Between RS2 and RS1

3.2. Flow Characteristic Calculation

The next step after creating river geometry is to specify the discharges values, flow regime and boundaries conditions to perform the calculations. In this study, the steady flow component has been used. The known downstream depth equal to 2.4 m is used as a boundary condition. Four steady flow discharges: 50m^3/s (PF1), 500m^3/s (PF2), 4000m^3/s (PF3) and 8000m^3/s (PF4)have been fixed at upstream corresponding to Niandouba Damoutlet. For a given discharge, flow characteristics including water surface profiles, energy grade line, water surface elevation, flow velocity, flow area, wetted perimeter, Froude number, top width, spec if force, shear total, power total, and slope,…have been computed.

4. Results and Discussion

4.1. Wetted Sections

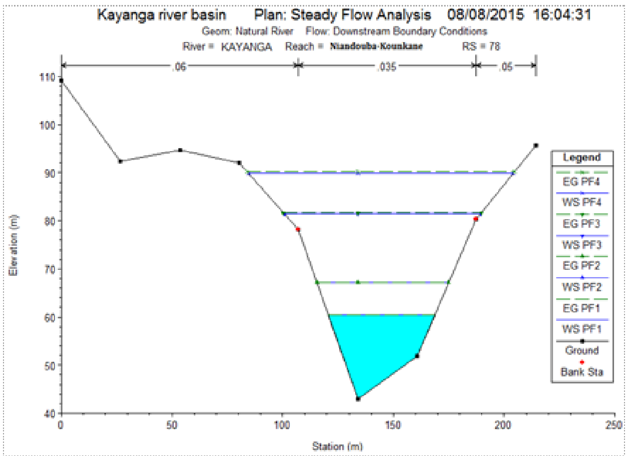

Figure 4.a. Wetted section at RS 78

For a given discharge specified in the upstream, we present in Figure 4.a; Figure 4.b and Figure 4.c wetted sections respectively at Niandouba Dam (Section 78), at the confluence Dam store (Section 45) and at Kounkane threshold (Section 1).We can see that the wetted section is narrow at cross section 78, and larger atcross sections 46 and 1.For RS78 and RS45,the flow is done in the main channel and in the floodway but for RS1 (downstream) ,the flow is channeled .These results show that with the increase of roughness coefficient, water level profile is no longer uniform and appears as a gradual variable. Thus, the water level profile decrease from upstream cross sections to downstream; this consequently leads to the decrease of flow capacity in the floodway.

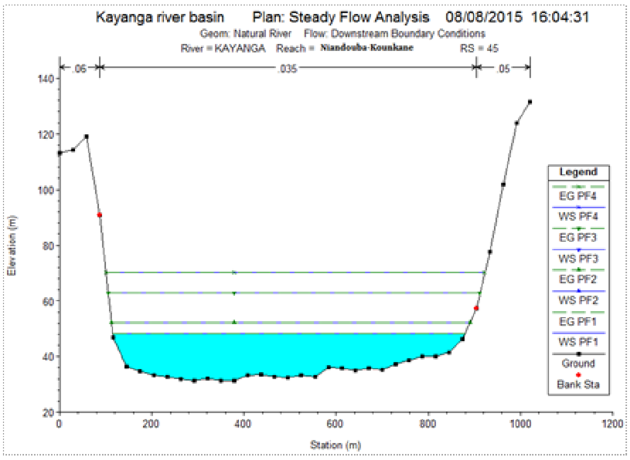

Figure 4.b. Wetted section at RS 45

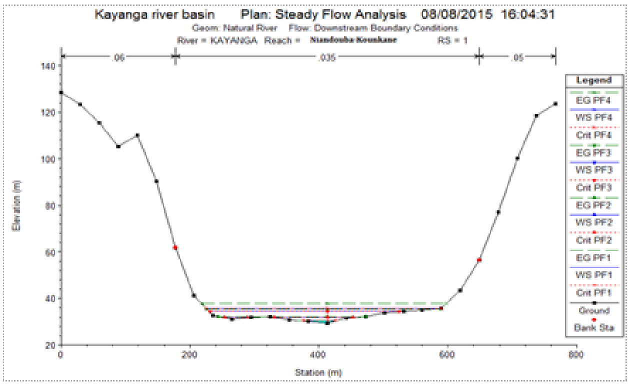

Figure 4.c. Wetted section at RS 1

4.2. Water Surface Profiles

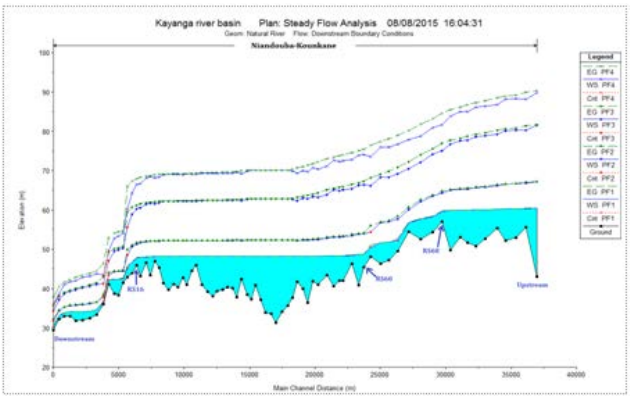

Figure 5. Water surface profiles distributions

We present in Figure 5 water surface profiles for the different streamflows fixed at the upstream. For given discharge, water surface profile remains constant firstly from upstream to cross sections 68 and secondly from cross section 60 to cross section 16.In these, free surface slope is very close to zero. From cross section 68 to cross section 60 and from cross section 16 to cross section 1,water surface profile decreases quickly. Free surface slope is important in these areas. These results show that the Kayanga area is sensitive to water level profile fluctuations and deformation of bottom slope of the river. This can reduceflow velocity in the floodway.

4.3. Velocities Profiles

Figure 6 shows the distribution flow velocity along the river for various discharges specified at the upstream. From cross section 57 to 21, velocities are lower. In these sections free surface slopes, stream power shear total are lower. The highest velocities are observed at cross sections 14; 10 and 61. In these sections, free surface slopes, stream power and shear total are more important and flow areas are smaller too. These results show that the variations of flow velocity are due to the significant changes in the topography of Kayanga river bed and the roughness coefficient effect. This decreases the capacity of flow velocity in floodway.

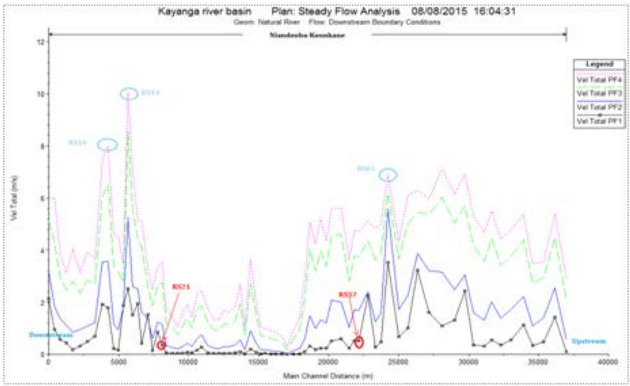

Figure 6. Flow velocities distribution

4.4. Flow Area

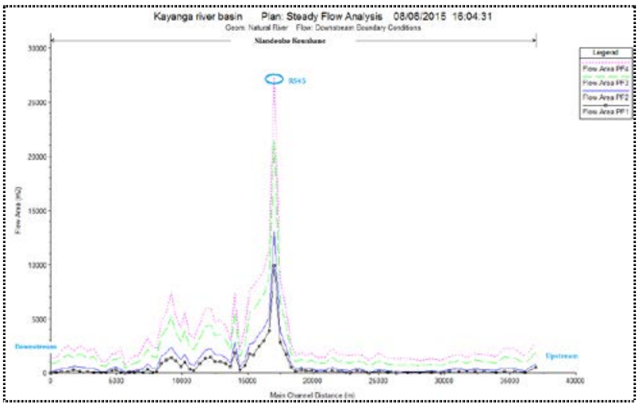

Figure 7. Flow areas distributions

We present in Figure 7 the distributions of flow areas for various discharges specified at the upstream. We can observe that flow area increases with discharge. From cross section 44 to downstream and from upstream to cross section 46, flow areas have the same level. In these areas, conveyance total, top width and specify forces are lower. The highest flow area is observed at cross sections 45corresponding to confluence dam store. This section corresponds to the highest wetted perimeter. Thus, the flow area changes according to manning roughness coefficient effect. This consequently leads to the decrease in river capacity.

4.5. Friction Slope

We present in Figure 8 the distribution of friction slope along the study reach for the various discharges fixed at the upstream. From upstream to RS69, friction slope is constant; particularly from RS63 to RS17, it is very close to zero. In these areas, friction loss and head loss are lower. The highest values are located at RS10, RS14, RS2and RS65.These cross sections correspond to higher values of stream power, shear and conveyance.

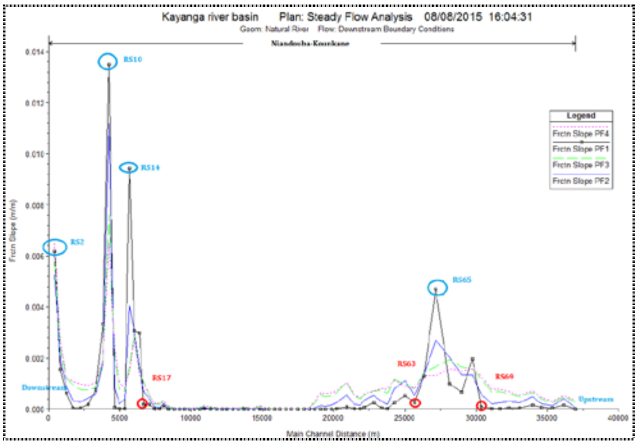

Figure 8. Friction slope distributions

4.6. Volume

Figure 9. shows the cumulated volume along the river system for various discharges. We can see that the volume increases with discharge. For given streamflow, the volume decreases slowly from upstream to cross section 16 and quickly from this section to downstream. This can be due to the soil texture through its permeability, evaporation and roughness coefficient effect. This can negatively impact on the water availability to downstream for agricultural needs.

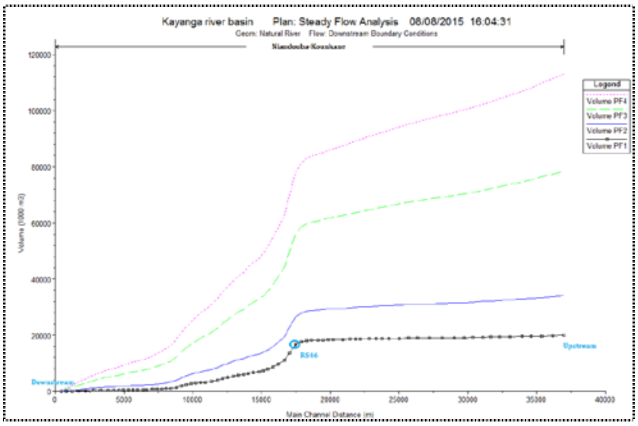

Figure 9. Total volume profiles

4.7. 3D Representation

We present for example, in Figure 10.a and Figure 10.b Perspective plot respectively from RS50 to RS45 and from RS45 to RS39 for the different streamflows fixed at the upstream. We can see that cross sections have not the same width: there are narrow and larger cross sections. The water level profile in cross sections changes according to the top width and consequently leads to the decrease in river capacity. The wetted perimeter in the floodway is much higher than in the main channel for the most of cross sections. Thus, friction forces between the water and channel bed have a greater influence in flow resistance in the floodway, leading to lower values of the Manning coefficient. As consequence, the flow velocity and conveyance are substantially higher in the main channel than in the floodway as shown in these two examples of reach. This confirms the various analyses made in top.

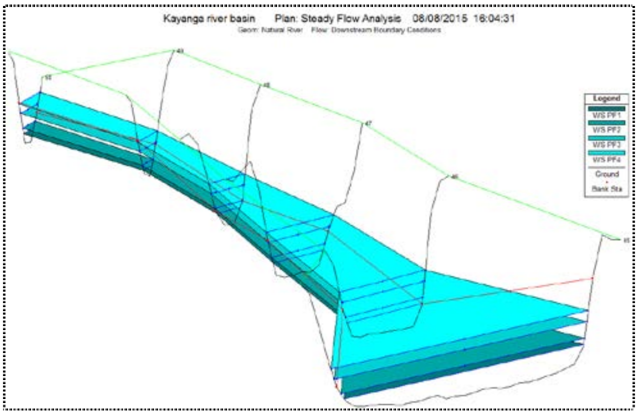

Figure 10.a. Perspective plot from RS50 to RS45

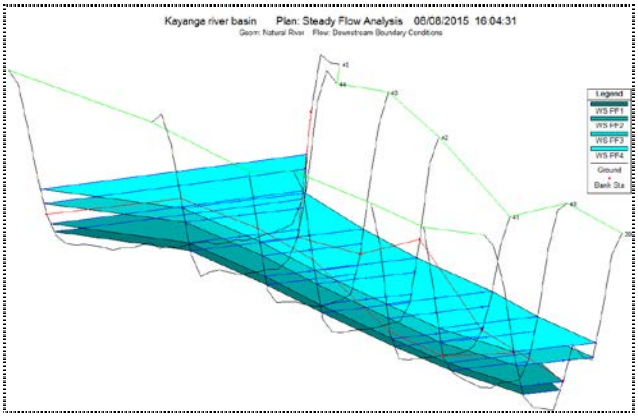

Figure 10.b. Perspective plot from RS45 to RS39

5. Conclusion

The aim of this paper is to analyze the dynamic of flow in Kayanga river basin. For this, Hec-ras model was used to calculate the main flow characteristics along the study reach. This has allowed locating the high, low and constant flow characteristics areas; the large and narrow section areas have also been identified. Certain parameters such as total surface area, volume… decrease from upstream to downstream. These results are very useful to the decision makers for water allocation, water management, hydraulic structure implementation, environmental planning, flood control ministration…in Kayanga River. However, it is useful to note that in this study the flow regime is supposed subcritical along the study reach whereas actually, in this river the flow is sometimes subcritical, supercritical or sometimes mixed regime. Complementary research considering supercritical or mixed flow regime, are required to definitively characterize Kayanga river flow and better establish the relationship between waterflow dynamics and its characteristics spatial evolution .

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