WATER FLOWS ANALYSIS OF THE KAYANGA-ANAMBÉ-LAKE WAÏMA HYDROLOGICAL COMPLEX BY FLOW-FLOW CORRELATION AND RAINFALL-FLOW MODELING APPROACHES

ABSTRACT

This article presents an assessment of the surface water resources of the Kayanga-Anambé hydrological complex, located in West Africa. This hydrological complex, one of the main characteristics of which is exclusively agricultural and pastoral, is subject to a changing climate and strong anthropogenic pressures leading to resource use conflicts. Therefore, a better knowledge of water availability is essential to guide policies for the management and adaptation of this geosystem. Two approaches are used to estimate the contributions from the different sub-watersheds of the Kayanga: (i) a correlation between the flow rates of Wassadou and those of the other hydrometric stations of the Management and Planning Unit (UGP) of Casamance and eastern Senegal – in particular for filling the gaps observed in the data series from the Wassadou, Niandouba and Vélingara Pakane stations – and (ii) the implementation of a rainfall-runoff modeling approach at monthly time intervals, with the GR2M model, to reconstruct seasonal flows and contributions from the Kayanga-Anambé-Lake Waïma complex. The results show correlation coefficients which vary from 0.24 to 0.96 depending on the stations, showing a strong relationship between the flow rates of the Kayanga at Wassadou and those of the other stations. The maximum correlation coefficient is noted at the Mako station (0.96), on the Gambia river. Furthermore, a Nash of 0.86 was obtained with the GR2M model. Thus, the parameters X1 and X2 of the model were used to reconstruct the seasonal flows and contributions from the Kayanga-Anambé-Lac Waïma complex. This made it possible to have long enough time series of flow rates for a better estimation of water resources and their temporal fluctuation.

Keywords: Kayanga-Anambé-Lake Waïma; Flows; GR2M; Flow-Flow Correlation

I. INTRODUCTION

The Kayanga-Anambé-Lac Waïma hydrological complex is located in upper Casamance, in the Kolda region, in the south of Senegal, the central part of which is a vast flood basin of around 16,000 ha, Lake Waïma. The desire to control the water resources of the Kayanga River to fight against food and nutritional insecurity which threatens the populations, the State of Senegal, through the Agricultural Development Company (SODAGRI), has built hydro- agricultural areas on the main tributaries of the Kayanga. These are the Niandouba, Confluent (Kayanga-Anambé confluence dam), and Kounkané dams. The hydrological functioning of this Anambé-Kayanga system is relatively simple and purely gravity-based: the confluence reservoir (Confluent dam), which receives water from the Niandouba dam, fills by gravity Lake Waïma which also receives water from runoff from slopes. During low water, part of the water is trapped in Lake Waïma by the threshold of the Kounkané bridge which prevents the exit of water towards the Kayanga. This reservoir is then used for hydro-agricultural activities in the Anambé plain.

However, the hydrological regime of the Kayanga River, like that of tropical rivers, is marked by an alternation of wet periods and dry periods. Wet decades of 1950 and 1960, followed by dry periods of the 1970s and 1980s, which have been highlighted by several authors

(Dacosta, 1989; Decroix, 2015; Sambou, 2019; Thiaw, 2017, 2020, 2021). Today we are witnessing a slight return of humid conditions, in general, in the Sahel and, in particular, in the Kayanga basin, demonstrated by certain authors including Sambou, (2019). But, this return of humid conditions in the basin will only be effective from 2060 (Thiaw, 2023). However, very few studies have focused on the effect of climate variability and anthropogenic action (hydro-agricultural dams) on the hydrological regime of the Kayanga. This situation is justified by the lack of hydrological information on the river, the flow chronicles being incomplete, discontinuous, of short duration, and therefore difficult to exploit for a reliable hydrological analysis. A reliable response to this problem will make it possible to define the distribution of the characteristic hydrological series which are the basis for the sizing and calculation of profitability of the hydraulic structures in place. Thus, modifying a distribution assumed to be constant over time would have disproportionate socio-economic impacts. The objective of this work is therefore to simulate and then extend, as far as possible, the hydrological series using a linear regression method, flow-flow correlation, and a rainfall-flow model, at monthly time steps, GR2M.

II. MATERIAL AND METHODS

1. Study area

The Anambé watershed is a tributary of the Kayanga, in upper Casamance in southern Senegal, the central part of which is a vast flood-prone basin of around 16,000 ha, Lake Waïma (fig.1). It is located, in its entirety, in the Kolda region which is limited to the South by Guinea Conakry and Guinea Bissau, to the North by Gambia, to the East by the Tambacounda region and to the West by the Sédhiou region. It is crossed by the thirteenth parallel of the northern altitude and covers an area of approximately 1,100 km² (Thiaw, 2023).

The Kayanga basin straddles Guinea, Senegal, and Guinea Bissau. The Kayanga has its source in a marshy area at the foot of Fouta Djallon in Guinea. It flows in a northwest direction until it enters Senegalese territory where it makes a loop taking a southwest direction to enter Guinea Bissau where it takes the name of Rio Gêba. At the Niapo bridge, the Kayanga drains a watershed of 1,775 km² with a length of 95 km. In Senegalese territory, its main tributary is the Anambé whose flow is oriented north-south until its confluence with the Kayanga, 10 km south of Kounkané.

The Anambé basin has an almost circular shape with a peduncle that connects it to the Kayanga (fig.1). The Anambé and its tributaries have a complex layout. Indeed, if its main axis has a simple layout, the shape of the basin creates a significant branching of the third-order tributaries on the right bank, with a convergence of the secondary network towards the center of the basin (fig.1). The left bank, for its part, receives a few tributaries with temporary flow.

Two dams were built on the Kayanga, at Niandouba (upstream) and at the confluence with the Anambé, and a threshold was built at the Kounkané bridge (fig.1). The Confluent Dam was built in 1983 for a reservoir capacity of sixty million m3 (with an endowment flow of two m3 s-1). The Niandouba dam was necessary to improve the system which was not operational; it was conducted in 1994 for a reservoir of ninety million m^3 and an endowment flow of 4.2 m^3 s-1. (Hathie *et al.* 2015).

The Kounkané threshold blocks the outlet of Lake Waïma to increase storage possibilities upstream of the Kounkané bridge during low water and thus allows a retention of twenty-five million m3 within the Anambé floodplain for the realization of hydro-agricultural projects (fig. 2).

The Kayanga-Anambé system is finally presented as a series of reservoirs and hydraulic axes: upstream, the Niandouba reservoir with ninety million m^3, the Niandouba-Confluent dam hydraulic axis, then the Confluent dam reservoir of sixty million m^3 and finally the reservoir of Lake Waïma at the threshold of the Kounkané bridge with twenty-five million m^3 (Hathié et al. 2013).

The hydrological functioning of this Anambé-Kayanga system is simple and purely gravity: the confluence reservoir, which receives water from the Niandouba dam, fills Lake Waïma by gravity, which also receives runoff water from the slopes. In low water, part of the water is trapped in Lake Waïma by the threshold of the Kounkané bridge which prevents the water from exiting towards the Kayanga. This reservoir is then used for hydro-agricultural activities in the Anambé plain.

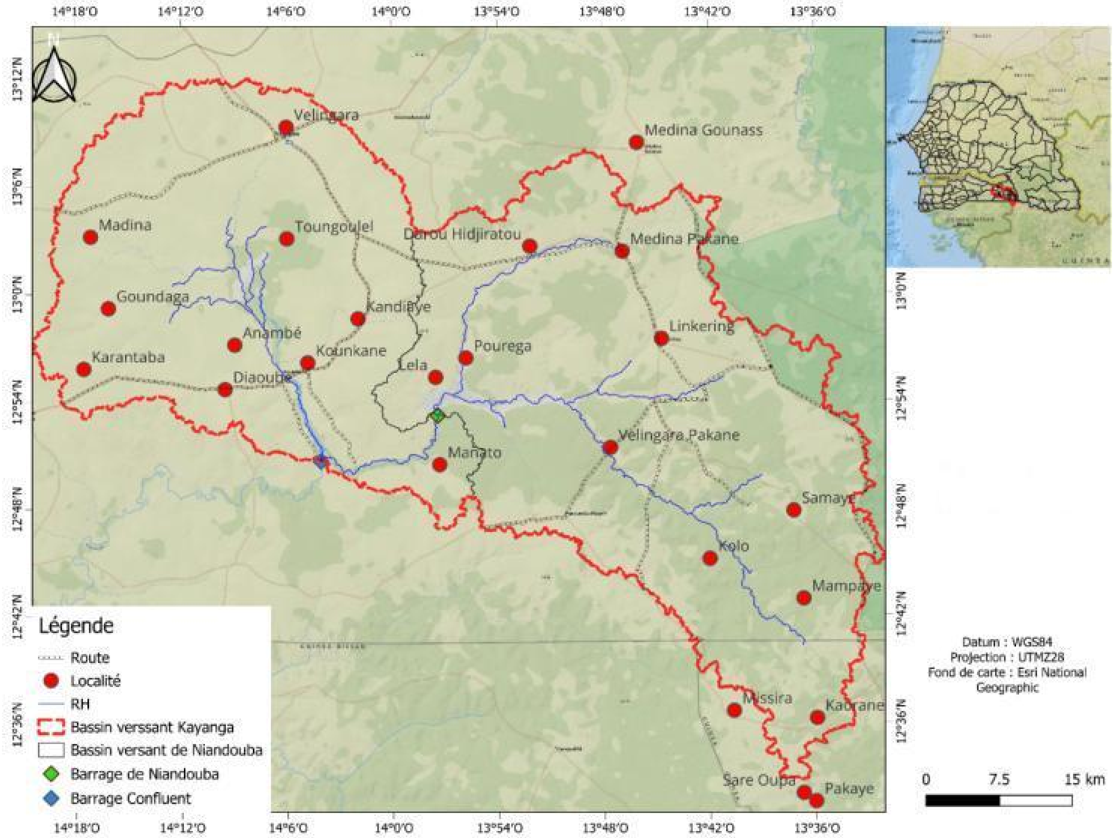

Figure 1. The Kayanga and Anambé watersheds

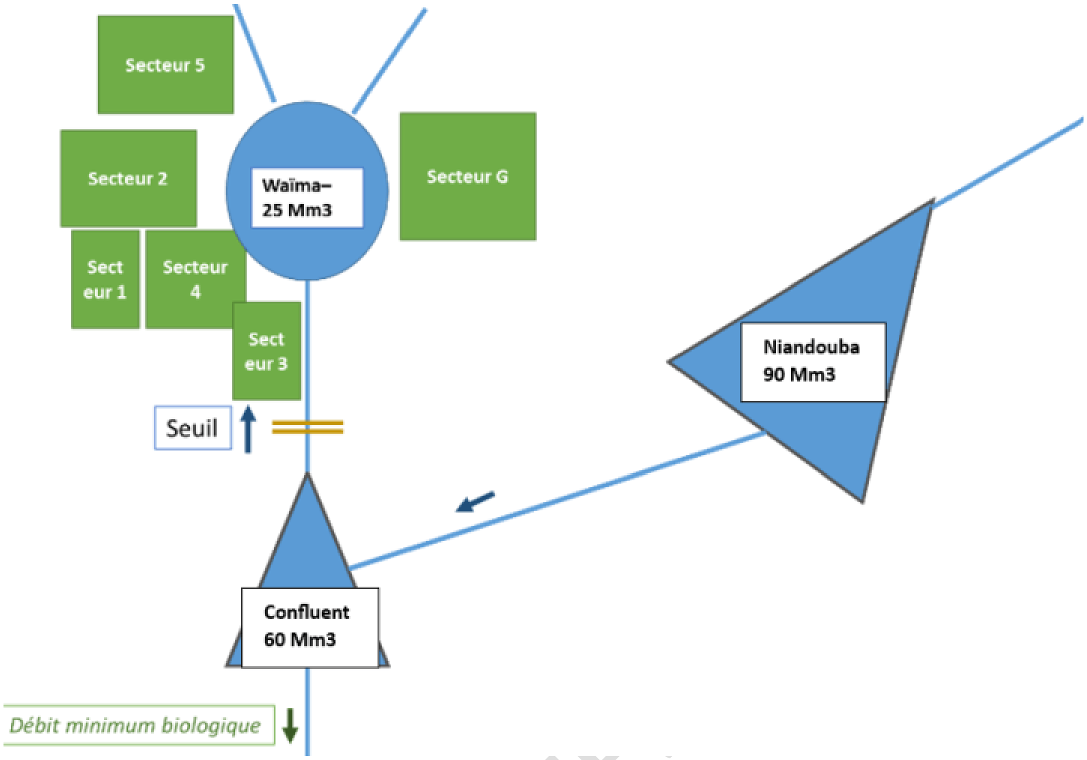

Figure 2. Diagram of the general arrangement of the Kayanga – Anambé – Lac Waïma system

The hydrographic network of the study area is made up of the Kayanga and its tributary the Anambé. The Anambé flows in a north-south direction, with a slope of 0.2 to 0.3%. It drains a watershed of 1,150 km² at Lake Waïma, it flows into the Kayanga about 9 km south of the N6 bridge. At the Confluent dam, its catchment area is 2,960 km².

The Kayanga has its source in the west of Fouta Djallon, the area of its watershed at the Niandouba dam is 1,700 km². At the confluence with the Anambé, its watershed is 1,755 km² with a length of 95 km. The slope is small, around 0.02%. The Kayanga enters Guinea Bissau where it takes the name of Rio Geba.

In addition to these two main axes, there is an important secondary network of backwaters, the most important of which are the Goundaga and the Hegal, tributaries of the Kayanga, and the Waïma, a tributary of the Anambé.

With a view to optimizing the availability of surface water resources in Kayanga in order to reduce the cereal deficit in Senegal and increase the income of producers, in particular through the development of irrigated agriculture – the State of Senegal, through the Agricultural and Industrial Development Company of Senegal (SODAGRI) – has built several hydro-agricultural works on the Kayanga including those of Niandouba, Confluent, and the Kounkané and Wassadou bridges (fig.3). However, most of these structures were built during the drought that hit the Sahel hard from the early 1970s to the mid-1990s and the return of rainfall conditions to normal since 1993 (Bodian *et al.* 2016; Decroix et al. 2015; Faye 2018, Sambou, 2019; Thiaw, 2020), which then requires the resizing of all the discharge and overflow structures built during the drought period.

1.1. Characteristics of hydraulic infrastructures

The main hydro-agricultural infrastructures built in the project area are shown in figure 3. They consist of:

- the Confluence dam in 1984 with a capacity of sixty million m3.
- The Niandouba dam in 1997 with a capacity of ninety million m3.
- Five pumping stations with their intake channels.
- The irrigated perimeters with an area of approximately 5,000 ha divided into six sectors. Irrigation is done in total control of water pumped from the reservoir of the confluence dam at Lake Waïma.
- Sector protection dykes.
- The development of the Vélingara Pakane Dam.
- Protective facilities (dyke/cassis/bunds) in Wassadou

1.2. The Confluence Dam

Built on the Kayanga River, the Confluence dam is located south of the town of Kounkané, about 500 m downstream from the confluence of the Anambé with the Kayanga. Its commissioning dates from 1984.

Table 1: Characteristics of the Confluence dam (after its commissioning)

Sea wall	- Type: Homogeneous in soil - Volume of backfill: 50,000 m^3 - 210 m long and 5 m wide - Ridge elevation: 25.3 m IGN - Maximum height: 11m - Slopes of the upstream and downstream facings: 3/1 and 3/1
Water retention	- Normal retained elevation RN: 22.3 m IGN - Minimum operating level: 19.5 m IGN (2 million m^3) - Capacity: 60 million m3 - Surface of the body of water: 55 km2 - Usable volume : 48 million m^3
Spillway	- Type: Concrete Creager type spillway - Length: 20m - Design flood : 510 m3/s
Emptying/restitution work	- By-pass valves and Neyrtec type wagon

	- Flow: 3.5 m3/s under 3 m

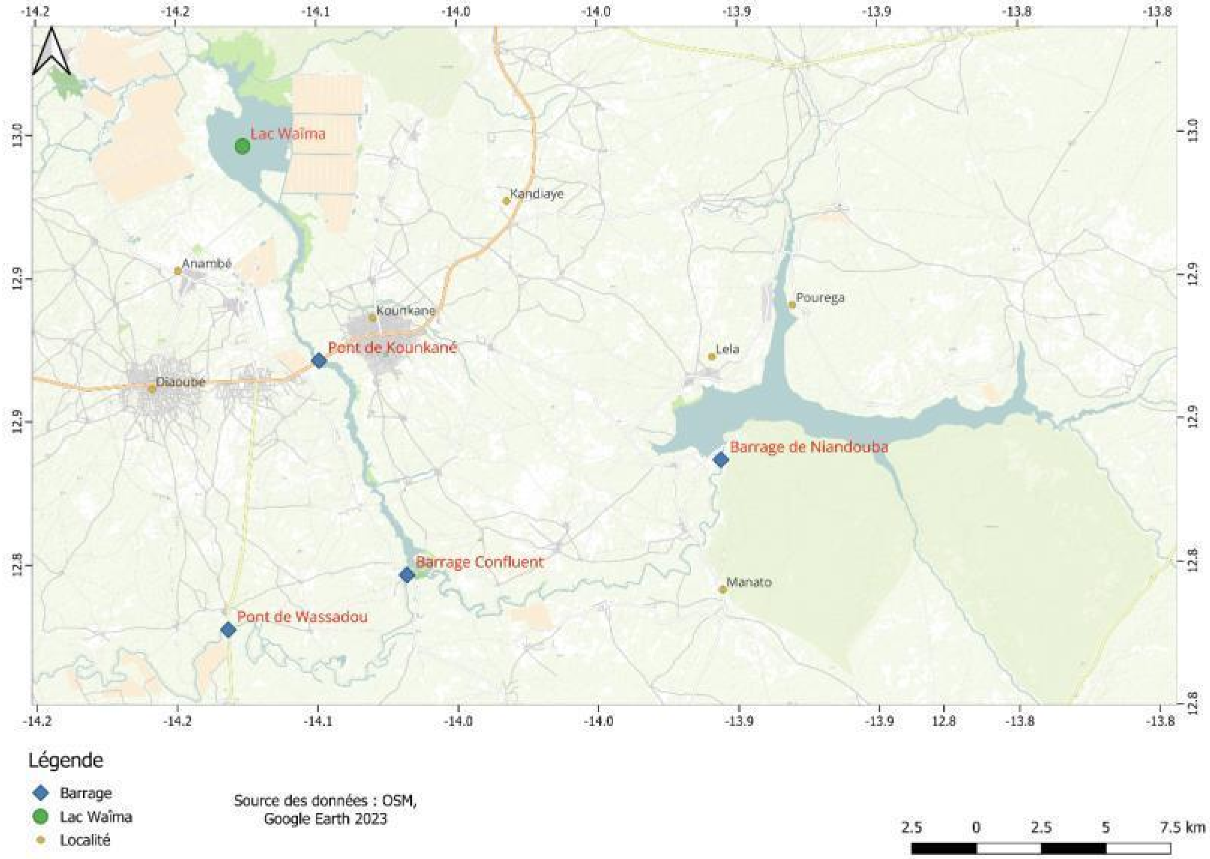

Figure 3: Location of water bodies and hydraulic infrastructure

1.3. The Niandouba Dam

The Niandouba dam is in the Kayanga basin on the bed of the river of the same name about 20 km upstream from its confluence with the Anambé river. Its commissioning dates from 1999.

Table 2: Characteristics of the Niandouba dam (after its commissioning)

Sea wall	- Type: Homogeneous in earth - Volume of backfill: 250,000 m3 - 1,320 m long and 5.5 m wide - Ridge elevation: 34 m IGN - Maximum height: 18m

	- Slopes of the upstream and downstream facings: 2.5/1 and 2/1
Water retention	- Normal restraint height RN: 30.9 m IGN - Minimum operating level: 26 m IGN (8 million m3) - Capacity: 90 million m3 - Surface area of the water body: 27.5 km² - Usable volume : 75 million m^3
Spillway	- Type: Concrete Creager type spillway - Length: 75 m - Design flood : 400 m3/s
Emptying/restitution work	- Flow: 8.5 m3/s nominal - Cofferdam valve - Roller valve - Debris grid - Restitution gallery (2.5x2.5), length 42 m

1.4. Hydraulic Channels

The perimeters are supplied with water by gravity feed channels from the Anambé River around Lake Waïma to the pumping stations.

Table 3. Supply Channels

Sectors	Developed area by sector. (ha)	Linear length of feed channels (m)
1	285	3 400
2	1080	
3	250	1 444
4	831	3 250
5	1 365	4 500

G	1 186	4 300

1.5. Pumping station

The abstraction structures consist of five pumping stations equipped with submersible pumps to pump water from the supply channels to the perimeters.

The pumping stations are each equipped with submersible electric pumps and supplied with electrical energy by generators (presented on skis and under soundproof cover) or from the SENELEC network.

Table 4: Characteristics of pumping stations

Sector	Station	Number of Pumps	Rated unit flow (l/s)	HMT (m)	Pu (KW)
1 et 2	SPA	2	1 400	15,4	290
3	SP3	3	222	10	37
4	SP4	2	750	7.4	75
5	SP5-ancien	2	600	7.5	63
	SP5.2	2	400	7.5	37
	SP5.1	2	1 150	7.5	75
G		2	1 200	9	135

1.6. Irrigated areas

From the pumping stations, water is pumped towards the perimeters using penstocks leading to primary canals.

The regulation and distribution structures (mask modules) are arranged at the head of the secondary canals and aim to ensure the regular distribution of water.

The irrigated areas (sectors) are developed on the periphery of the central depression of the Anambé basin. These are low areas mainly used for rice cultivation located above the 22 m level to avoid flooding.

Five sectors are developed on the right bank of the Anambé (sectors 1 to 5) and one on the left bank (sector G).

The construction of the perimeters began in 1982 and took place according to the following phases (Hathié *et al.* 2015):

- Phase 1 (1982 to 1991): 555 ha,
- Consolidation phase (1992 to 1996): 930 ha,
- Phase 2 (1996 to 1999): 2,805 ha,
- Phase 3 (2003 to 2009): 820 ha.

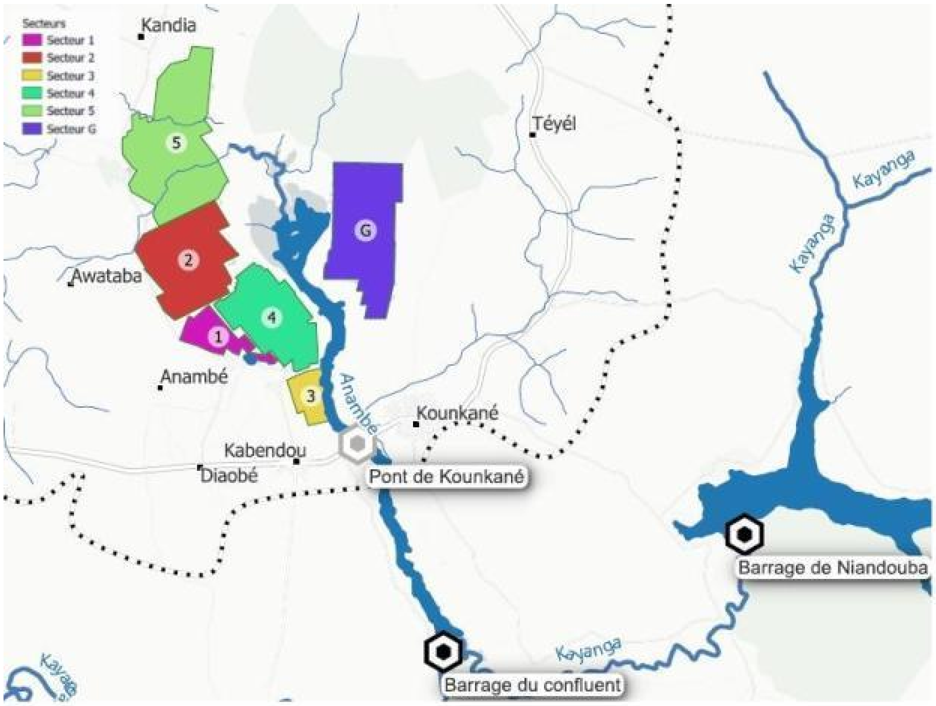

Figure 4: Irrigated sectors in the study area

2. Observed Data

2.1. Climatic Data

The Kayanga basin is part of what is called the region of hot and humid low latitudes. In this region, the rivers are fed exclusively by rain, and this gives precipitation a decisive role in explaining the modalities of river flow. The characterization of the rainfall regime and its variability is done using rainfall chronicles (annual and monthly) from the measurement networks. At the level of the Kayanga basin, the monitoring and collection of rainfall data is the responsibility of the meteorological departments of the various countries making up the region studied. These are the National Meteorological Directorates (DMN) of Guinea, Senegal, and that of Guinea Bissau. Table 5 gives the geographical coordinates of the rainfall stations whose data were collected. The selection criteria for rainfall stations are based on three fundamental factors:

- The importance of the sample size.
- Their proximity to the study area (i.e., their geographical position).
- The quality of the data (small gaps in the different series observed).

Based on these criteria, thirteen rainfall stations were selected as reference stations for the rainfall study (Table 5). Given the low density of rainfall stations, especially in the southern part of the basin, and the fact that Guinean climatic data (Guinea Conakry) could not be collected, two fictitious stations (SF5 and SF6) were added to complete the data. data observed with those of the CRU (Harris et al., 2020). Before using the CRU data, they were validated using data from the Kolda station which is the reference station in the area.

Table 5: List of rainfall stations selected for the study area.

Name of the Station	Latitude	Longitude	Obs. Variable	Period observed
Kounkane	12.93	14.08	Rain	1963-2012
Dabo	12.88	14.48		1975-2012
Fafacourou	13.07	14.57		1962-1998
Kolda	12.88	14.97	Rain, Temperatures	1940-2020
Médina Yoro	13.3	14.72	Rain	1973-2004
Vélingara	13.15	14.1		1940-2018
Basse	13.32	14.22		1942-2014
SF6	12.92	13.45	Rain, Temperatures	1940-2020
SF5	12.39	13.48	Rain, Temperatures	1940-2020
Pirada	12.67	14.17	Rain	1950-1989
Pakour	12.72	14		1997-2012
Linkering	12.97	13.73		1944-2004
Bonconto	13.02	13.93		1975-2004

Regarding potential evapotranspiration (ETP), given the fact that only the station of Kolda which has climatic data for the calculation of the ETP, the data of the CRU are used for the calculation of the average ETP of the Kayanga sub-watersheds. The coordinates of Rainfall data were used for the extraction of ETP data from the CRU. As reminded above prior to use CRU data has been validated using station data Kolda reference.

2.2. Hydrometric data

The Kayanga watershed is equipped with nine hydrometric stations which are: the stations of Mayel Maréwé, Sansankoto, Kouthidy, Koundiama, Sector 5, the Kounkané bridge, the Wassadou bridge, the Confluence dam and the Niandouba (Table 6).

The spatial distribution of these stations is illustrated in figure 5 below. All the stations were equipped with thalimede (configurable electronic encoders) attached to limnometric scales installed between 1999 and 2000. Each thalimede is attached to an IGN rating and instantly records water heights. At the two dams (Confluence and Niandouba), the thalimede records variations in the coasts of the body of water in the reservoir. Downstream of the two dams other thalimedes are installed. These make it possible to determine the leaks of water, which also makes it possible to monitor hydraulic structures because significant leaks indicate a malfunction or failure in the structure of the work which may constitute a danger potential for the safety of the latter.

Table 6: Characteristics of the hydrometric stations in the Kayanga watershed

Stations	Latitude	Longitude	Altitude m IGN	Date of activation
Mayel Maréwé	12° 57 N	13° 55 W	75	2005
Sansahkoto	12° 54 N	13° 46 W	90	2005
Kouthidy	12° 51 N	13° 47 W	75	2005
Koundiama	12° 41 N	13° 45 W	-	2005
Sector 5	13° 02 N	14° 10 W	60	2005
Kounkané bridge	12° 55 N	14° 05 W	17.2	1977
Wassadou bridge	12° 49 N	14° 07 W	13.9	1976
Confluence dam	12° 50 N	14° 04 W	22.3	-
Niandouba dam	12° 53’ N	13° 57’ W	30.9	1997

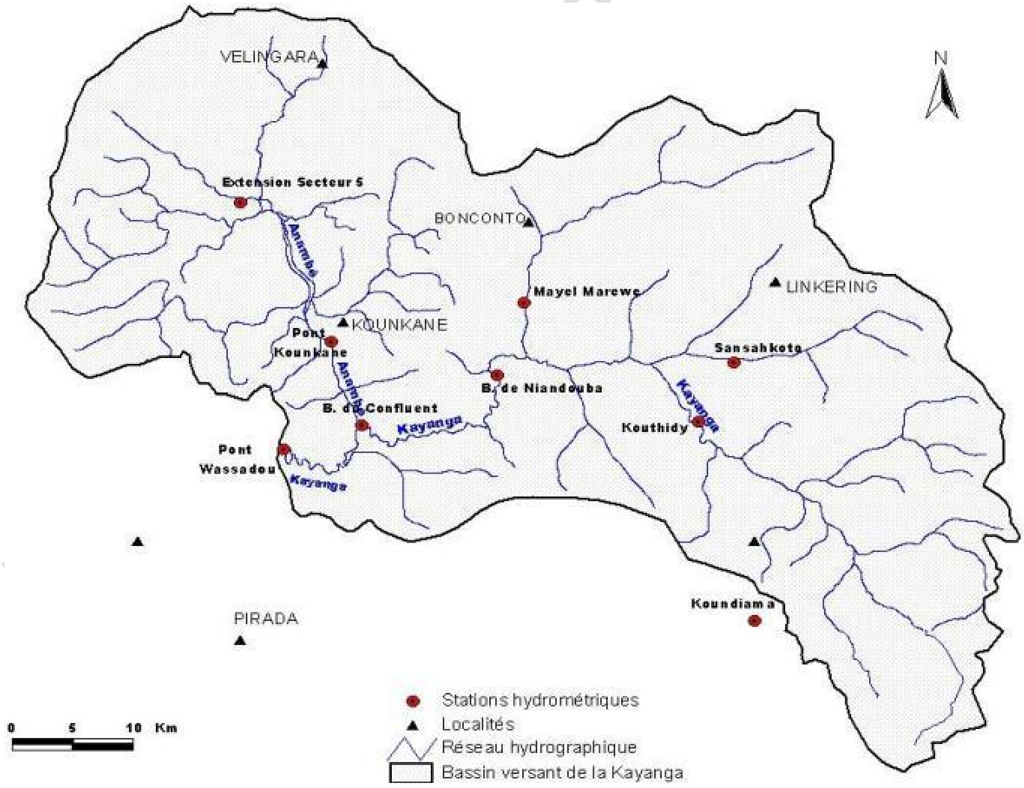

Figure 5: Hydrometric network of the Kayanga basin

3. Status of hydrometric data

Table 7 gives the inventory of the hydrological data of the Kolda brigade which follows the basin of Kayanga. It should be mentioned that the hydrological monitoring of the Kayanga-Anambé complex is too incomplete. Only the Wassadou station at the bridge has a rating curve (fig.6) by consequent amount of usable flow data. Indeed, most of the installed hydrometric stations only measure water levels. This situation constitutes a limit for the conduct of hydrological studies but also the assessment of water availability.

Table 7: Inventory of hydrological data of the Kolda brigade

Name	Longitude	Latitude	Start date	End date	% Gaps	Duration	Rivers
Alexandrie	-14.69	12.78	19/07/1988	09/12/1999	82	2	Tiangol
Confluence bridge	-14.07	12.85	11/08/1998	12/12/1999	0	1	Kayanga
Fafacourou	-14.55	13.05	02/01/1968	01/11/2000	85	5	Casamance
Kolda	-14.94	12.89	01/12/1963	19/10/2020	27	41	Casamance
Medina Abdoul	-14.58	12.85	30/10/1968	27/09/1993	40	15	Khorine
Medina Omar	-14.73	12.85	02/06/1967	02/08/2005	38	24	Khorine
Niapo	-14.07	12.85	22/05/1976	04/11/1982	25	5	Kayanga
Sare Fode	-15.35	13.08	11/05/1978	20/06/2001	78	5	Sougroungrou
Sare Keita	-14.94	12.83	02/01/1968	20/06/2001	65	12	Dioulakolon
Sare Koutayel	-14.88	12.93	19/10/1968	01/05/1990	31	15	Niampampo
Sare Sara	-14.75	12.84	02/06/1967	02/08/2005	38	24	Tiangol
Wassadou bridge	-14.13	12.83	01/05/1976	09/08/2005	27	21	Kayanga

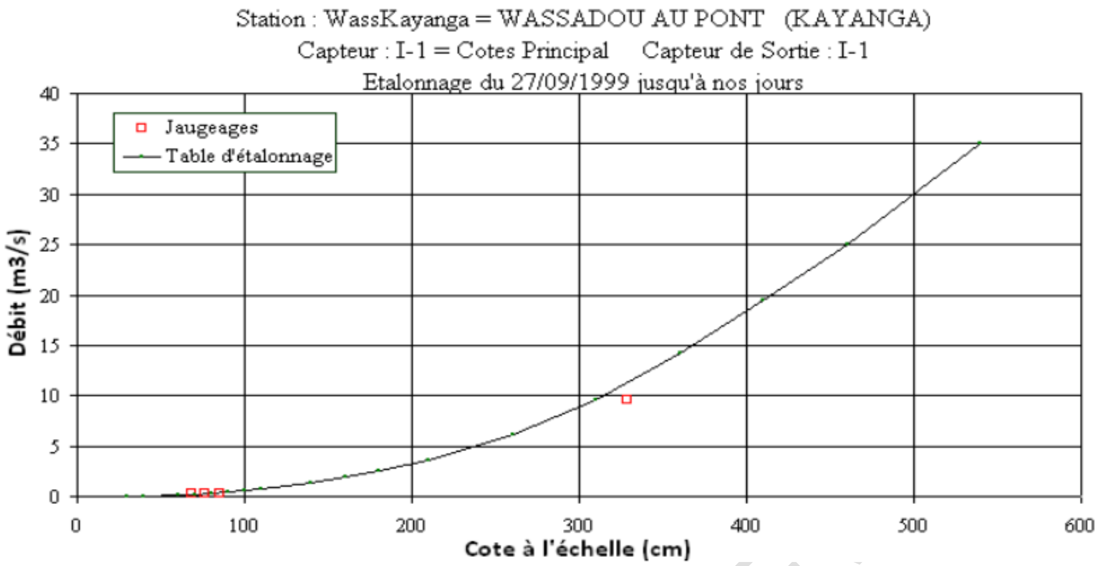

Figure 6: Calibration curve of the Kayanga at the Wassadou bridge

4. Critique of hydrological data and extension of series

The hydrological data from the Kayanga hydrometric stations do not make it possible to estimate the average contributions at the level of the various dams but also of the upstream basin of Vélingara Pakane. Indeed, the Wassadou station which has a few series controls all the flows Kayanga, including contributions from Anambé. But given the gradual implementation control structures on the watercourse, only the modules from 1976/77 to 1984/85 (commissioning of the Confluence dam) of this station will be taken into consideration, i.e., 9 years.

Indeed, after 1985 the Wassadou modules no longer correspond to the real contributions from the upstream basin: (i) the Kounkané threshold created the Lake Waïma reservoir (twenty-five million m^3) constituted by the contributions of the Anambé; (ii) the Confluence Dam created the transitional reservoir allowing the elevation of the plan in the Anambé basin. The volume of its reservoir is estimated at thirty-four million m^3; (iii) the Niandouba reservoir, in 1997, whose useful volume is of eighty-five million m^3. So only part of the basin's contributions upstream (ecological flow of SODAGRI) transits downstream and is measured at the Wassadou station currently. This situation requires only taking the data from Wassadou before the construction of the various dams to estimate the contributions of different sub-basins. Within the framework of this study, a correlation between the flows of Wassadou and those of the other hydrometric stations of the UGP (Management and Planning Units) of Casamance and eastern Senegal was used to estimate the contributions of the different sub-watersheds of the Kayanga.

5. GR2M Model

GR2M is a global conceptual hydrological model that operates on a monthly time step. It contains two free parameters to calibrate X1 and X2: X1 intervenes in the "production function" part then that X2 intervenes in the “transfer function” part. The production function reflects the actual transformation of rain into a layer of water available for runoff; the function of transfer translates the movement of this layer of water, accumulated on the ground during precipitation, towards the outlet of the watershed. These two parameters are determined for the entire catchment area. Figure 7 presents the conceptual diagram of the model. We refer to Makhlouf and Michel (1994) and to Paturel et al. (1995) for the detailed description of the model.

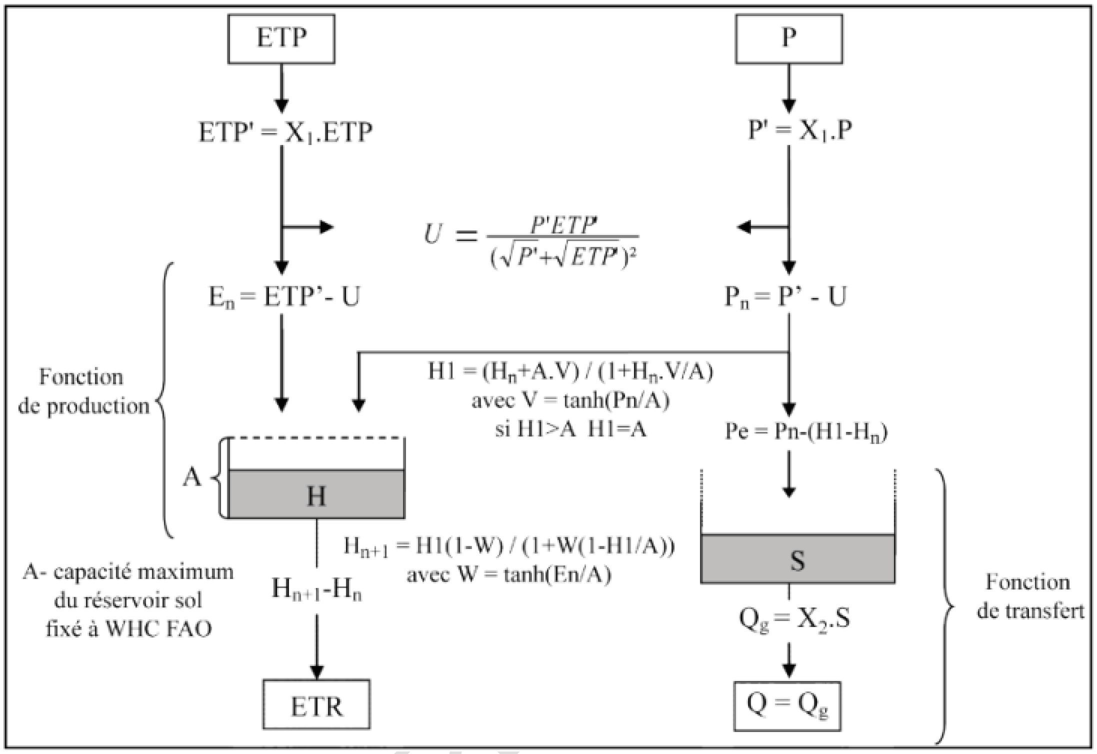

Figure 7: Conceptual diagram of the GR2M model (Bodian et al., 2012)

The robustness of this model to simulating flows in an African context has been shown in several studies (Paturel et al., 1995; Bodian et al., 2012 and 2015a) and it is not very data-intensive; it requires rain and ETP data as input.

5.1. Calibration and Validation of the GR2M model

Once the modeling structure has been chosen, it is necessary to estimate some of its parameters. We refer to this step as calibration of the model. Thus, setting a model consists of bringing the behavior of the model as closely as possible to that of the modeled basin reproduce as best as possible the hydrological behavior of the basin. In general, the method of bringing together these behaviors consists of perfecting the model parameters. In practice, there are two types of techniques for calibrating a model: manual techniques and automatic techniques. In this work a wedging automatic via one iteration was chosen.

Generally, it is cross-validation that is used in the literature to evaluate the performance of a hydrological model. This method consists of calibrating the model in a first time over a period then in a second time to conduct a critical examination of the latter by validating over another period (Bodian et al., 2012; 2015; Thiaw, 2020; 2021). Which allows you to appreciate the quality of the model on data which was not used for calibration. However, given the nature of data available from Kayanga to Wassadou (a very short series) so we calibrated the model

GR2M over the entire period of available data (period 1977-1984); the parameters as well determined were used to simulate the flows.

5.2. Evaluation of model performance

Optimization (or calibration) of model parameters requires the definition of an objective function quantifying the model error, the difference between the observed flow rates and the simulated flow rates. We can distinguish two types of criteria for evaluating model performance (Perrin & Littlewood 2000): quantitative criteria which use numerical evaluations. The qualitative criteria, for their part, are based on graphical observations (hydrographs comparing flow rates observed and simulated). They make it possible to compare, through illustrations, the simulations with reality observed and detect certain anomalies that are poorly detectable by traditional numerical criteria (Perrin & Littlewood 2000). The evaluation of the GR2M model was conducted using the Nash criterion and the coefficient correlation. The Nash criterion (Nash and Sutcliffe, 1970) calculated on flow rates is commonly used in hydrology. This criterion is based on the sum of squared errors and its formulation is as follows:

$$Nash\ (Q) = 1 - \frac{\sum_{i=1}^{n} (Q_{obs,i} - Q_{cal,i})^2}{\sum_{i=1}^{n} (Q_{obs,i} - \overline{Q_{obs}})^2}\ (1)$$

where:

Qobs, i is the observed flow at time step **i**; **Qcalc, i** is the simulated flow at time step i**;** $\overline{Q_{obs}}$ is the average observed flow; ***i*** is the time step; **n** is the total number of time steps of the simulation period.

The fitted model is all the better when the objective function is close to 1 (or 100% when we raise the values in percentage) and a criterion of less than 0.6 (or 60%) does not give a satisfactory agreement between the hydrographs observed and simulated by the model (Ardoin, 2004).

III. RESULTS AND DISCUSSION

1. Validation of CRU and ETP data

As reminded above prior to use CRU data has been validated using station data Kolda reference. Figure 8 provides a summary of CRU data validation and Figure 9 gives the seasonal cycle of the ETP at the level of some stations.

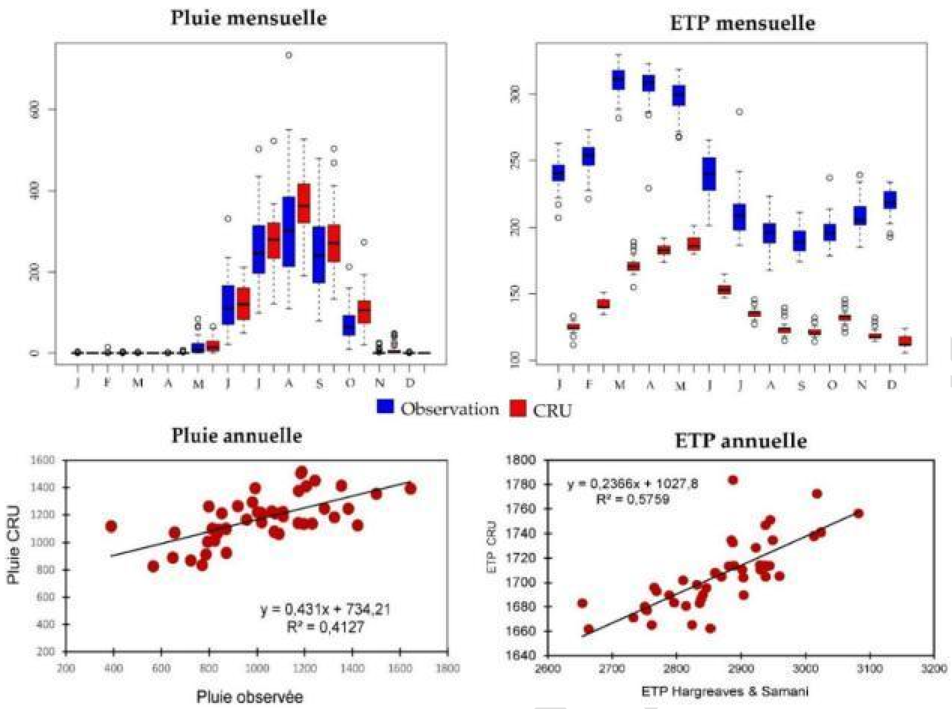

Figure 8. Validation of CRU rainfall and ETP data with station data Kolda reference

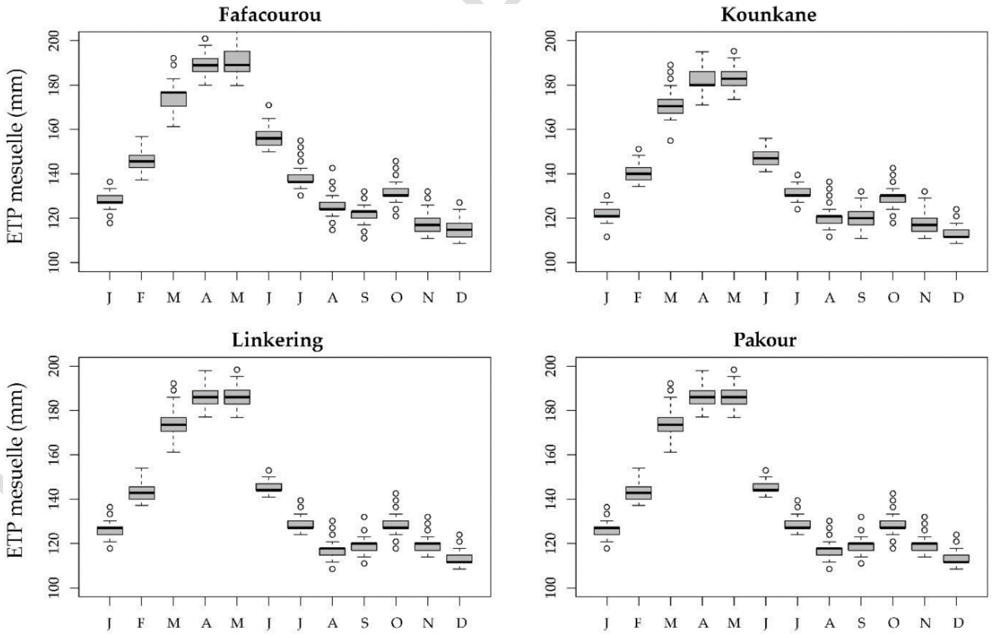

Figure 9. Seasonal cycle of the ETP of some stations of the Kayanga basin

In the approach of a global modeling, the average rains were calculated by the method of the inverse squared distance (Bodian et al., 2015; Thiaw, 2020) at the sub-catchment scale using the point data. The results obtained are shown in figure 10. The average rainfall and

ETP in figure 10 are used for the calibration of the GR2M model then for the simulation of the monthly flows of the different sub-watersheds.

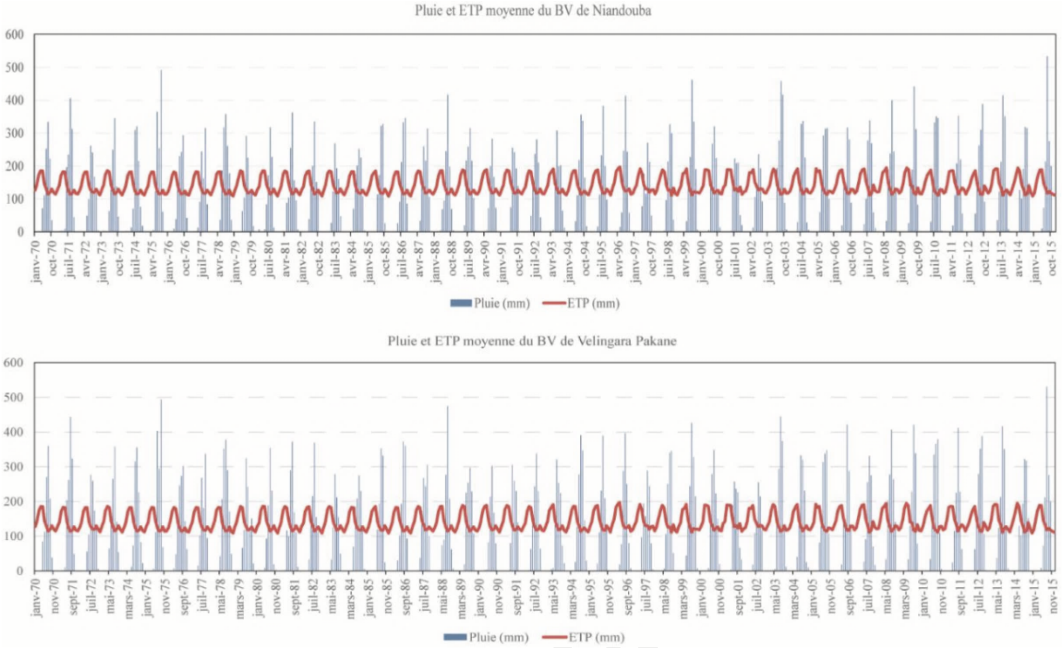

Figure 10: Average rainfall and ETP used for calibration-validation and flow simulation sub-watershed monthly.

2. Flow-flow Correlation

From the data in figure 11 below, a correlation was sought between the annual modules of the Kayanga in Wassadou and those of other hydrometric stations.

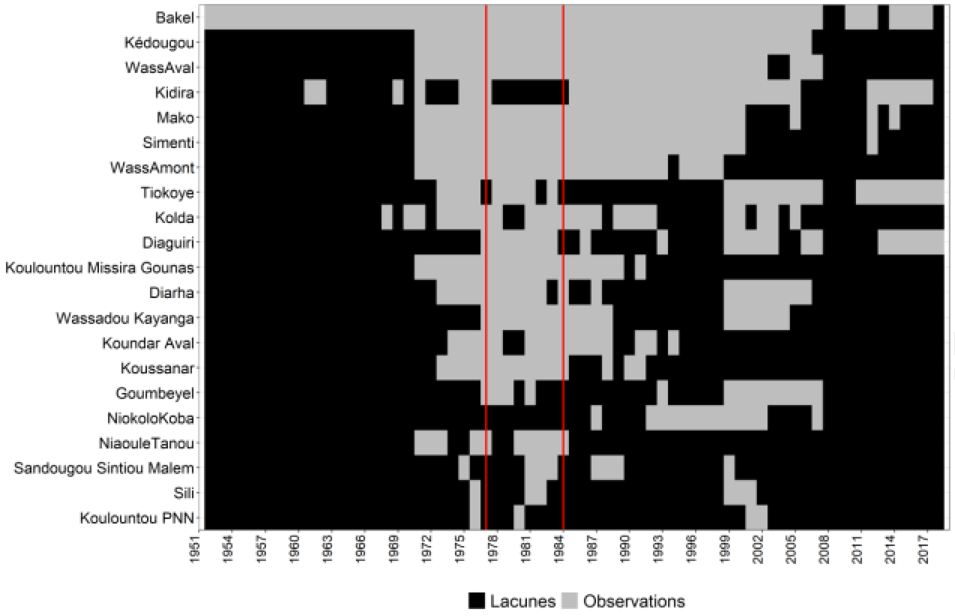

Figure 11. Inventory of annual modules of the different hydrometric stations of the UGP of the Casamance and Eastern Senegal

Table 8 gives the coefficients correlation and determination of the flow rates of Wassadou-Kayanga and those of the stations of Bakel, Kedougou, Koussanar, Mako, Koulountou, Simenti, Wassadou upstream and Wassadou downstream of the Gambia. These eight stations are those which have a common data period with the Wassadou-Kayanga station (figure 11). Thus, the correlation coefficients vary from 0.24 to 0.96 depending on the stations showing overall a strong relationship between the flow rates of Wassadou-Kayanga and those of the other stations. The Maximum correlation coefficient is noted at mako station (0.96). The determination coefficients vary in the same proportion with values ranging from 0.06 to 0.92 (Table 8).

Table 8: Correlation and determination coefficients of the flows of Wassadou and the others hydrometric stations

Station	Correlation coefficient (r)	Coefficient of determination (r²)
Bakel	0,91	0,84
Kedougou	0,95	0,91
Koussanar	0,24	0,06
Mako	0,96	0,92
Koulountou	0,72	0,52
Simenti	0,88	0,77

Wassadou upstream	0,89	0,79
Wassadou downstream	0,89	0,79

The linear relationship in figures 12-14, between the flow rates of Wassadou Kayanga and the flow rates of Mako (river Gambia) was used to reconstruct the annual modules of Kayanga-Wassadou over the period 1971-2000 (Table 9). The reconstructed flows of the Kayanga- Wassadou were then used to reconstruct the flows from the Vélingara Pakane basin and the inflows from the Niandouba dam. Indeed, the APD of the Vélingara Pakane dam considers that the Vélingara Pakane sub-basin represents 40% of the flow of the Kayanga-Wassadou. Subsequently, the surface ratio between the basin of Wassadou and Vélingara Pakane was used to calculate the contributions from the Niandouba basin. The results obtained from these different flow-flow correlations are presented in the table 9. The flow-flow correlation even if it made it possible to reconstituting the annual modules does not consider the monthly scale. Furthermore, because of the Kayanga exchanges and the Anambé-Lac Waïma complex, the flow-flow correlation will not be used to restore the flows of the basin controlled by the confluence dam. For the reconstitution of seasonal flows and contributions to the confluence dam the rainfall-flow modeling is privileged.

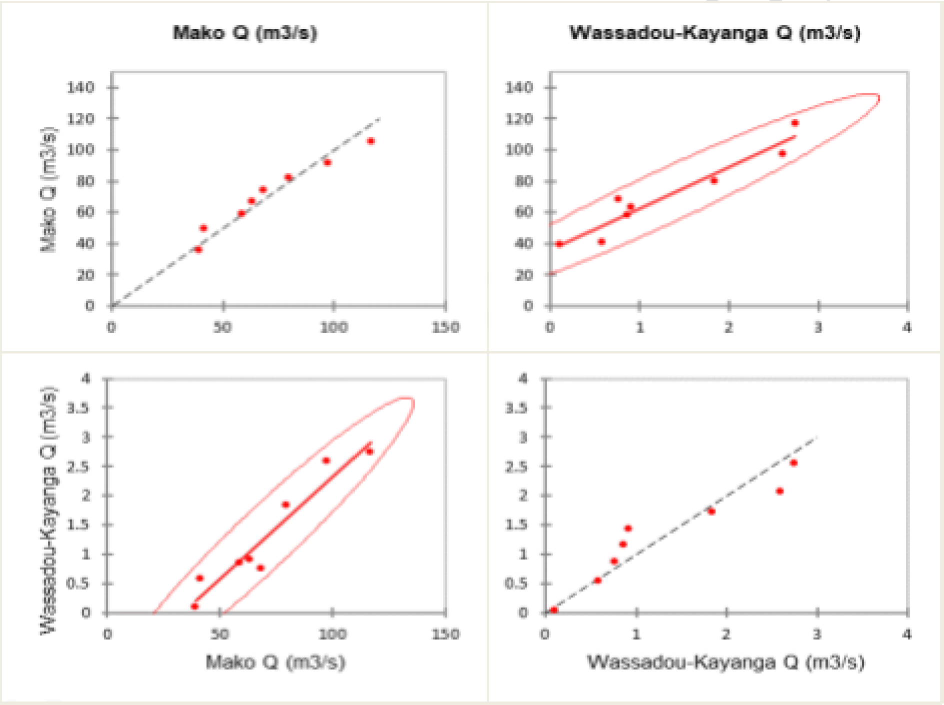

Figure 12. Linear relationship between Wassadou-Kayanga and Gambia discharges at Mako (River Gambia)

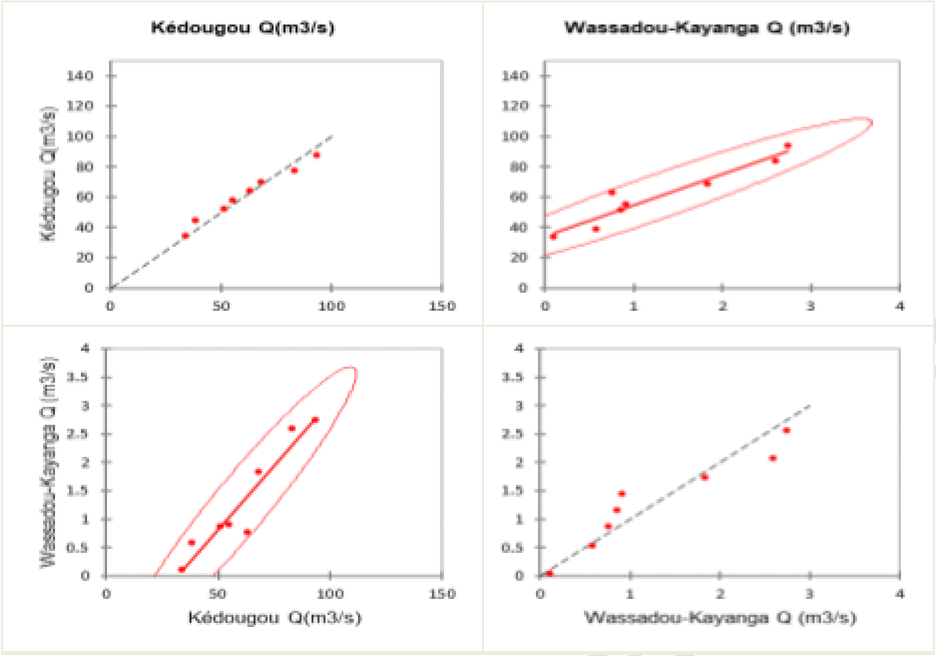

Figure 13. Linear relationship between Wassadou-Kayanga and Gambia discharges at Kedougou

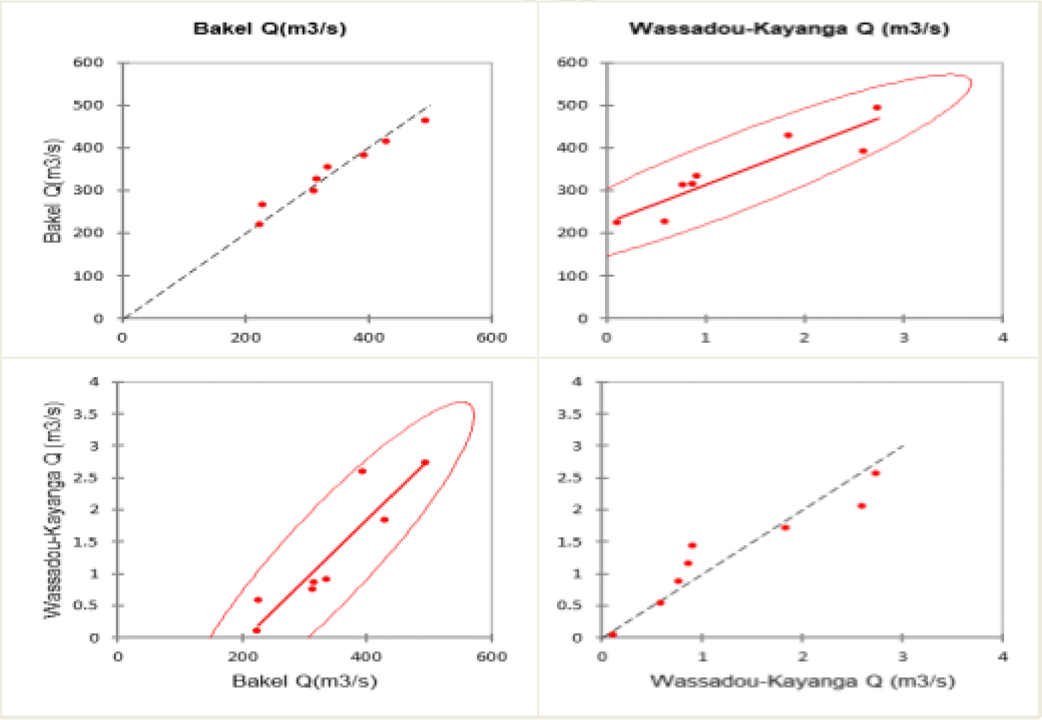

Figure 14. Linear relationship between Wassadou-Kayanga discharges and Bakel discharges

Table 9. Reconstituted annual flows (m3/s) of the Kayanga and the corresponding volumes in m3.

Year	Mako	Obs. Q (m3/s) Wassadou	Calc. Q (m3/s) Wassadou	Calc. Q(m3/s) Velingara Pakane	Calc. Q(m3/s) Niandouba	Vol. (m3) Wassadou	Vol. (m3) Vélingara P.	Vol. (m3) Niandouba
1971	79.95		1.62	0.65	1.56	51 182 455	20 472 982	49 135 157
1972	72.11		1.46	0.59	1.41	46 163 437	18 465 375	44 316 900
1973	95.18		1.93	0.77	1.85	60 932 409	24 372 963	58 495 112
1974	128.4		2.61	1.04	2.5	82 199 215	32 879 686	78 911 246
1975	107.2		2.18	0.87	2.09	68 627 382	27 450 953	65 882 286
1976	84.07		1.71	0.68	1.64	53 820 000	21 528 000	51 667 200
1977	63.19	0.9	1.28	0.51	1.23	40 453 025	16 181 210	38 834 904
1978	116.8	2.7	2.37	0.95	2.28	74 773 117	29 909 247	71 782 193
1979	58.44	0.9	1.19	0.47	1.14	37 412 166	14 964 866	35 915 679
1980	97.27	2.6	1.97	0.79	1.9	62 270 386	24 908 155	59 779 571
1981	79.69	1.8	1.62	0.65	1.55	51 016 008	20 406 403	48 975 368
1982	68.22	0.8	1.38	0.55	1.33	43 673 134	17 469 254	41 926 209
1983	41.1	0.6	0.83	0.33	0.8	26 311 431	10 524 572	25 258 974
1984	39.13	0.1	0.79	0.32	0.76	25 050 275	10 020 110	24 048 264
1985	96.26		1.95	0.78	1.88	61 623 804	24 649 522	59 158 852
1986	55.03		1.12	0.45	1.07	35 229 149	14 091 660	33 819 983
1987	62.68		1.27	0.51	1.22	40 126 533	16 050 613	38 521 471
1988	76.17		1.55	0.62	1.48	48 762 572	19 505 029	46 812 069
1989	94.93		1.93	0.77	1.85	60 772 363	24 308 945	58 341 469
1990	69.76		1.42	0.57	1.36	44 659 013	17 863 605	42 872 652
1991	79.06		1.6	0.64	1.54	50 612 694	20 245 078	48 588 186
1992	56.12		1.14	0.46	1.09	35 926 946	14 370 779	34 489 869
1993	62.93		1.28	0.51	1.23	40 286 578	16 114 631	38 675 115
1994	147		2.98	1.19	2.86	94 106 578	37 642 631	90 342 314
1995	122.1		2.48	0.99	2.38	78 166 076	31 266 430	75 039 433
1996	100.7		2.04	0.82	1.96	64 466 207	25 786 483	61 887 558
1997	127.1		2.58	1.03	2.48	81 366 980	32 546 792	78 112 300
1998	112.8		2.29	0.92	2.2	72 212 394	28 884 958	69 323 898
1999	112.7		2.29	0.92	2.2	72 148 376	28 859 350	69 262 441
2000	85.12		1.73	0.69	1.66	54 492 190	21 796 876	52 312 502
Mean	**86.4**	**1.3**	**1.8**	**0.7**	**1.7**	**55 294 763**	**22 117 905**	**53 082 973**

3. Flow simulation with GR2M model

The results of the flow simulation with the GR2M model are presented in figure 15, which gives the comparative evolution between the flow rates observed and calculated. There value of the Nash criterion obtained is 0.86, therefore greater than 0.60. However, the analysis of observed and simulated hydrographs (fig.15) shows that the model has difficulty simulating flow rates extremes. This situation is inherent to the modeling approach used which is only a simplified vision of the complexity of the functioning of the watershed (Le Lay, 2006). Moreover, Kingumbi (2006) identifies four sources of uncertainty in the differences between data measured in the field and outputs simulated by a model: (i) the random or systematic errors arising from the data (precipitation, evapotranspiration) used to represent the variation in space and time of system inputs as well as its boundary conditions; (ii) random or systematic errors in the model output data (water levels in a river, piezometric levels, flow rates of a river, etc.); (iii) errors due to an incomplete or biased structure of the model, which may not be suitable for representing the phenomena involved in the system; (iv) errors due to model parameter values that may not be optimal.

Despite this limitation of the GR2M model of which we are aware, and which may be due to the nature data used and the length of the series used, the parameters (X1 and X2) thus obtained are used for the simulation of flows from the Vélingara Pakane basin, Niandouba and the Kayanga before the Confluence over the period 1971-2000. The results of this simulation are used to evaluate water supplies to the Kayanga-Anambé-Lac Waïma complex on a monthly scale to complete the annual time step.

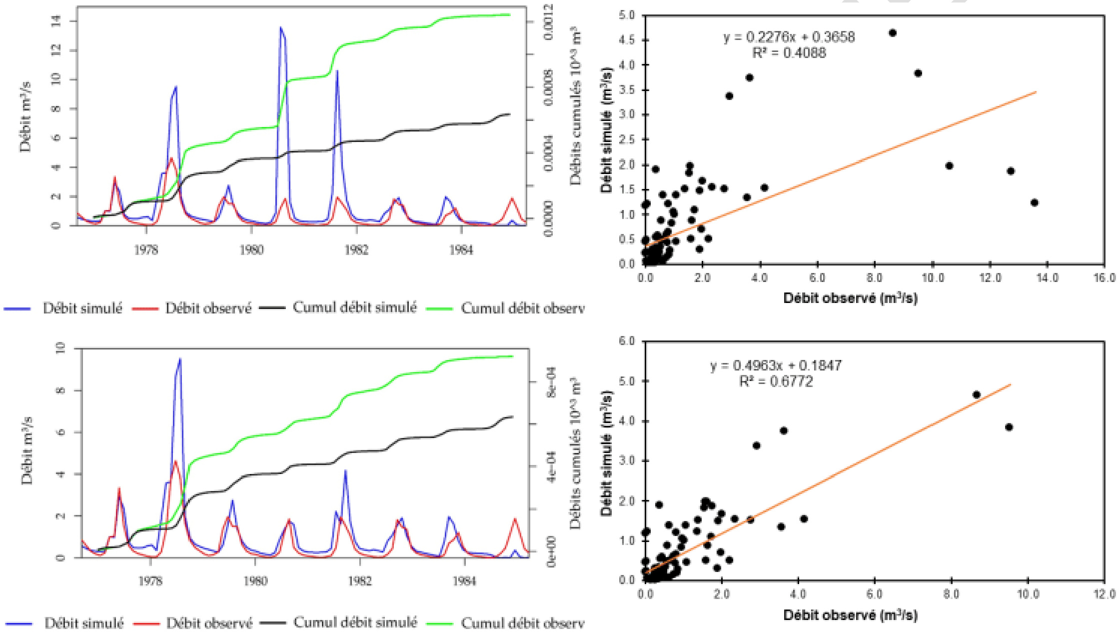

Figure 15: Calibration of the GR2M model at the Wassadou-Kayanga station over the period 1976-1984.

The analysis of tables 10 and 11 allows us to see that the differences between the modules calculated from Mako and those simulated with GR2M are significant. Thus, the ratio between the volumes calculated from Mako data and those simulated with GR2M is 2.4 for the Velingara Pakane basin and three for the Kayanga basin in Niandouba and before the Confluence. Which makes an average value of 2.8. This value is used to correct monthly volumes of different sub-watersheds.

Table 10. Average annual flows of the Kayanga sub-watersheds

Year	Pakane Cal Mako	Pakane Cal GR2M	Niandouba Cal Mako	Niandouba Cal GR2M	Confluent Cal Niandouba	Confluent Cal GR2M
1971	0.65	0.577	1.56	1.145	1.656	1.217135
1972	0.59	0.244	1.41	0.475	1.494	0.504925

1973	0.77	0.213	1.85	0.426	1.972	0.452838
1974	1.04	0.227	2.5	0.434	2.66	0.461342
1975	0.87	0.53	2.09	1.02	2.221	1.08426
1976	0.68	0.398	1.64	0.692	1.742	0.735596
1977	0.51	0.247	1.23	0.406	1.309	0.431578
1978	0.95	0.592	2.28	1.019	2.42	1.083197
1979	0.47	0.297	1.14	0.515	1.211	0.547445
1980	0.79	0.169	1.9	0.287	2.015	0.305081
1981	0.65	0.254	1.55	0.425	1.651	0.451775
1982	0.55	0.216	1.33	0.404	1.413	0.429452
1983	0.33	0.119	0.8	0.234	0.851	0.248742
1984	0.32	0.178	0.76	0.342	0.811	0.363546
1985	0.78	0.207	1.88	0.386	1.994	0.410318
1986	0.45	0.28	1.07	0.541	1.14	0.575083
1987	0.51	0.28	1.22	0.562	1.298	0.597406
1988	0.62	0.358	1.48	0.639	1.578	0.679257
1989	0.77	0.298	1.85	0.665	1.967	0.706895
1990	0.57	0.131	1.36	0.26	1.445	0.27638
1991	0.64	0.151	1.54	0.235	1.638	0.249805
1992	0.46	0.216	1.09	0.33	1.163	0.35079
1993	0.51	0.191	1.23	0.287	1.304	0.305081
1994	1.19	0.414	2.86	0.668	3.045	0.710084
1995	0.99	0.3	2.38	0.584	2.529	0.620792
1996	0.82	0.275	1.96	0.514	2.086	0.546382
1997	1.03	0.223	2.48	0.312	2.633	0.331656
1998	0.92	0.251	2.2	0.353	2.337	0.375239
1999	0.92	0.499	2.2	1.042	2.335	1.107646
2000	0.69	0.367	1.66	0.726	1.763	0.771738
Mean	**0.7**	**0.29**	**1.68**	**0.53**	**1.79**	**0.56**

- **Pakane cal Mako**: data from the Kayanga watershed at Vélingara Pakane calculated from discharge data from the Mako station in the Gambia.
- **Pakane Cal GR2M**: Data from the Kayanga watershed at Vélingara Pakane calculated with the GR2M model.
- **Niandouba Cal Mako**: Data from the Kayanga watershed in Niandouba calculated at from flow data from the Mako station in the Gambia.
- **Niandouba Cal GR2M**: Data from the Kayanga watershed in Niandouba calculated with the GR2M model.
- **Confluent Cal Niandouba**: Data from the Kayanga watershed upstream of the confluence calculated from flow data from the Niandouba station compared to surface area between the Kayanga at Niandouba and the Kayanga upstream of the Confluence.
- **Confluent Cal GR2M**: Data from the Kayanga watershed upstream of the confluence calculated with the GR2M model by transposition of simulations conducted in Niandouba.

Table 11. Availability of surface water in the Kayanga sub-watersheds

Year	Pakane Cal Mako	Pakane Cal GR2M	Niandouba Cal Mako	Niandouba Cal GR2M	Confluent Cal Niandouba	Confluent Cal GR2M
1971	20 472 982	18 196 272	49 135 157	36 108 720	52 230 672	38 383 569

1972	18 465 375	7 694 784	44 316 900	14 979 600	47 108 865	15 923 315
1973	24 372 963	6 717 168	58 495 112	13 434 336	62 180 304	14 280 699
1974	32 879 686	7 158 672	78 911 246	13 686 624	83 882 655	14 548 881
1975	27 450 953	16 714 080	65 882 286	32 166 720	70 032 871	34 193 223
1976	21 528 000	12 551 328	51 667 200	21 822 912	54 922 233	23 197 755
1977	16 181 210	7 789 392	38 834 904	12 803 616	41 281 503	13 610 244
1978	29 909 247	18 669 312	71 782 193	32 135 184	76 304 471	34 159 701
1979	14 964 866	9 366 192	35 915 679	16 241 040	38 178 367	17 264 226
1980	24 908 155	5 329 584	59 779 571	9 050 832	63 545 684	9 621 034
1981	20 406 403	8 010 144	48 975 368	13 402 800	52 060 816	14 247 176
1982	17 469 254	6 811 776	41 926 209	12 740 544	44 567 560	13 543 198
1983	10 524 572	3 752 784	25 258 974	7 379 424	26 850 289	7 844 328
1984	10 020 110	5 613 408	24 048 264	10 785 312	25 563 304	11 464 787
1985	24 649 522	6 527 952	59 158 852	12 172 896	62 885 859	12 939 788
1986	14 091 660	8 830 080	33 819 983	17 060 976	35 950 642	18 135 817
1987	16 050 613	8 830 080	38 521 471	17 723 232	40 948 324	18 839 796
1988	19 505 029	11 289 888	46 812 069	20 151 504	49 761 229	21 421 049
1989	24 308 945	9 397 728	58 341 469	20 971 440	62 016 981	22 292 641
1990	17 863 605	4 131 216	42 872 652	8 199 360	45 573 629	8 715 920
1991	20 245 078	4 761 936	48 588 186	7 410 960	51 649 242	7 877 850
1992	14 370 779	6 811 776	34 489 869	10 406 880	36 662 730	11 062 513
1993	16 114 631	6 023 376	38 675 115	9 050 832	41 111 647	9 621 034
1994	37 642 631	13 055 904	90 342 314	21 066 048	96 033 880	22 393 209
1995	31 266 430	9 460 800	75 039 433	18 417 024	79 766 917	19 577 297
1996	25 786 483	8 672 400	61 887 558	16 209 504	65 786 474	17 230 703
1997	32 546 792	7 032 528	78 112 300	9 839 232	83 033 375	10 459 104
1998	28 884 958	7 915 536	69 323 898	11 132 208	73 691 304	11 833 537
1999	28 859 350	15 736 464	69 262 441	32 860 512	73 625 975	34 930 724
2000	21 796 876	11 573 712	52 312 502	22 895 136	55 608 190	24 337 530
Mean	**22 117 905**	**9 147 542**	**53 082 973**	**16 743 514**	**56 427 200**	**17 798 355**

4. Analysis of annual and monthly flows

The different methods used made it possible to reconstruct the annual modules of the different sub-sections basins and calculate the corresponding water volumes. Figure 16 below shows the variation in the reconstituted flows of Wassadou- Kayanga. We can notice, a variability of the flows modeled on the evolution of the rainfall, with:

- a period of water deficit between 1971 and 1992 during which the modules decreased by 11% compared to the interannual module of Wassadou-Kayanga, 1.8 m3/s; This period is also the most deficient in terms of rainfall in the entire Kayanga basin (Sambou, 2019, Thiaw, 2023) and,

- a period of excess water between 1993 and 2000 during which the modules exceed the interannual module of Wassadou by 22%. This increase in modules is a result of the improvement in the rainfall which however remains fluctuating from one year to another and particularly in years consecutive dry and wet periods, so that the tendency towards a replenishment of resources remains uncertain in the future and does not allow easy or robust prediction of the availability of water resources in the coming years. Moreover, this return of flows has as a corollary the more frequent waterlogging and silting of rice plots, thus severely compromising the resilience of producers to climate and food insecurity.

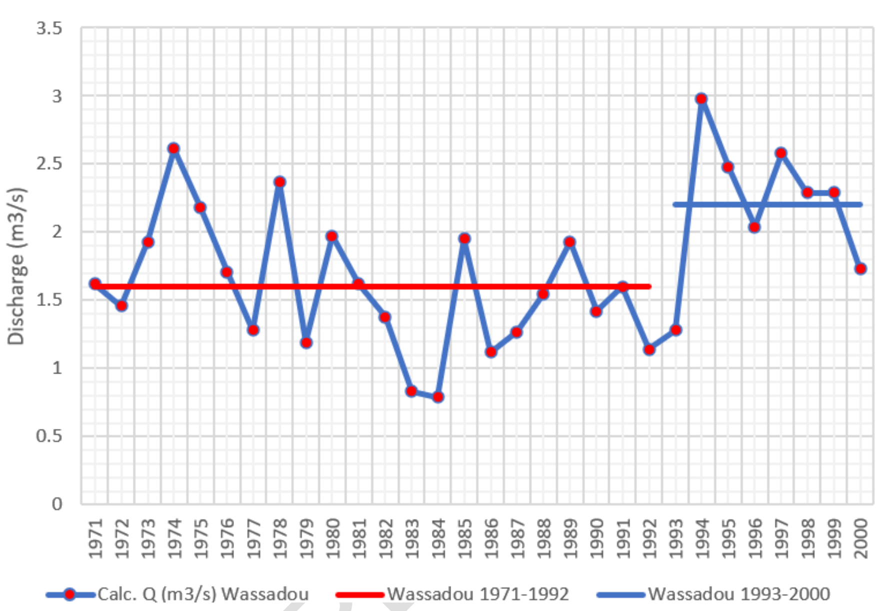

Figure 16. Annual variation of the flows of Wassadou-Kayanga (reconstituted with Mako flows) over the period 1971-2000

Tables 12 and 13 give the statistics of the modules and monthly average flow rates from the simulations with GR2M. The analysis of monthly average flow rates makes it possible to highlight the price regimes water and their inter-seasonal variations. The coefficient of variation shows that for all stations, the variation in flow rates is significant. This irregularity is stronger during periods of low water and especially at the start of the rainy season. Examination of monthly flow rates also shows a variation seasonal characteristic of the uni-modal regime with a dry season and a wet season. The flow lowest monthly flow is between April and May and the maximum flow between August and of September. The statistical characteristics are supplemented by the monthly flow coefficient (CMD) allowing the periods of high water and low water to be determined. CMDs less than unity correspond to the months of low water and the CMD greater than unity represent the months of high waters (tables 12 and 13). For the Kayanga basin at Vélingara Pakane and Niandouba, the high waters last 3 months from August to October.

Table 12: Statistical characteristics of monthly flows (m3/s) at Niandouba

Parameter	Mai	Juin	Juillet	Août	Sept	oct	nov	dec	janv	fev	Mars	Avril	Annuel

Moyenne	0.04	0.14	0.52	1.56	2.43	1.29	0.52	0.28	0.17	0.12	0.06	0.04	0.6
Médiane	0.03	0.14	0.48	1.41	2.21	1.1	0.45	0.24	0.15	0.1	0.06	0.03	0.54
Maximum	0.22	0.41	1.14	3.5	6.01	3.2	1.27	0.6	0.38	0.25	0.14	0.08	1.24
Minimum	0	0.03	0.11	0.38	0.59	0.37	0.13	0.06	0.04	0.03	0.01	0.01	0.15
Ecart Type	0.04	0.08	0.26	0.72	1.36	0.73	0.29	0.15	0.09	0.06	0.03	0.02	0.28
Coef. Variation	0.84	0.55	0.5	0.46	0.56	0.57	0.55	0.53	0.52	0.51	0.51	0.52	0.47
Coef. Variability	44	14.64	10.66	9.08	10.21	8.65	9.91	9.28	9.64	9.54	9.64	9.87	8.17
Coef. Dispersion	1.32	1	1.07	1.11	1.1	1.17	1.16	1.16	1.17	1.15	1.14	1.14	1.11
CMD	0.07	0.24	0.86	**2.6**	**4.06**	**2.15**	0.87	0.46	0.29	0.19	0.11	0.06	

Table 13: Statistical characteristics of monthly flow rates (m3/s) at Velingara Pakane

Parameter	Mai	Juin	Juillet	Août	Sept	oct	nov	dec	janv	fev	Mars	Avril	Annuel
Moyenne	0.02	0.08	0.28	0.84	1.25	0.68	0.28	0.15	0.09	0.06	0.03	0.02	0.32
Médiane	0.02	0.07	0.25	0.81	1.14	0.57	0.24	0.13	0.08	0.06	0.03	0.02	0.29
Maximum	0.1	0.18	0.62	1.84	3	1.61	0.75	0.35	0.21	0.14	0.08	0.05	0.59
Minimum	0	0.01	0.07	0.24	0.38	0.19	0.08	0.05	0.03	0.02	0.01	0.01	0.1
Ecart Type	0.02	0.04	0.13	0.34	0.63	0.34	0.14	0.07	0.04	0.03	0.02	0.01	0.13
Coef. Variation	0.73	0.52	0.46	0.4	0.5	0.5	0.51	0.47	0.46	0.46	0.46	0.46	0.41
Coef. Variability	24.5	13.14	9.18	7.55	7.88	8.68	9.51	7.73	7.21	7.26	7.7	7.5	5.82
Coef. Dispersion	1.2	1.06	1.15	1.04	1.1	1.19	1.19	1.14	1.12	1.11	1.12	1.11	1.1
CMD	0.08	0.24	0.89	**2.64**	**3.95**	**2.14**	0.89	0.47	0.29	0.2	0.11	0.06	

5. Water availability in the Anambé-Lake Waïma complex

Previously we showed that the ratio between the annual volumes calculated from data from Mako and those simulated with GR2M is 2.4 for the Velingara Pakane basin and 3 for the the Kayanga at Niandouba and before the confluence. Which makes an average value of 2.8. Thus, the data flow rates in tables 14 and 15 are multiplied by 2.8 to correct them. From the corrected flow rates, the volumes were calculated as the product of flow and time. This operation made it possible to calculate the monthly water volumes of the Kayanga at Vélingara Pakane, Niandouba and before the confluence on the period 1971-2000. The monthly and annual contributions from the Niandouba watershed are transposed to estimate the water resources of the Anambé-Lake Waïma complex.

The different results obtained are presented in tables 16 to 17. These tables give the monthly water availability in the different watersheds of the Kayanga-Anambé-Lac complex Waïma. Thus, the average annual contribution from Kayanga to Niandouba is 53 million m^3. Figure 17 gives a summary of water availability in the Kayanga-Anambé- Lake Waïma.

Table 14: Annual and seasonal water availability in the Kayanga watershed at the water station Vélingara Pakane

Month	Quantile 95% T = 5 years DR	Quantile 80% T = 20 years DR	Average Intake	Quantile 80% T= 5 years WR	Quantile 95% T = 20 years WR
May	45 947	82 222	179 307	253 558	425 297
June	162 097	284 746	515 883	716 471	1 052 363
July	846 782	1 303 095	2 119 978	2 833 283	3 973 319
August	2 587 190	4 012 581	6 094 570	8 013 683	10 546 410
September	3 531 075	5 419 310	9 411 045	12 772 914	19 025 947
October	1 873 048	2 856 732	4 930 220	6 677 545	9 919 083
November	815 755	1 238 193	2 130 716	2 877 859	4 268 076
December	443 276	676 017	1 123 224	1 508 546	2 165 581
January	269 969	410 599	676 111	906 007	1 291 715
February	187 044	286 037	466 675	624 362	880 753
March	63 651	153 148	246 923	340 699	430 199
April	38 311	92 895	149 820	207 282	261 868
Year	**12 175 857**	**18 244 084**	**28 043 531**	**36 865 004**	**49 665 092**

DR: Dry recurrences
WR: Wet recurrences

Table 15: Annual and seasonal water availability in the Kayanga watershed at the water station Niandouba

Month	Quantile 95% T = 5 years DR	Quantile 80% T = 20 years DR	Average Intake	Quantile 80% T=5 years WR	Quantile 95% T = 20 years WR
May	74 987	140 190	325 718	461 545	795 256
June	286 228	519 249	966 338	1 352 061	2 008 819
July	1 393 820	2 256 641	3 873 843	5 273 361	7 606 405
August	4 145 825	6 810 341	11 317 402	15 333 327	21 418 153
September	6 196 265	9 675 597	18 233 719	25 171 721	39 955 683
October	3 148 856	4 805 902	9 340 531	12 956 883	21 407 551
November	1 327 158	2 089 961	3 912 193	5 407 124	8 508 415
December	712 535	1 135 684	2 079 753	2 867 728	4 405 368
January	430 257	691 834	1 257 544	1 732 973	2 635 193
February	299 740	487 272	873 524	1 201 949	1 798 293
March	159 630	260 151	463 992	637 849	949 130
April	44 859	161 283	283 277	405 270	521 705

Year	**20 271 701**	**31 629 761**	**52 902 213**	**71 396 067**	**102 187 840**

Table 16: Annual and seasonal water availability in the Kayanga watershed before the confluence with the Anambé

Month	Quantile 95% T = 5 years DR	Quantile 80% T = 20 years DR	Average Intake	Quantile 80% T=5 years WR	Quantile 95% T = 20 years WR
May	79 760	149 112	346 449	490 921	845 871
June	304 446	552 298	1 027 843	1 438 116	2 136 675
July	1 482 532	2 400 270	4 120 402	5 608 995	8 090 530
August	4 409 694	7 243 799	12 037 722	16 309 249	22 781 356
September	6 590 639	10 291 420	19 394 242	26 773 828	42 498 745
October	3 349 271	5 111 784	9 935 029	13 781 551	22 770 079
November	1 411 628	2 222 981	4 161 192	5 751 272	9 049 951
December	757 886	1 207 967	2 212 123	3 050 251	4 685 757
January	457 642	735 867	1 337 583	1 843 272	2 802 915
February	318 818	518 286	929 121	1 278 449	1 912 749
March	169 790	276 709	493 523	678 447	1 009 539
April	47 715	171 548	301 307	431 064	554 910
Year	**21 561 935**	**33 642 902**	**56 269 284**	**75 940 217**	**108 691 796**

Table 17: Annual and seasonal water availability of the Anambé-Lake Waïma complex

Month	Quantile 95% T = 5 years DR	Quantile 80% T = 20 years DR	Average Intake	Quantile 80% T=5 years WR	Quantile 95% T = 20 years WR
May	35 586	68 247	154 571	219 028	377 392
June	162 993	296 310	550 281	769 931	1 143 922
July	817 573	1 323 679	2 272 281	793 079	4 461 691
August	2 493 068	4 095 360	6 805 656	9 220 610	12 879 685
September	3 815 714	5 958 317	11 228 483	15 500 965	24 605 056
October	1 767 093	2 697 003	5 241 772	7 271 217	12 013 611
November	488 585	769 407	1 440 250	1 990 601	3 132 322
December	482 611	769 216	1 349 954	1 861 423	2 859 495
January	90 629	145 727	264 888	365 033	555 076
February	175 307	284 987	510 891	702 975	1 051 754
March	88 991	145 030	258 667	355 590	529 123
April	27 186	97 740	171 671	245 601	316 163
Year	**11 989 658**	**18 707 361**	**31 288 913**	**42 227 067**	**60 438 802**

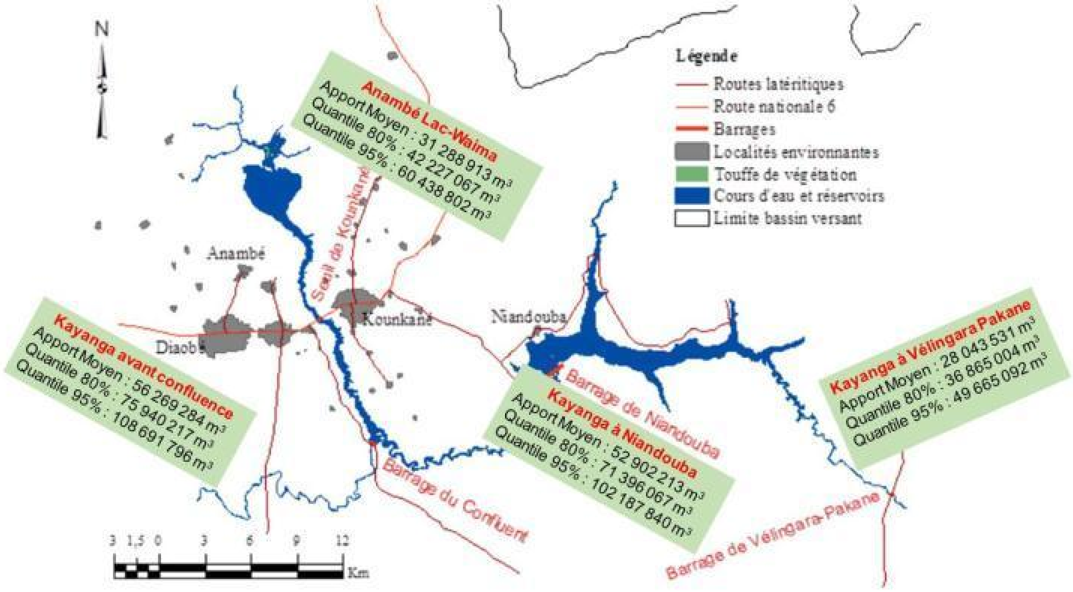

Figure 17: Water availability at the various hydraulic structures in the system Kayanga-Anambé-Lake Waïma

IV.CONCLUSION

The aim of this article was to estimate and then extend, as much as possible, the hydrological series of the Kayanga using a linear regression method, flow-flow correlation, and rainfall-flow modeling, at monthly time steps, GR2M. The results showed a very good relationship between the flow rates observed at Mako, on the Gambia River, and those observed at Kayanga-Wassadou. The correlation coefficient is 96%, thus showing a good relationship between the flow rates of the two rivers. This is justified by the fact that these watersheds are subject to the same climatic environments, and similar physical and morphometric characteristics; this is why they react in much the same way to rainfall impulses.

Furthermore, for the simulation of monthly inflows, the GR2M model showed a good match between the observed and simulated flows from the Kayanga to Wassadou, illustrated by a Nash coefficient of 86%. However, this model encounters difficulties in simulating extreme flows and low flows. This situation is inherent to the modeling approach used which is only a simplified vision of the complexity of the functioning of the watershed (Le Lay, 2006, Bodian, 2012; Thiaw, 2021). Moreover, Kingumbi (2006) identifies four sources of uncertainty in the differences between data measured in the field and outputs simulated by a model: (i) the random or systematic errors arising from the data (precipitation, evapotranspiration) used to represent the variation in space and time of system inputs as well as its boundary conditions; (ii) random or systematic errors in the model output data (water levels in a river, piezometric levels, flow rates of a river, etc.); (iii) errors due to an incomplete or biased structure of the model, which may not be suitable for representing the phenomena involved in the system; (iv) errors due to model parameter values that may not be optimal. Thus, to take this limit into account, we consider the ratio between the flow rates calculated from Mako data and those simulated with GR2M, to correct the annual and monthly contributions from the Kayanga sub-basins. This made it possible to reconstruct and extend the Kayanga series over the same observation period as the Mako, 1971-2000.

The analysis of the flows of the Kayanga revealed a variability of flows modeled on the rainfall evolution, with:

- a period of water deficit between 1971 and 1992 during which the modules decreased by 11% compared to the interannual module of Wassadou-Kayanga, 1.8 m^3/s; This period is also the most deficient in terms of rainfall in the entire Kayanga basin (Sambou, 2019, Thiaw, 2023) and,

- a period of excess water between 1993 and 2000 during which the modules exceed the interannual module of Wassadou by 22%. This increase in modules is a result of the improvement in the rainfall which however remains fluctuating from one year to another and particularly in years consecutive dry and wet periods, so that the tendency towards a replenishment of resources remains uncertain in the future and does not allow easy or robust prediction of the availability of water resources in the coming years. Moreover, this return of flows has as a corollary the more frequent waterlogging and silting of rice plots, thus severely compromising the resilience of producers to climate and food insecurity.

Moreover, the reconstituted series of flow rates made it possible to identify the following annual contributions:

- a contribution of fifty-three million m^3 from Kayanga to Niandouba dam for an average year, and thirty-two million m^3 for a dry five-year year,

- a contribution of fifty-six million m^3 from the Kayanga before the confluence for an average year, and thirty-four million m^3 for a dry five-year year,

- a contribution of thirty-one million m^3 from Anambé to Lake Waïma for an average year, and nineteen million m^3 for a dry five-year year.

Under normal rainfall conditions, the water resources available in the Kayanga-Anambé-Lake Waïma complex should be sufficient to ensure a double crop of rice on 2,500 and 1,500 ha, respectively in the rainy season and in the off-season. The initial objectives of SODAGRI are not achievable today due to the mismatch between water supply and demand due to the anticipation of farmers in the development of land in relation to the pace of development, causing use uncontrolled water resources, due to unsuitable and poorly operational management of dams (particularly for the Confluent dam at which leaks are equivalent to more than 60%) (Dacosta, Coly & Soumaré 2002), and because of water waste linked to compliance with irrigation rules (due to a lack of training for farmers) and lack of maintenance of canals

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