

WATER FLOW 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-Lake 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 extends between latitudes 12°40' and 13°10' North and longitudes 13°40' and 14°20' West and covers an area of 1 077 km² at the Kounkané bridge, while at the Confluent dam its area is 1 157 km² (fig.1).

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 Wassadou bridge, the Kayanga drains a watershed of 3 107 km² with a length of 280 km. In Senegalese territory, its main tributary is the Anambé river whose flow is oriented north-south until its confluence with the Kayanga, 10 km south of Kounkané (fig.1).

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.

Three 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 60 million m³ (with an endowment flow of 2 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 90 million m³ and an endowment flow of 4.2 m³ s⁻¹. (Hathie *et al.* 2015).
- The Kounkané threshold (or Kounkané bridge) blocks the outlet of lake Waïma to increase storage possibilities upstream of the Kounkané bridge during low water and thus allows a retention of 25 million m³ within the Anambé floodplain for the realization of hydro-agricultural projects (Hathie *et al.* 2015).

The Kayanga-Anambé system is finally presented as a series of reservoirs and hydraulic axes: upstream, the Niandouba reservoir with 90 million m³, the Niandouba-Confluent dam hydraulic axis, then the Confluent dam reservoir of 60 million m³, and finally the reservoir of lake Waïma at the threshold of the Kounkané bridge with 25 million m³ (Hathié *et al.* 2015). 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.

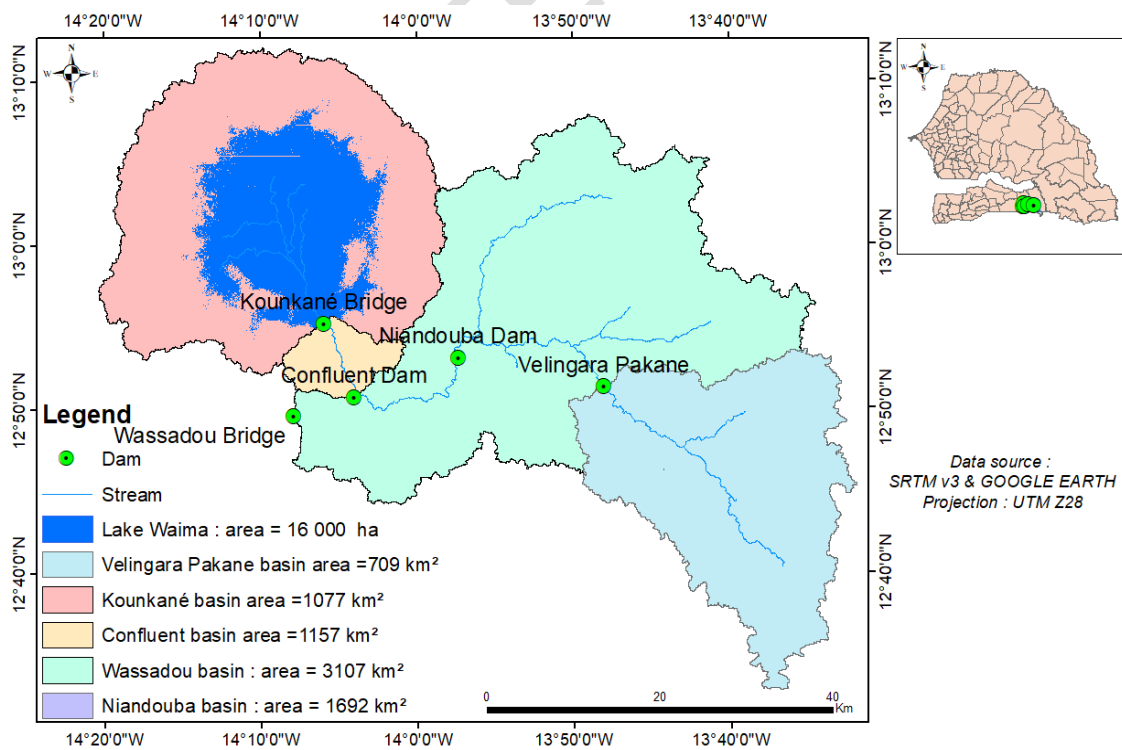


Figure 1. The Kayanga and Anambé watersheds

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 1 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 1). 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 1: List of rainfall stations selected for the study area.

| Name of the Station | Latitude | Longitude | Obs. Variable | Period observed |
|---------------------|----------|-----------|--------------------|-----------------|
| Kouankane | 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 of Kolda as reference.

2.2. Validation of CRU and ETP data

As reminded above prior to use CRU data has been validated using station data Kolda reference. Figure 2 provides a summary of CRU data validation and Figure 3 gives the seasonal cycle of the ETP at the level of some stations.

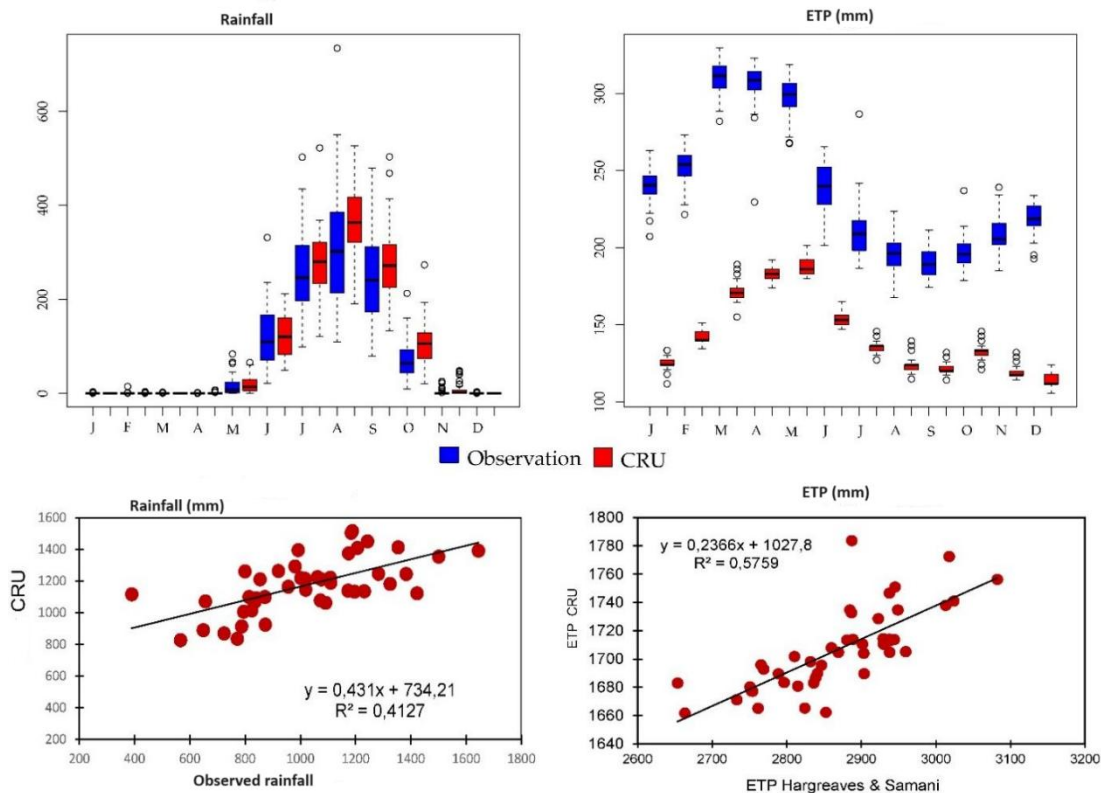


Figure 2. Validation of CRU rainfall and ETP data with station data Kolda reference

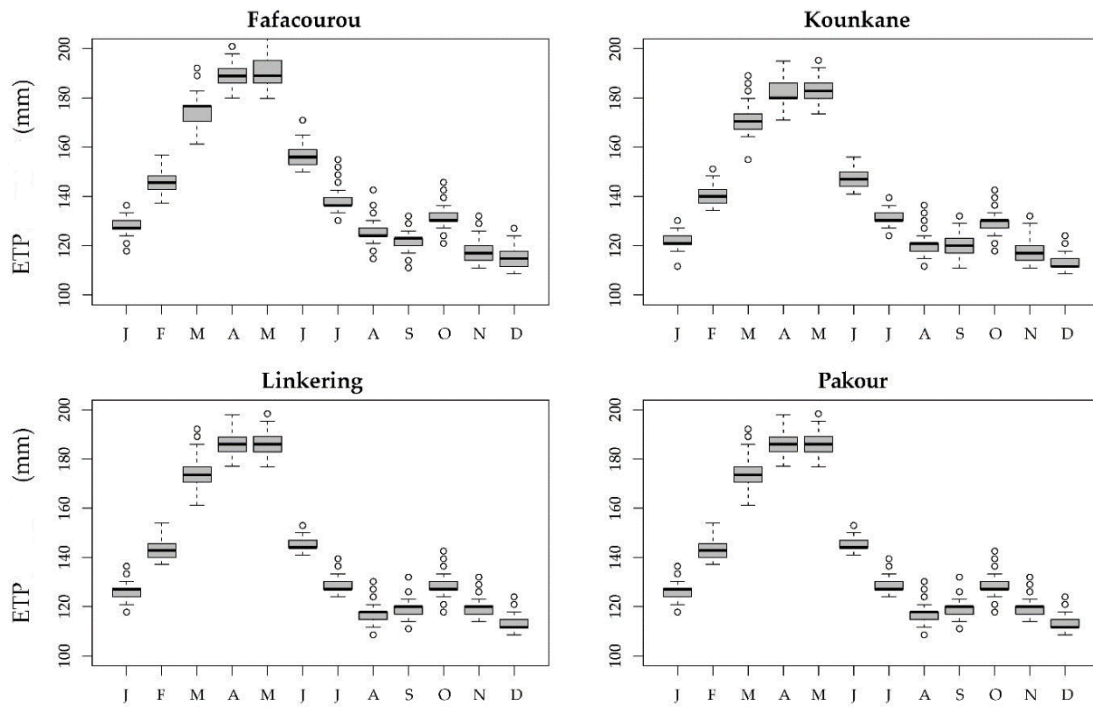


Figure 3. Seasonal cycle of the ETP of some stations of the Kayanga basin

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.

UNDER

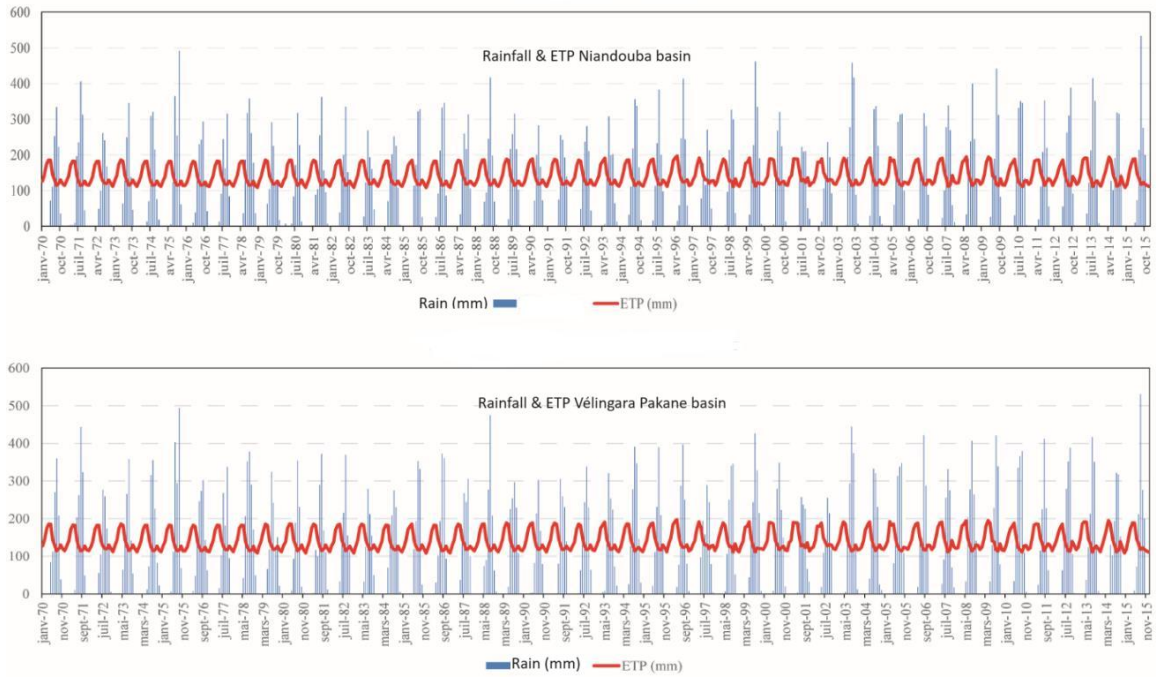


Figure 4: Average rainfall and ETP used for calibration-validation and flow simulation sub-watershed monthly.

2.3. 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 2).

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 2: 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 |
| Koukané 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 |

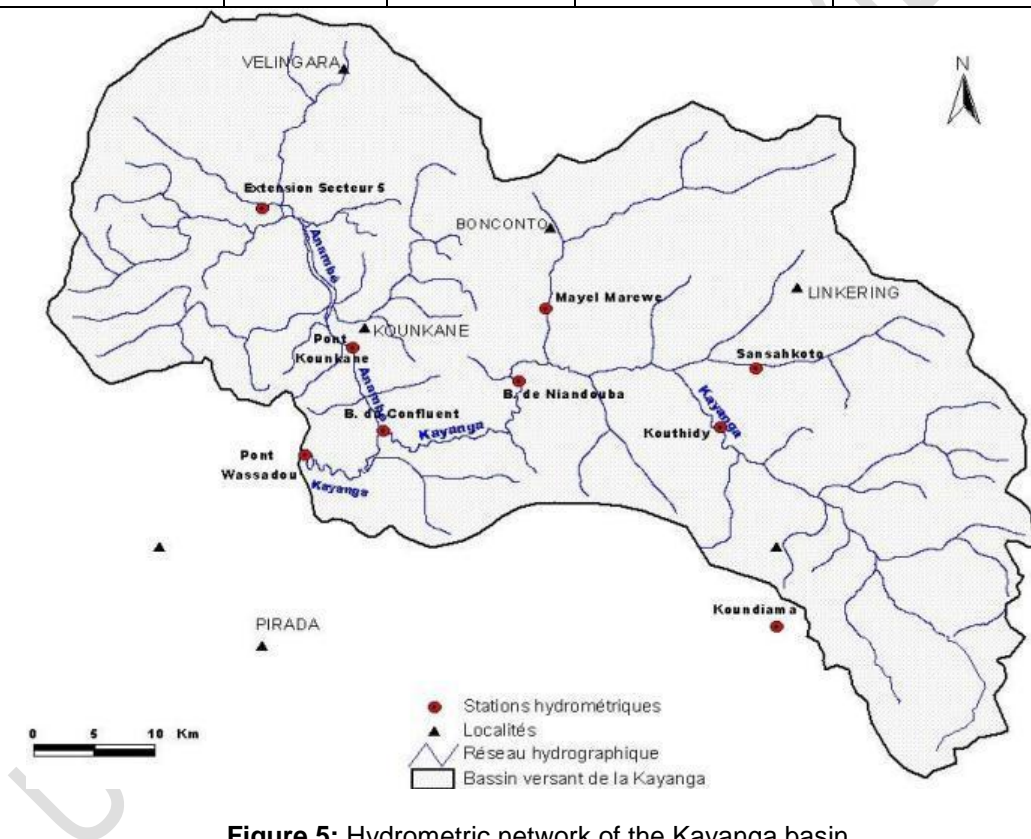


Figure 5: Hydrometric network of the Kayanga basin

3. Status of hydrometric data

Table 3 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 3: 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 |

Station : WassKayanga = WASSADOU AU PONT (KAYANGA)

Capteur : I-1 = Cotes Principal Capteur de Sortie : I-1

Etalonnage du 27/09/1999 jusqu'à nos jours

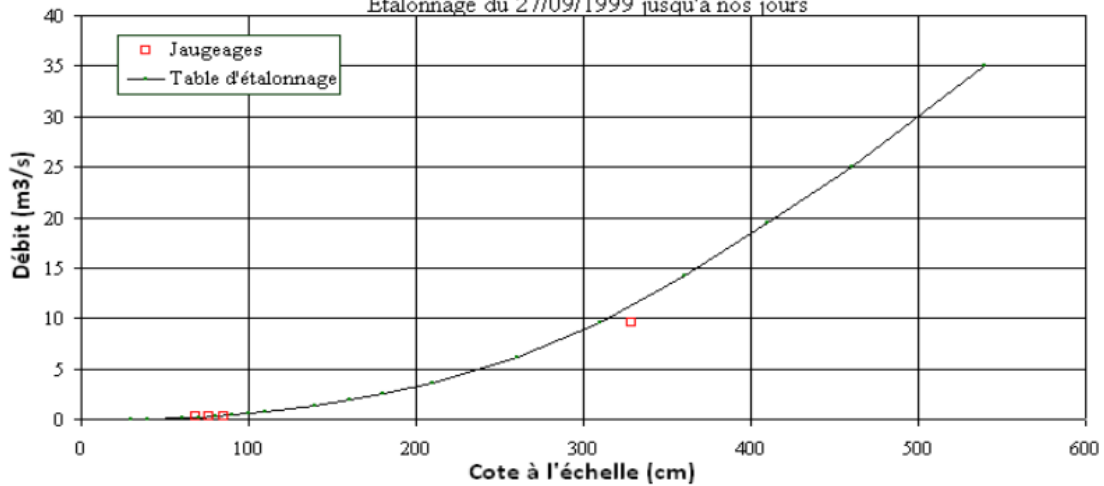


Figure 6: Calibration curve of the Kayanga at the Wassadou bridge

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 m³) 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 m³; (iii) the Niandouba reservoir, in 1997, whose useful volume is of eighty-five million m³. 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 Paturol et al. (1995) for the detailed description of the model.

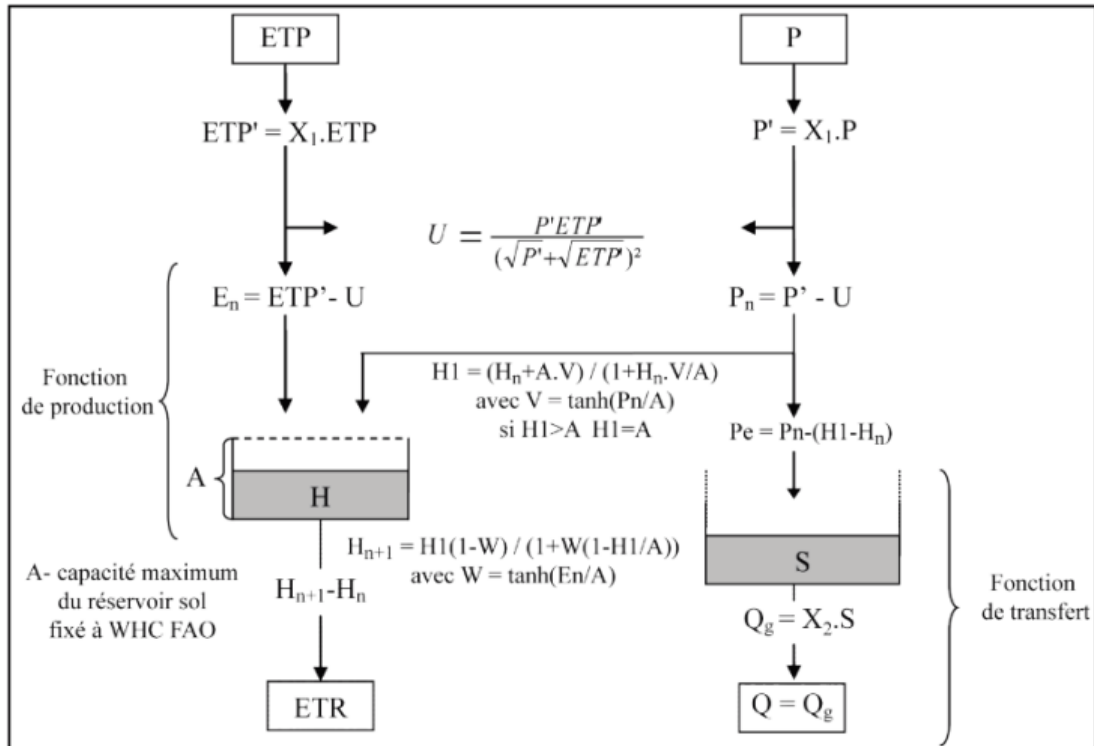


Figure 7: Conceptual diagram of the GR2M model (Bodian et al., 2012)

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

Calibration of 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 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). **These graphical observations** 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:

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

where:

Q_{obs, i} is the observed flow at time step **i**; **Q_{calc, i}** is the simulated flow at time step **i**; \underline{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

1. Flow-flow Correlation

From the data in figure 8 below, a correlation was sought between the annual modules of the Kayanga in Wassadou and those of other hydrometric stations. Table 4 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 (fig.8). 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 4).

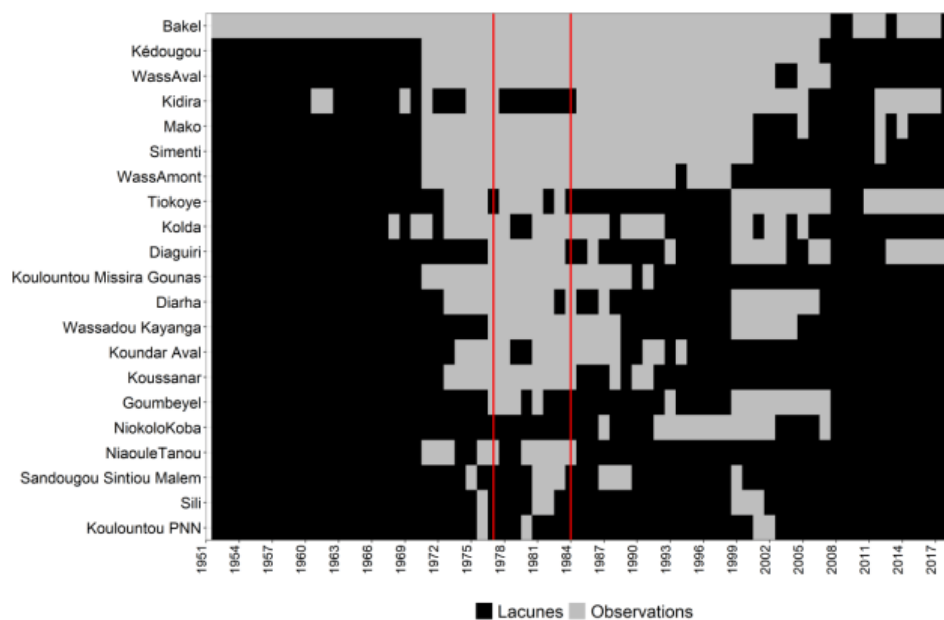


Figure 8. Inventory of annual modules of the different hydrometric stations of the UGP of the Casamance and Eastern Senegal

Table 4: Correlation and determination coefficients of the flows of Wassadou and the others hydrometric stations

| Station | Correlation coefficient (r) | Coefficient of determination (r ²) |
|---------------------|-----------------------------|------------------------------------------------|
| 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 9-11, 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 5). 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 5. 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.

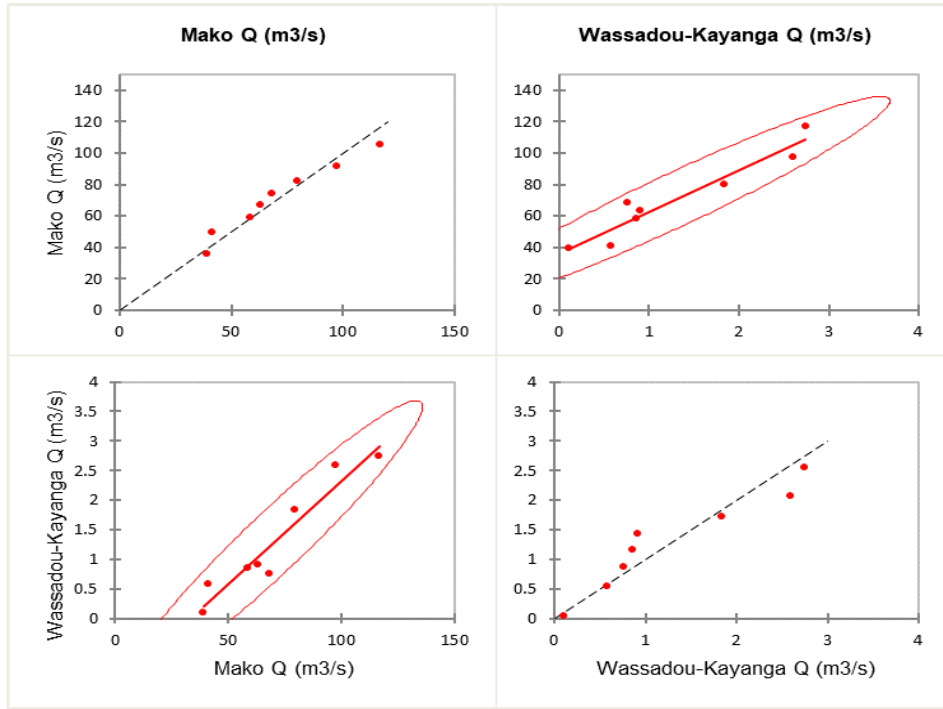


Figure 9. Linear relationship between Wassadou-Kayanga and Gambia discharges at Mako (River Gambia)

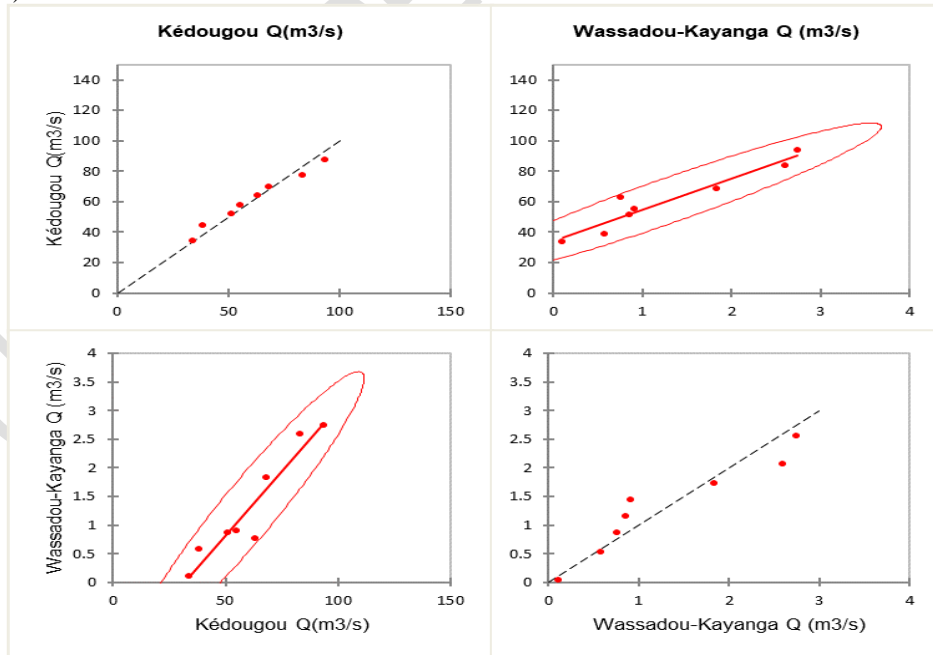


Figure 10. Linear relationship between Wassadou-Kayanga and Gambia discharges at Kedougou

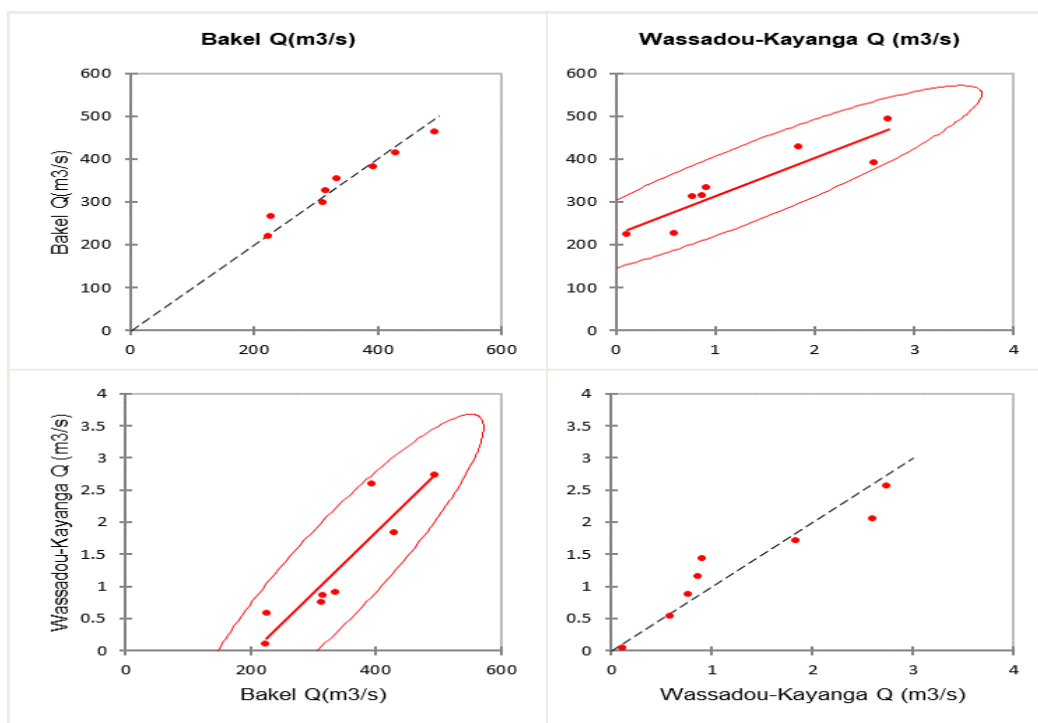


Figure 11. Linear relationship between Wassadou-Kayanga discharges and Bakel discharges

Table 5. Reconstituted annual flows (m³/s) of the Kayanga and the corresponding volumes in m³.

| Year | Mako | Obs. Q (m ³ /s) Wassadou | Calc. Q (m ³ /s) Wassadou | Calc. Q(m ³ /s) Velingara Pakane | Calc. Q(m ³ /s) Niandouba | Vol. (m ³) Wassadou | Vol. (m ³) Vélingara P. | Vol. (m ³) 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 |

2. Flow simulation with GR2M model

The results of the flow simulation with the GR2M model are presented in figure 12, which gives the comparative evolution between the flow rates observed and calculated. The value of the Nash criterion obtained is 0.86, therefore greater than 0.60. However, the analysis of observed and simulated hydrographs (fig.12) 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.

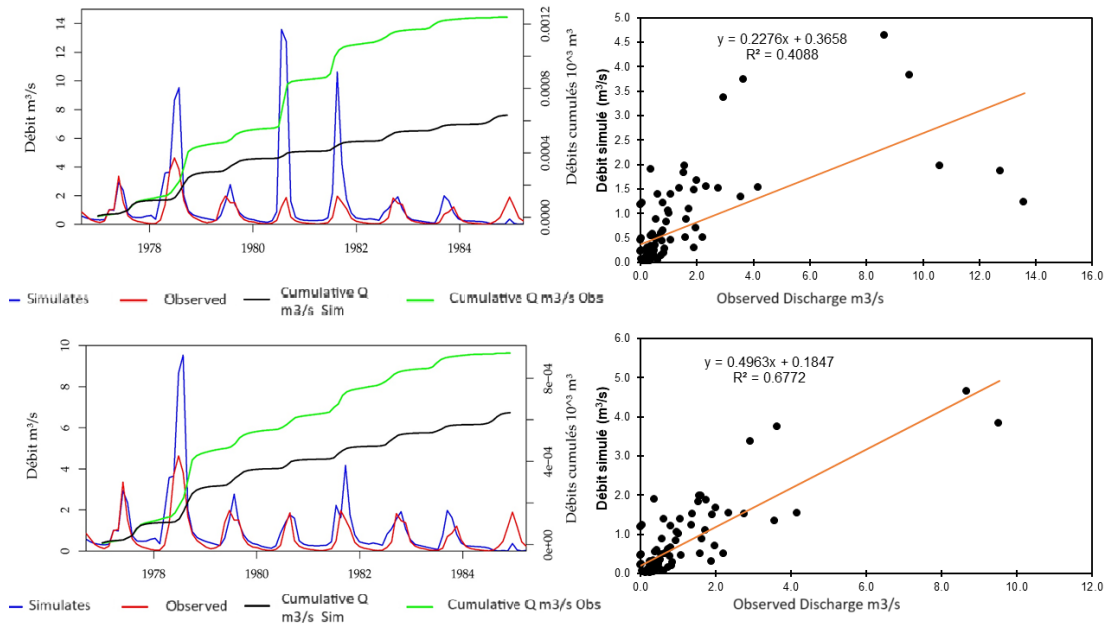


Figure 12: Calibration of the GR2M model at the Wassadou-Kayanga station over the period 1976-1984.

The analysis of tables 6 and 7 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 6. 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 |

With:

- **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 7. 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 |

3. 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 13 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.

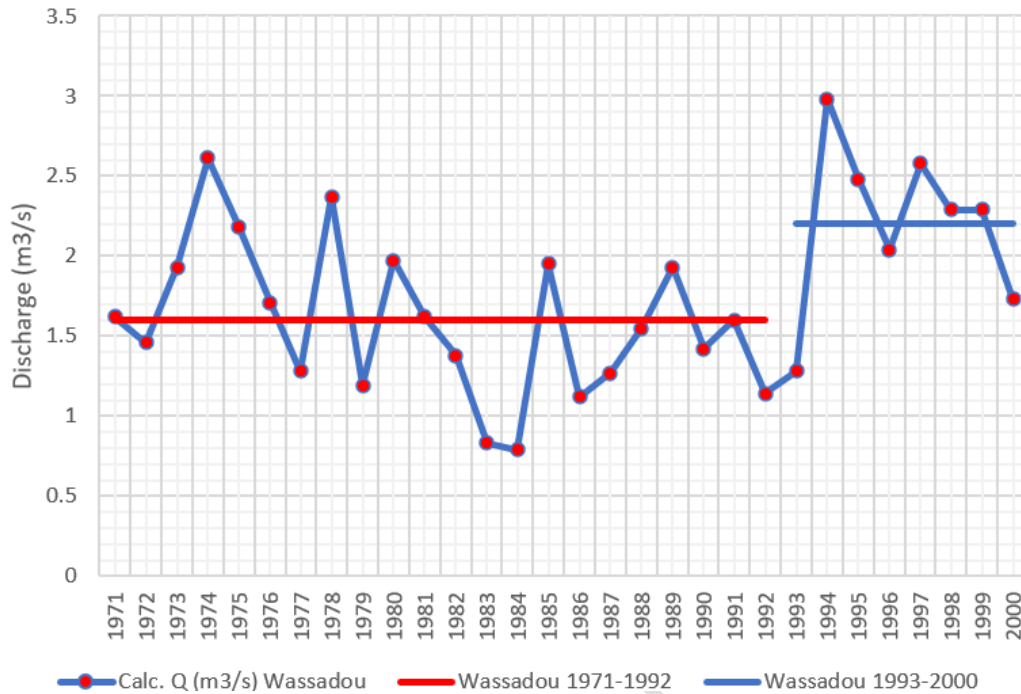


Figure 13. Annual variation of the flows of Wassadou-Kayanga (reconstituted with Mako flows) over the period 1971-2000

Tables 8 and 9 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 unimodal 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 8 and 9). For the Kayanga basin at Vélingara Pakane and Niandouba, the high waters last 3 months from August to October (Tables 8 & 9).

Table 8: Statistical characteristics of monthly flows (m³/s) at Niandouba

| Parameter | May | June | July | Aug | Sept | oct | nov | dec | jan | fev | March | April | year |
|-------------------|------|-------|-------|------------|-------------|-------------|------|------|------|------|-------|-------|------|
| 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 9: Statistical characteristics of monthly flow rates (m³/s) at Velingara Pakane

| Parameter | May | June | July | Aug | Sept | oct | nov | dec | jan | fev | March | April | year |
|-------------------|------|-------|------|-------------|-------------|-------------|------|------|------|------|-------|-------|------|
| 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 | |

4. 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 Kayanga at Niandouba and before the Confluence. Which makes an average value of 2.8. Thus, the data flow rates in tables 10 and 11 are multiplied by 2.8 to correct them. From the corrected flow rates, the volumes were calculated by taking the product of flow rate 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-lac Waïma complex. This transposition is carried out using the following equation:

$$A_i = A_k \times \frac{P_i}{P_k} \times \frac{S_i}{S_k} \quad (2)$$

With:

- A_i : Calculated water intake of subbasin "i" (m³/year),
- A_k : Observed water intake of subbasin "xxx" (m³/year),
- P_i : Average precipitated layer observed for subbasin "i" (mm/year),
- P_k : Average precipitated blade observed for subbasin "xxx" (mm/year),
- S_i : Area of watershed "i" (km²),
- S_k : Area of the watershed "xxx" at the gauging station (km²).

Analysis of the tables below shows that the average contributions from the Kayanga sub-basins vary between 28 million m³ (Vélingara Pakane) and 56 million m³ at the Confluent dam (Tables 10-12). In the Anambé-lake Waïma hydrological complex, the contributions are estimated at 12 million m³ in a dry five-year recurrence and 36.8 million m³ in a wet five-year recurrence (Table 13).

Table 10: 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 11: Annual and seasonal water availability in the Kayanga watershed at 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 12: 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 13: 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 |

IV. DISCUSSIONS AND 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, $1.8 \text{ m}^3/\text{s}$; 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 result is consistent with those of Amogu *et al.* (2010) who noted an increase in the flow index during the period 1994 to 2006 on the tributaries of the Senegal river. Note, however, that the signals of this new climatic phase are only perceptible at the level of the average flow. Such a thesis is supported by Nouaceur (2009) with the same method of analysis, supplemented by that of moving averages, through a study of rainfall in Mauritania.

In the Kayanga watershed, the increase in flows 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 53 million m^3 from Kayanga to Niandouba dam for an average year, and 20 million m^3 for a dry five-year year,

- a contribution of 56 million m³ from the Kayanga before the confluence for an average year, and 22 million m³ for a dry five-year year,
- a contribution of 31 million m³ from Anambé to lake Waïma for an average year, and 12 million m³ 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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