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**Integrated Water Resources Management in Burkina-Faso through  
numerical modeling: Case study of the Mouhoun Basin**

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I, Sonagnon Lucesse M. VLAVONOU ZANNOU, hereby declare that this thesis titled “**Integrated Water Resources Management in Burkina-Faso through numerical modeling: Case study of the Mouhoun Basin**” is my original work realized to the best of my knowledge and has not been submitted to a University or any other institute or published earlier for the award of any degree or diploma. I also declare that all information, material and results from other works presented in this thesis have been duly cited and recognized as required of academic rules and ethics.

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## **Abstract**

This study is being conducted in the Mouhoun watershed, which covers an area of 91,036 km<sup>2</sup>. It is located in West Africa, in Burkina Faso. This is an area where the pressure on water resources is enormous due to high population growth. In addition, the high climate variability leads to a high variability in the hydrological regime, which hinders the availability of water resources and strongly influences the management of water resources in the locality. Due to the problem of lack of data, the Nwokuy sub-basin was used as a modeling area. Two models were used, namely the GR2M model and the WEAP model. The GR2M (the hydrological model) was applied to fill the gaps in the historical flow data set obtained at the Nwokuy station and provided a time series of uninterrupted flows. The model was calibrated and validated for the sub-basin with a model performance (NSE equal to 56.27 and 67.5 respectively for the calibration and validation periods) and a coefficient of determination equal to 0.37 and 0.67 respectively in calibration and validation over the period 1989-2013. The flow thus generated has a certain degree of uncertainty that should not be overlooked, but it is reasonable to use it in view of the acceptable performance of the hydrological model. With the WEAP model, four scenarios were created, the minimum flow, the average flow, the maximum flow and the Samendeni scenario (which takes into account the existence of the Samendeni dam). The Samendeni flow scenario considers that in a deficit year, the existence of the dam could reduce the river flow by 50%. It is therefore important to know the effect that the existence of the dam may have on the demand for water in the future. Projections have been made up to the year 2100. The application of scenarios using the WEAP model shows that in deficit years as well as in wet years, water demands for irrigation and domestic use are covered at 100% for minimum, medium, and maximum flow scenarios. However, a major anthropogenic action such as the construction of the Samendeni dam could, in the more or less distant future, lead to cases of unmet demand. The Samendeni flow scenario shows that the water deficit for irrigation could start in 2080 and the water deficit for domestic needs in 2090. In view of these results, it is therefore important to come to the formulation of some measures for a good integrated water resource management in this basin.

**Keywords:** Water resources- Mouhoun basin- Nwokuy sub-basin Drinking water needs- Irrigation water needs- WEAP model

## **RÉSUMÉ**

Cette étude est menée dans le bassin versant du Mouhoun, d'une superficie de 91 036 km<sup>2</sup>. Elle est située en Afrique de l'Ouest, au Burkina Faso. Il s'agit d'une zone où la pression sur les ressources en eau est énorme en raison de la forte croissance démographique. En outre, la forte variabilité du climat entraîne une forte variabilité du régime hydrologique, ce qui entrave la disponibilité des ressources en eau et influence fortement la gestion des ressources en eau dans la localité. En raison du problème du manque de données, le sous-bassin de Nwokuy a été utilisé comme zone de modélisation. Deux modèles ont été utilisés, à savoir le modèle GR2M et le modèle WEAP. Le GR2M (le modèle hydrologique) a été appliqué pour combler les lacunes dans l'ensemble des données historiques sur les flux obtenues à la station de Nwokuy et a fourni une série chronologique de flux ininterrompus. Le modèle a été calibré et validé pour le sous-bassin avec une performance du modèle (NSE égale à 56,27 et 67,5 respectivement pour les périodes de calibration et de validation) et un coefficient de détermination égal à 0,37 et 0,67 respectivement en calibration et en validation sur la période 1989-2013. Le débit ainsi généré présente un certain degré d'incertitude qui ne doit pas être négligé, mais il est raisonnable de l'utiliser compte tenu des performances acceptables du modèle hydrologique. Avec le modèle WEAP, quatre scénarios ont été créés, le débit minimum, le débit moyen, le débit maximum et le scénario Samendeni (qui prend en compte l'existence du barrage de Samendeni). Le scénario de débit de Samendeni considère que dans une année déficitaire, l'existence du barrage pourrait réduire le débit du fleuve de 50%. Il est donc important de connaître l'effet que l'existence du barrage peut avoir sur la demande en eau dans le futur. Les projections ont été faites jusqu'à l'année 2100. L'application des scénarios utilisant le modèle WEAP montre que dans les années déficitaires comme dans les années humides, les demandes en eau pour l'irrigation et l'usage domestique sont couvertes à 100% pour les scénarios de débit minimum, moyen et maximum. Cependant, une action anthropique majeure telle que la construction du barrage de Samendeni pourrait, dans un avenir plus ou moins lointain, conduire à des cas de demande non satisfaite. Le scénario de débit de Samendeni montre que le déficit en eau pour l'irrigation pourrait commencer en 2080 et le déficit en eau pour les besoins domestiques en 2090. Au vu de ces résultats, il est donc important d'en arriver à la formulation de certaines mesures pour une bonne gestion intégrée de la ressource en eau dans ce bassin.

**Mots-clés :** Ressources en eau- Bassin du Mouhoun- Sous-bassin du Nwokuy Besoins en eau potable- Besoins en eau pour l'irrigation- Modèle WEAP

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## **List of abbreviations**

<b>GDP</b>	Gross Domestic Product
<b>GIS</b>	Geographic Information System
<b>HDI</b>	Human Development Index
<b>IRSTEA</b>	National Research Institute of Science and Technology for Environment and Agriculture
<b>IWRM</b>	Integrated Water Resource Management
<b>LCW</b>	Local Water Committees
<b>NGO</b>	Non-Governmental Organization
<b>NISD</b>	National Institute of Statistics and Demography
<b>SEI</b>	Stockholm Environment Institute
<b>SPI</b>	Standardized Precipitation Index

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## **CHAPTER ONE: INTRODUCTION**

### **1 GENERAL INTRODUCTION**

#### **1.1 Research background**

Integrated water resources management is an essential factor of human development. The first Dublin principle states that "freshwater, a fragile and non-renewable resource is essential for life, development and the environment" (Joern , Nguyen, Wilhelm, 2009) . The situation of this resource is becoming alarming in Africa especially with (i) the harmful effects of climate change, (ii) an increase demand driven by population growth, and (iii) a poor management of hydro systems. There is great evidence that scientific research holds the keys to better water management in Africa.

Many digital tools have been developed to facilitate the management of water resources in a sustainable way. Hydrologic models are tools for monitoring and forecasting water resources and / or water quality. They make it possible, for example, to estimate flows, to predict the evolution of a pollution or, from a valid management model, to help define management plans or assess the consequences of various factors on water reserves.

#### **1.2. Problem statement**

Like many West African countries, Burkina Faso faces extreme weather conditions that expose it to a high risk of floods and drought. Climate change is expected to make these events more frequent and severe (Quentin, Fahad, 2019) . The country's surface water resources come solely from meteoric waters. They consist of flows in the river system. Some of these flows are stored in 1,700 surface reservoirs such as lakes, ponds, etc. However, these storage reservoirs are not permanent except for the Mouhoun and Comoe basins. As for groundwater, aquifers are generally of low production over more than 80% of the country's surface (Serge, 2017).

The country depends solely on rainfall for most of its water needs, including agriculture. When water points dry up, people from the central plateau migrate to the eastern part of the country in search of better living conditions (Serge, 2017). As a result, these migrations lead to overpopulation and environmental degradation of the host areas. The permanent water deficit leads to severe shortages, low agricultural productivity, famine, desertification and the death of herds and wildlife. Between 1980 and 2014, the country suffered numerous episodes of drought, with more than 2.5 million people affected in 1991 and one million in 2001, resulting in a cereal deficit of about 500,000 tons (Conasur, 2002). In the same period, recurrent droughts have also

led to population migration from the North to the South, and consequently to an intensification of the exploitation of low flood areas for agriculture.

In addition to these problems, the country is faced with rapid population growth, in the order of 3% / year over the last decade (UNDP, 2019), which leads to increasing pressure on limited water and land resources. In 2000, the Mouhoun basin had about 4.5 million inhabitants in Burkina Faso, Ghana, Côte d'Ivoire and Mali. It is estimated that this population will reach about 8 million by 2025, with population density in the basin ranging from 8 to 133 persons/km<sup>2</sup> (Allwaters Consult Limited, 2012). In view of this situation, quantitative assessment of available water is an indispensable prerequisite for the development and management of water resources, for food, agriculture and other needs. An integrated approach to water resources management will better respond to the challenges and is an important step towards sustainable development. Since one cannot manage resources that are not well known, integrated water resource management relies primarily on the assessment and monitoring of these resources, hence the importance of our topic.

Data scarcity features the vast majority of West African catchments . This applies to the Nwokuy catchment. An initial evaluation of the available observed discharge data exhibited important gaps that hamper their direct use in water allocation and planning. This calls for developing approaches to fill these gaps.

So far, the EAM (Agence de l'Eau du Mouhoun) is lacking a water management and planning tool, rendering decision making at the catchment scale very challenging, while several drivers (climate, population growth, and dam buiding) affect the available water resources in the catchment. Setting up a water allocation and planning tool for the catchment might be of interest for the AEM for informative purposes, while exploring the impact of the above-mentioned drivers through the application of scenarios might improve the long-term water management in the catchment.

### **1.3. Research questions**

The following questions are asked to guide the research process:

- How effective is the GR2M model in simulating the hydrological behavior of the Nwokuy catchment?
- Are actual and future different water demands satisfied in the catchment?

- Wish additional actions can be recommended to improve integrated water resources management in the catchment?

## **1.4. Objectives of the study**

### **1.4.1. General objective of the study**

The main objective of this study is to contribute to a sustainable water management in the Mouhoun basin by evaluating the availability and the sustainability in the use of water resources of the Nwokuy sub-basin through hydrological modeling.

### **1.4.2. Specific objectives**

Specifically, we will:

- simulate the flowrate of water in the Nwokuy sub-basin using the GR2M model;
- apply scenarios to assess the satisfaction of future water demands in the sub-basin; and
- propose measures for a more balanced management.

## **1.5. Outline of the study**

The structure of this thesis consists of five chapters. These chapters are organized as follows:

- Chapter 1 presents the context of the study, the definition of the problem in the study area, the objectives;
- Chapter 2 deals with the review of the literature on key studies related to hydrological models and in particular the GR2M and WEAP models.
- Chapter 3 deals with study area presentation
- Chapter 4 present the applied methodology. The methods and materials used for the analysis and modeling are described in this chapter.
- Chapter 5 presents the results and discussions.
- Chapter 6 presents the strategic guides for good water resource management at the study area level and then the conclusion.

## CHAPTER TWO

### 2. LITERATURE REVIEW

#### 2.1. General information on hydrological models

##### 2.1.1. Model definition

A model is a simplified, relatively abstract representation of a process, a system, with a view to describing, explaining or predicting it (according to the International Glossary of Hydrology). It is a physical, mathematical or logical System representing the essential structures of a reality and capable at its level of dynamically explaining or reproducing its functioning (Musy, et al., 1998).

In catchment hydrology, a model is a numerical tool for representing the hydrological behavior of a watershed. It can be used to transform time series describing the climate of a given watershed (precipitation and temperature series, for example, which are the inputs to the hydrological model) into a series of flows (output from the hydrological model). Many hydrological models have been developed since the late 1960s. The choice of the type of model to be used generally depends on the modelling objective and the available input data.

##### 2.1.2. Classification of hydrological models

Several authors have proposed a classification of hydrological models, and as it is said that "there are as many models as there are hydrologists, the same applies to the classification of these models. According to Refsgaard and Storm (1996), hydrological models can be classified according to the description of physical processes as conceptual or physical and according to the spatial description of processes at the watershed level as distributed or global.

###### *a- Conceptual models*

The conceptual model considers the watershed as an assembly of interconnected moisture reservoirs, which are supposed to represent several levels of storage, along a vertical dimension. This model is based on the knowledge of the physical phenomena that act on the inputs to obtain the outputs. Conceptual models follow an opposite approach: they do not seek to describe the functioning of the system's components, but the system as a whole. However, these models can be considered as distributed to a certain extent if the basin is subdivided into sub-basins and a model is applied to each unit.

***b- Physical models***

In contrast to previous models that focus on the representation of final (outflow) hydrological behavior, physics-based models attempt to use physical explanations for this behavior. They use the theoretical framework of physics equations (Perrin, 2000).

***c- Distributed models***

The distributed model explicitly takes into account the spatial variability of processes and/or input variables and/or boundary conditions and/or watershed characteristics. These spatialized models are implemented from a discretized elementary unit (Boudhar, 2009).

***d- Global models***

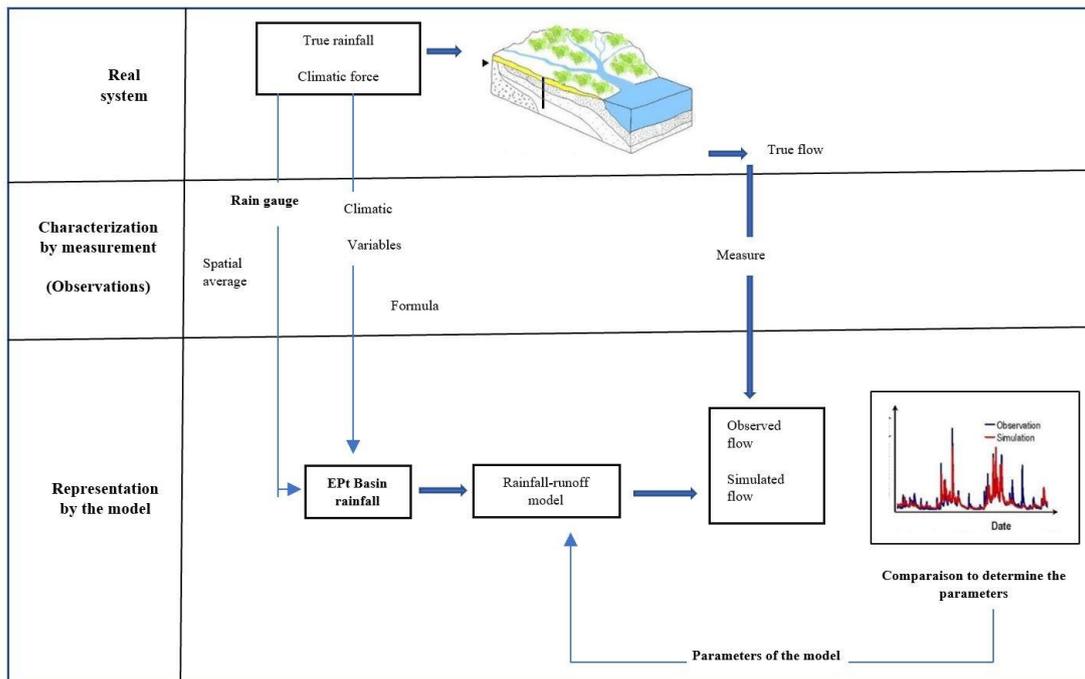
In a global model the basin is considered as a single geographical entity. Empirical (experiential) relationships link inputs and outputs. The equations are often ordinary differential equations that do not take into account the spatial variability of processes, inputs, boundary conditions and the geometric characteristics of the basin (Boudhar, 2009). Global models are very relevant for the simulation of flows at the basin outlet. Their structure is simple, both technically and conceptually, making it easier to work with them, especially for operational applications. Their reduced number of parameters facilitates calibration and validation. Their simplicity also makes it possible to apply sophisticated calibration methods (Segui, 2008).

***e- Hydrological rainfall-runoff model***

A rainfall-runoff model tries to find a link between the flows and rainfalls. Authors (Michel, 1989; Refsgaard et al, 1996; and Perrin; 2000) listed problems solved by rainfall-runoff modelling as follows:

- simulation of flows, for filling gaps in data series, reconstructing historical flows (rainfall data often being available over much longer periods than flows) or for statistical processing;
- predetermination of flood or low flows: one wishes to know how often flood flows (above a risk threshold for example) or low flows (below an instream flow for example) are likely to occur, and over what duration. This is a frequency analysis approach. This knowledge can be used to design structures and reservoirs or facilities in the bed (minor to major) of the watercourse;

- forecasting floods and low water levels: this involves evaluating in advance the flood flows likely to present risks (flooding) or the low water levels that may require special management of the resource (by dams and reservoirs, for example) to ensure water supply or the preservation of fish life. This is part of an ongoing analysis of the basin;
- Influence of developments on hydrology: we want to be able to predict changes in the basin's response to man-made changes in the characteristics of the basin or to environmental changes.



**Figure 1:** Schematization of a global rainfall-runoff model (Koffi,2007)

### 2.1.3. Component of hydrological models

A hydrological rainfall-runoff model is generally defined by (Mathevet, 2005):

- its input variables (independent variables): these are the model inputs, which are the rainfall, evapotranspiration or temperature;
- its output variables (dependent variables): these are the model outputs, which are the simulated flows at the outlet of the watershed, piezometric levels, etc.;
- its state variables: these are the variables internal to the system, which change over time and report on the state of the system at a given time. Typically, these variables are the filling levels of the various reservoirs (snow/production/routing);

- its parameters: the parameters of the hydrological models are used to adapt the parameterization of the laws governing the functioning of the model to the watershed under study; and
- its performance: this involves estimating the amplitude of modeling errors, generally calculated on the basis of a measurement of the difference between the simulated values and the measured values.

#### **2.1.4. Choice of a model**

The choice of a hydrological model is based on the following elements (Abdelmounim, 2015):

- **the objectives of the hydrological study:** they are multiple according to which one can neglect or simplify certain parameters in the modeling;
- **the availability of data:** the frequency of uncertainties that some models present compared to others, the lack of data forces us to use them;
- **the nature of the model:** the robustness and simplicity of the model influence the choice, especially in the case where time or cost is a constraint.

#### **2.1.5. The GR models**

The GR simulation models operate at annual, monthly, daily and hourly time steps.

##### ***2.1.5.1. Development objectives***

The simulation of the flow at the outlet of a watershed is necessary for many engineering and water resource management applications. Cemagrefa began to develop hydrological models in the early 1980s, in order to establish a link between the level of water precipitated on a watershed and its flow at the outlet (Michel, 1983).

Beyond their practical aspect, these models have raised essential questions about how to represent the transformation of rainfall into flow at the watershed scale (Andreassian et al., 2007).

##### ***2.1.5.2. Mode of development***

Although the GR models are sometimes likened to conceptual models because of their reservoir structure, they are in fact empirical models: they were constructed on the basis of large data sets and by progressively discovering the structure that best reproduces the hydrological behavior of the watershed (i.e. its response to rainfall). The following ideas gradually emerged during the development of these models to enable reliable and robust models to be obtained (Mathevet, 2005):

- Global representation of the watershed;
- Empirical development approach without a priori recourse to flow physics;
- Gradual increase in the complexity of the model structure starting from simple structures;
- Justification of the complexity of the structure of a model by its performance;
- Search for general model structures (applicable to various basins);
- Use of large samples of watersheds to test model performance (Andreassian et al, 2006);
- evaluation of a model by comparison with other model structures.

#### ***2.1.5.3. The GR1A annual rainfall-runoff model***

The GR1A model is a single-parameter global rainfall-runoff model. Its development was initiated at Cemagref at the end of the 1990s, with the aim of developing a robust and reliable rain-flow simulation model for use in water resource assessment and management applications. The version we will present is the one proposed by Mouelhi (2003) and Mouelhi, et al 2006.

#### ***2.1.5.4. The GR2M monthly rainfall-runoff model***

The GR2M model is a global 2-parameters rainfall-runoff model. It is a monthly time step model. It works around two reservoirs, one production (or ground reservoir) and one routing reservoir, on which the adjustments and interception are done differently on the inputs. The model uses the average rainfall and evapotranspiration as inputs, and provides the flow rate as an output Sossou (2011). Its development was initiated at Cemagref at the end of the 1980s, with application objectives in the field of water resources and low water levels. Several versions of this model were successively proposed by Kabouya (1990), Kabouya and Michel (1991), Makhoulf (1994), Makhoulf and Michel (1994), Mouelhi (2003) and Mouelhi et al (2006b), which gradually improved the model's performance. Its structure, although empirical, makes it similar to conceptual reservoir models, with a procedure for monitoring the moisture status of the basin that seems to be the best way of taking account of previous conditions and ensuring continuous operation of the model. It combines a production reservoir and a routing reservoir as well as an opening to the outside other than the atmospheric environment. These three functions make it possible to simulate the hydrological behaviour of the basin.

#### ***2.1.5.5. The GR4J daily rainfall-runoff model***

The GR4J model is a global rainfall-runoff model with four parameters. Its development was initiated at Cemagref in the early 1980s, with the aim of developing a robust and reliable

rainfall-flow simulation model for use in water resource management and engineering applications (design of structures, flood and low-water forecasting, reservoir management, impact detection, etc.).

#### **2.1.6. Environment of the GR model**

The GR model is developed under several environments:

- airGR which is a package that incorporates in the R software the hydrological modeling tools used at Irstea-HBAN (France), including GR models such as GR2M, GR1A. Each model core is coded in FORTRAN in order to allow fast executions. The other functions of the package (i.e. mainly the calibration algorithm and efficiency criteria) are coded in R (Coron, et al., 2017).
- The GR version on Excel is available on the IRSTEA website (ex-Cemagref).

#### **2.1.7. Calibration and validation**

The calibration of a model consists in looking for the parameters that will allow to reproduce as well as possible the functioning of a measured variable. Indices such as the Nash-Sutcliffe criterion allow to determine mathematically the parameters for which the series of measured and simulated data are the closest. A good calibration consists in obtaining an optimum Nash-Sutcliffe criterion greater than or equal to 70% and a significant correlation coefficient between the simulated and observed flows close to 1, and a good superposition of the curves of the observed and simulated flows. The calibration operation consists in finding values of the model parameters that minimize the modeling error over the considered period.

However, the calibration step is not enough to ensure the realism of the model. It still needs to be validated, by checking whether the calibrated model correctly simulates series of spatiotemporal reference data not used during the calibration process, if possible, on several variables of interest and not only on flow rates, as is still too often the case.

## **2.2. The Water Evaluation And Planning system (WEAP)**

During the last decades, an integrated approach to water development with a global vision taking into account the demand, quality and preservation of ecosystems has emerged. Based on this approach, a model called WEAP (Water Evaluation and Planning System) integrating these values in an integrated management approach has been developed (Droogers, et al., 2011).

### **2.2.1. Presentation of the software**

The WEAP software is based on a representation of the hydraulic system in the form of a network where the different sites represent nodes, which are connected by transmission or return links (Boukolia-Hassane, 2011). WEAP was developed by the Stockholm Environment Institute (SEI) by researchers: Jack Seiber, Water Systems Modeler; Chris Swartz, Research Associate; and Annette Huber - Lee, SEI Water Resources Program Director (Rakotondrabe , 2007). This model enables the assessment of planning and management issues related to water resources development for microcomputers. It provides a comprehensive, flexible and user-friendly structure for policy analysis (Arranz, 2006). It is based on a coherent basin-wide approach (Aichouri, 2016). A growing number of water professionals have found WEAP to be a useful addition to their toolbox of models, databases, spreadsheets, and other software. WEAP is already being used in various countries around the world (Tutorial, 2008).

It operates on a monthly basis on the basic principle of water balance accounting. The user represents the system in terms of its various sources of supply (e.g., rivers, groundwater, and reservoirs), withdrawals, water demands, and ecosystem needs.) It is considered a conceptual model taking into account the physical system mapping approach and the nature of the models used to describe hydrological processes (Riepl, 2013). WEAP has been described as "comprehensive, simple and easy to use, and attempts to assist rather than replace the qualified planner" (University of Kassel, 2002). It addresses a wide range of issues such as:

- Sectoral analysis of demand;
- Water conservation;
- The right to water and allocation priorities;
- Ground and surface water simulation;
- Reservoir management;
- The production of hydraulic energy;
- The follow-up of physico-chemical characteristics and pollution;
- The requirements of ecosystems;
- Vulnerability measures;
- Benefit-cost analyses of projects.

### **2.2.2. WEAP applications**

Several studies around the world have been conducted through WEAP. In Greece, WEAP has been applied in the Ali Efenti watershed to design water efficiency measures to address water shortages due to rapidly increasing water withdrawals (Psomas A., Panagopoulos, Konsta, & Mimikou, 2016). A study conducted in the Sourou Valley in Burkina Faso has shown that in the face of the effects of random changes in climatic regimes and anthropogenic actions, there could be difficulties in meeting water demand from 2033 onwards, with a water deficit that could reach 27.3% by 2053 (Moktar, 2017).

Höllermann, et al (2010) modelled the water balance of the Oueme-Bonou basin using WEAP software. This study analyzed the future water situation of Benin under different scenarios of socio-economic development and climate change up to 2025. Hoff, et al (2011) used WEAP software to analyze transboundary water resources management in the Jordan River basin. In Ghana, Integrated water resources management plan was developed for the Densu River Basin using WEAP as a tool to allocate future water demand and supply under different scenarios (Water Resources Commission, 2007). In the city of Volos, Greece, future water demand was assessed taking into account the impact of water prices and climate change based on scenarios (Mylopoulos, Fafoutis, Sfyris and Alamanos, 2017).

The Chancay-Huaral Basin in Peru plays a key role in the socio-economic development of the province of Lima. Al-zubari, El-sadek, Al-aradi and Al-mahal, (2018) assessed the impacts of climate change on the municipal water management system in the Kingdom of Bahrain. They used WEAP to assess the performance of the water management system (vulnerability and adaptation) taking into account the effects of climate change on municipal water demands and their associated costs. Droogers, et al., (2012) used WEAP software for green water management in the Sebou Basin in Morocco as a modeling tool to assess the impact of three water management measures (demand, supply, and cost-benefit analysis). Alfarra, et al (2011) constructed a management model using the WEAP software to assess the variation in water supply. They then described five alternative water supply scenarios for their study area: Usual situation, use of treated wastewater in irrigation, climate change, and two other scenarios combined on climate change with increased reuse, and agricultural patterns to calculate the impact on the supply demand gap to 2050. Due to the competitive and increasing demand for water in the basin (resulting from population growth), Olsson et al (2017) studied the impact of climate change on future river flows using WEAP.

Hadded, et al (2013) developed a decision support tool by coupling WEAP with the groundwater modelling software MODFLOW. The stalled DSS was used to assess the impacts of development and seawater desalination on the piezometric levels of the control points. A study conducted with WEAP on water resources and their uses in the Oued Kébir Ouest watershed (Algeria) showed that the confrontation of future water supply/demand under different scenarios using the WEAP model revealed future water stresses that are likely to affect the area in the future (Daifallah, 2017).

## **2.3. Integrated Water Resources Management (IWRM)**

### **2.3.1. General presentation of the IWRM context in Burkina Faso**

Burkina Faso embarked on the IWRM process in the 1990s, in line with the recommendations of major international conferences, notably those of Dublin (1992), Ouagadougou (1998) and Johannesburg (2002). The IWRM approach in Burkina Faso started at the conceptual and institutional level with the following tools:

- 10 September 1998, adoption by the Government of the document "Water Policy and Strategies" by decree n°98-365/PRES/PM/MEE;
- February 2001, adoption by the National Assembly of the law n°002-2001/AN relating to water management;
- May 2001, inventory of water resources in Burkina Faso and their management framework;
- 06 May 2003, adoption by the Government of the IWRM Action Plan by Decree No. 2003-220/PRES/PM/MAHRH.

The implementation of IWRM Action Plan is placed under the responsibility of the Ministry in charge of water, namely the Ministry of Agriculture, Hydraulics and Fishery Resources. It is carried out on a daily basis under the direct responsibility of a mission administration, the Permanent Secretariat of IWRM Action Plan attached to the General Secretariat of the Ministry. The steering is ensured by a National Steering Committee (NSC) which reflects the collegial responsibility of the national actors and partners involved in IWRM Action Plan and which allows the association, at the national level, of representatives of all IWRM Action Plan stakeholders. The country has worked to implement the IWRM Action Plan, with the support of Danish and Swedish cooperation, as well as the European Union and the United States. Some NGOs, such as the Global Water Initiative, the Dutch and French decentralized cooperations

have contributed to the implementation of the action plan. Three (3) phases characterize the implementation of IWRM Action Plan:

- **IWRM Action Plan phase 1 (2003 - 2009)** whose actions were mainly focused on the establishment of the institutional framework of IWRM; the elaboration of the application texts of the law of orientation relating to water management; the setting up in the pilot basin of Nakanbe, of water resources management structures at the scale of the basin and sub-basins; the design and development of a National Water Information System ; the reinforcement of the capacities of the structures and actors concerned; the planning and development of human resources;
- **IWRM Action Plan phase 2 (2010 - 2015)** with the following strategic thrusts: operationalizing the water agencies; consolidating the State's sovereignty missions in water matters; consolidating applied knowledge and research in the field of water in relation to climate change; continuing the development of human resources;
- **IWRM Action Plan phase 3 (2016 - 2030)** whose objectives are to: consolidate and promote the State's sovereign missions; ensure the continuous adaptation of the institutional framework and management instruments; strengthen knowledge of water resources, their uses and risks; ensure effective protection of water resources; increase participation and ownership of water resource management by users and stakeholders. Many results have been achieved, notably the creation of IWRM bodies at different levels: National Water Council; Technical Committee for Water; Water Agencies; Local Water Committees; thus concretizing the reform desired by the State (United Nation Environment Program, 2016).

## **2.3.2. Management tools for the implementation of IWRM**

### **2.3.2.1. Water Agencies**

The Water Agencies are areas of expertise that promote integrated water resource management in a concerted manner. They enable problems to be resolved on a watershed basis. For the delimitation of these areas of competence, the hydrological basin was considered as the main criterion, to which secondary criteria of an environmental, economic and social nature were associated. On the basis of a decree, five Water Agencies were created, including the Mouhoun Agency on 9 June 2003 (Fulgence, et al., 2013).

### ***2.3.2.2. The Water Development and Management Master Plan***

The Water Development and Management Master Plan is the guiding and legal tool that sets for each river basin the fundamental guidelines for sustainable water resource management in the general interest and in compliance with the principles of the Water Law. It is a valuable planning tool that:

- It is essential for the decisions of local authorities, public institutions or other users in terms of water management at the level of river basins;
- Guides public development programs;
- Defines the rules of coherence that should frame the mobilization and management of water resources at basin level (Mouhoun Water Agency, 2014).

### ***2.3.2.3. The Water Police***

The Water Police is a means of coordinating the actions undertaken by the existing services in charge of prevention, control and repression, in the implementation of water resource legislation. It is made up of sworn agents.

### ***2.3.2.4. The National Water Information System***

The National Water Information System is an operational chain that aims to provide political decision-makers, planners, local authorities and water operators with all useful information relating to water resources, its uses and the risks associated with this resource. It is essential to integrated water resource management because without knowledge of the various aspects of water, sustainable management is not possible.

## **2.3.3 Synthesis of the issues related to IWRM in the Mouhoun Basin**

The analysis of the state of the art provides a synthesis of the main elements of water resource management for the three main areas of the Mouhoun basin (Mouhoun Water Agency, 2014):

### **The upper Mouhoun is characterized by:**

- Abundant rainfall in the south, ensuring good surface water productivity;
- The presence of an extensive sedimentary aquifer is still little exploited;
- The presence of numerous springs that contribute to the base flow of the river, most of which is in the process of degradation;

- A potential in irrigable land for medium or small-scale irrigation schemes, but also, in the slopes, for lowland schemes through partial flood control;
- Water management problems that vary according to local specificities - conflicts of use in the Kou valley (large perimeter, small-scale irrigation, fishing, etc.), pollution risks in the urban area of Bobo-Dioulasso and in rural areas (cotton-growing areas in particular), tensions along the banks of the Mouhoun, etc

**The Sourou is characterized by:**

- A deficit of surface water resources compensated by transfers from the south, stored in the Sourou reservoir but subject to strong evaporation;
- An extensive sedimentary aquifer but little exploited;
- An important land potential for both irrigation and livestock;
- Problems of conflicts of use (farmers, stockbreeders, fishermen...), inefficient management of irrigated areas, environmental degradation in a context strongly linked to the transboundary management of surface and groundwater with Mali.

**The lower Mouhoun presents:**

- A significant potential in surface water resources, increasing towards the south;
- Limited regulation of runoff, which is concentrated in the rainy season;
- Low groundwater potential (basement zone);
- An earth potential, increasing towards the south;
- Strong pressures resulting from anthropic activities (agriculture, gold panning, livestock breeding...) and leading to bank erosion, pollution risks, degradation of ecosystems in a context of transboundary water resources management.

**2.3.4. Issues at stake in the management and protection of water resources in Mouhoun basin**

At the end of the diagnosis of the state of the art, the preceding observations led to the identification of six groups of strategic issues corresponding to the fundamental dimensions of sustainable development (Mouhoun Water Agency, 2014):

- The technical issue, which refers to knowledge of water resources and uses, the definition of the main orientations in terms of structural works, the equitable distribution of water resources;

- The social issue, which includes drinking water supply, sanitation, improving food security and protecting people and property against water-related risks;
- The economic issue, which concerns the vectors of growth that are irrigated agriculture, animal husbandry, fishing, aquaculture, mining and industrial activities, hydroelectric production;
- The environmental issue, which includes the protection and restoration of watersheds, streams and water bodies and aquatic ecosystems, public awareness and environmental monitoring;
- The governance issue which covers the fundamental missions of the Water Agency: setting up and operationalizing Local Water Committees; planning water resources through the Master Plan for Water Development and Management; preparing multi-year intervention programs; raising awareness and involving users; supporting transboundary water management, etc.
- The financial issue which concerns the mobilization of financial resources for the functioning of the structures and the implementation of actions.

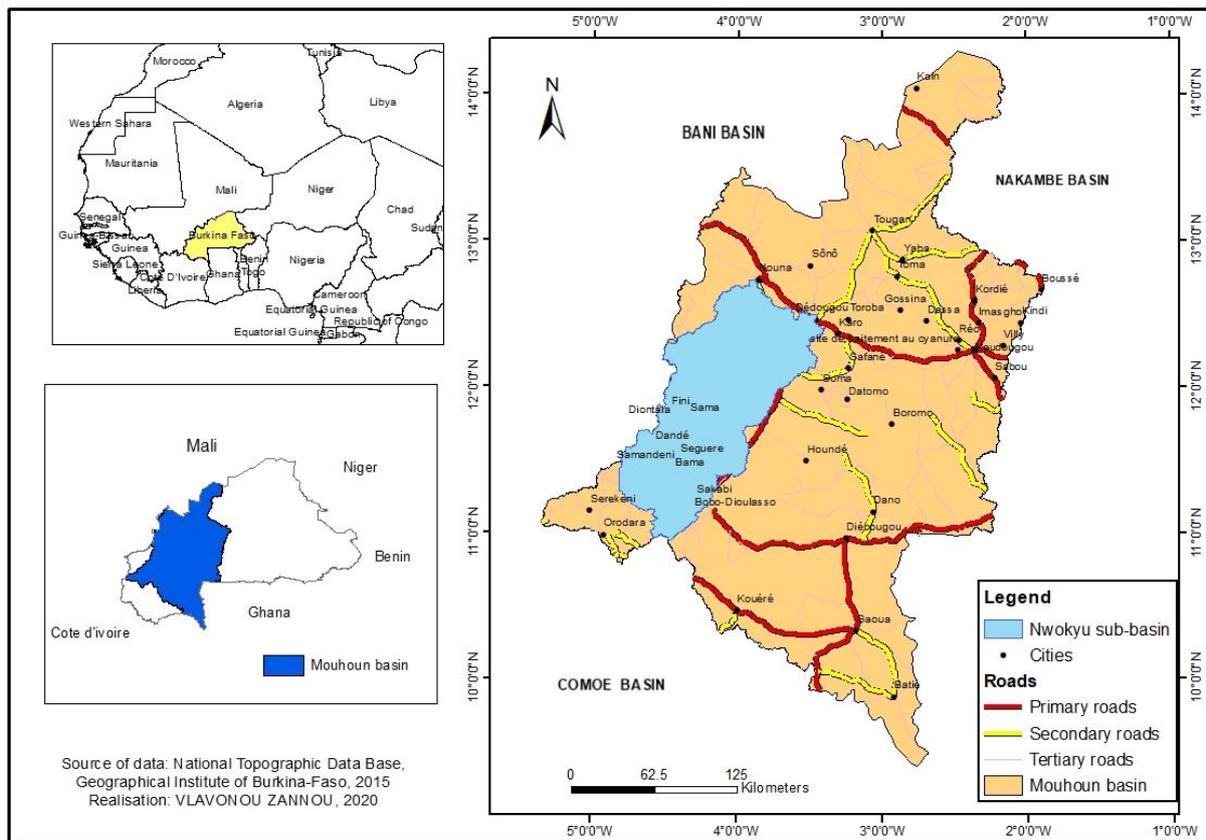
## CHAPTER THREE

### 3. PRESENTATION OF STUDY AREA

#### 3.1. GEOGRAPHIQUE SITUATION

Located in West Africa, Burkina Faso is made up of four major watersheds: the Niger Basin; the Nakanbe Basin; the Mouhoun Basin and the Comoe Basin.

Our study area is the Mouhoun basin and is located between 5° and 2° West longitude, and between 9° and 14° North latitude. Due to the limitations of data availability, our modeling area is the Nwokuy sub-basin of the Mouhoun basin.



**Figure 2:** Map showing the geographic situation of Mouhoun basin

#### 3.2. Presentation of the physical environment

The Mouhoun basin is part of the large international Volta basin with an area of 91,036 km<sup>2</sup>, representing 33% of the national territory of Burkina-Faso. It is a transnational hydrographic network shared between Mali, Burkina-Faso, Ghana and Ivory Coast. It is subdivided into three national sub-basins namely Sourou (15,225 km<sup>2</sup>), Lower Mouhoun (54,802 km<sup>2</sup>) and Upper Mouhoun (20,978 km<sup>2</sup>) and regional sub-basins. It is a basin of great

hydrographic importance at national and regional level. The storage capacity of the reservoirs in the Mouhoun basin is greater than 438 million m<sup>3</sup> with an average annual filling rate of 65% (François, et al., 2019).

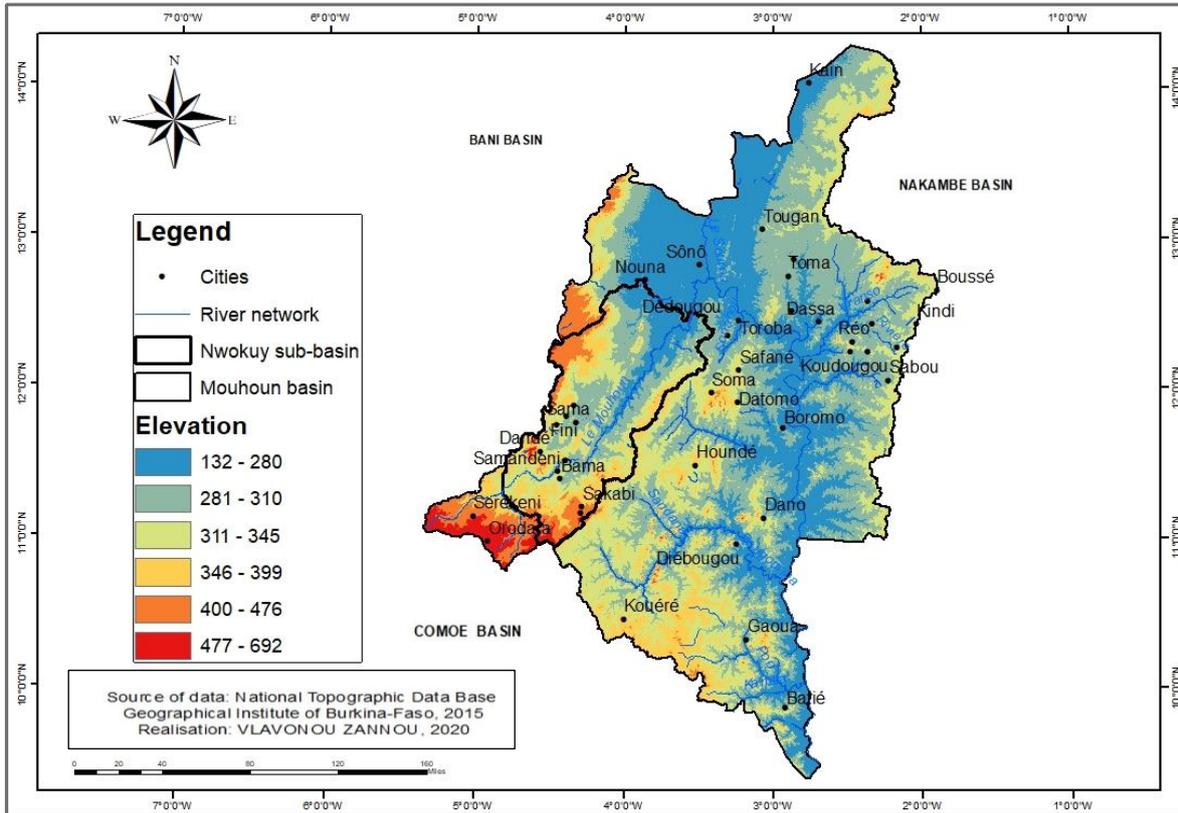
### **3.3. Hydrography and relief of the Mouhoun basin**

The Mouhoun basin's hydrographic network is dense and is made up of rivers of capital importance for the country. It comprises nine (09) main tributaries and 27 sub-basins. With a total length of about 1,000 km in Burkina Faso, the Mouhoun drains unevenly at the national level the territories of six (06) regions. The last tributaries on the left bank of the Mouhoun come from sub-catchments in Ghana and Côte d'Ivoire. The number of springs in the Mouhoun basin has been estimated at about 183 springs, 142 of which are perennial. They are mainly located in the southern part of the basin (Water Agency of Mouhoun, 2014).

The upper Mouhoun, which comes from the same sandstone massif as the Comoé but flows towards the north-east, has perennial flows in its upstream part with low water levels that are rarely less than 2 m<sup>3</sup>/s both at the Samandeni station and on the Kou at Nasso. Limited to the confluence of the Sourou, the watershed of the upper Mouhoun and its main tributaries (Plandi, Kou, Voun Hou) reaches 20,800 km<sup>2</sup> and provides an average flow that is however very irregular.

The Sourou drains the ancient lake plain of Gondo, whose 15,200 km<sup>2</sup> watershed is totally Sahelian and provides only low runoff. In its natural state, during floods, the Mouhoun River feeds its tributary the Sourou. In times of floods, the Sourou River feeds the Mouhoun.

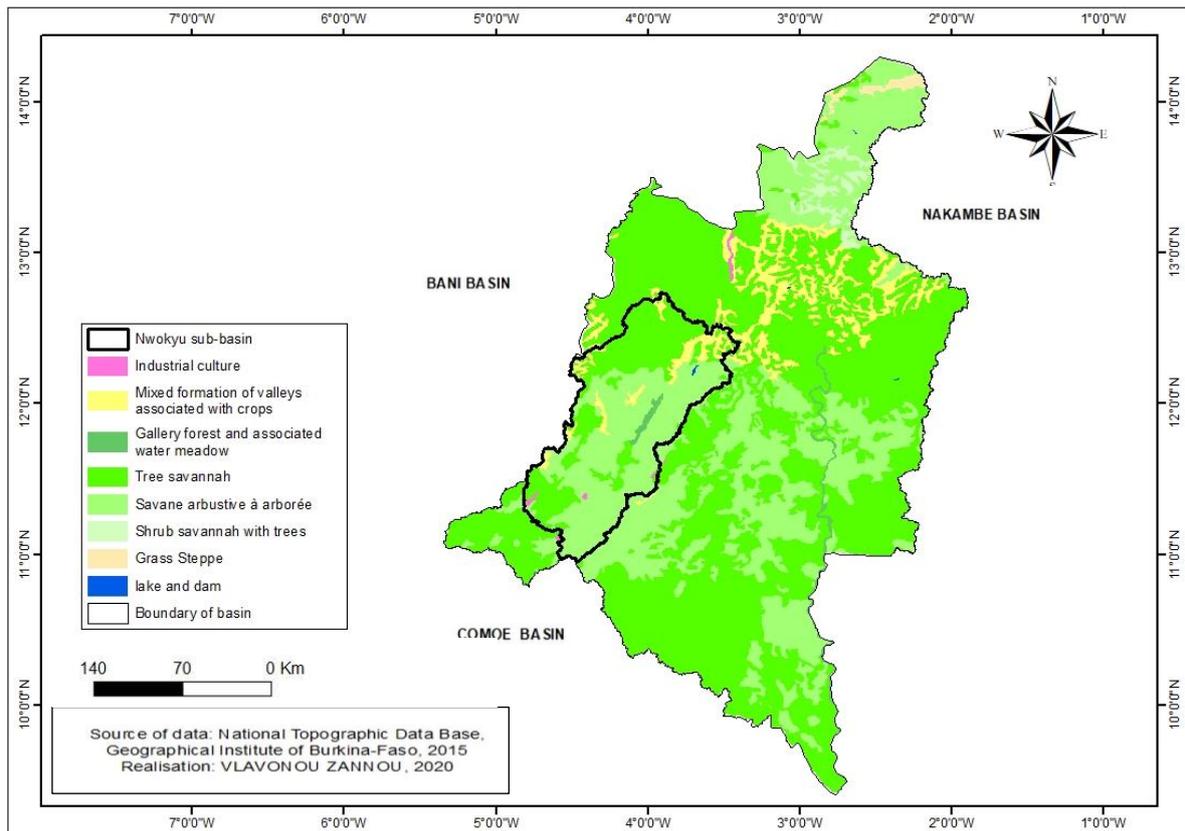
The lower Mouhoun river changes direction abruptly after the Sourou loop and flows southeast, then due south, forming the border with Ghana from Ouessa. The development of the Sourou River and run-of-river withdrawals (Tenado, Poura) disrupt the natural regime both in low and high water (Serge, 2017). The relief of the basin is quite monotonous with an average slope of 2%. The altitudes are between 273 m and 733 m (Tiemtore, 2017).



**Figure 3:** Map showing the hydrographic network and the relief of the Mouhoun basin

### 3.4. Vegetation

Forestry in the Mouhoun basin is marked by a composite vegetation, a diversity of fauna and numerous wetlands. The vegetation cover of the basin is essentially made up of wooded savannas, open forests and forest galleries along the permanent watercourses, whose width increases as one goes southwards. At the Sourou level in particular, the vegetation is characterized by the transition from shrubby steppe to wooded steppe, dotted with thin riparian open forests. This is the zone where many Sahelian and Sudanese species coexist. The extreme north of the basin (in the northern region) is home to typical Sahelian vegetation made up of shrubby savannah, gallery forests and thorn trees. At the Banifing level, the exuded soils support a more or less degraded wooded savannah made mostly of nere, shea and cauliflower. The partially or permanently flooded areas bear shrubby vegetation with a significant herbaceous carpet. The Banifing does not contain any classified forest (SP/PAGIRE, 2014).



**Figure 4:** Map showing the vegetation of the Mouhoun basin

### 3.5. Soils

There are several types of soil, namely:

- **Soils with little evolution of erosion of non-climatic origin**

These are young or rejuvenated soils, whose pedoclimate allows for their evolution. They are regic soils developed on a substrate allowing root penetration. Regic soils, on gravelly material, are abundantly represented in the basin north of the Soromo-Ouagadougou line.

- **Vettisols**

These are soils with a high clay content of more than 40% where swelling clays (montmorillonite) frequently dominate. These characteristics combined with those of the climate determine alternating swelling and shrinkage causing internal movements. There are topomorphic vertisols, with no external drainage, which, formed in flat or depressed areas, undergo hydromorphy of topographic origin, and lithomorphic vertisols sanitized by sufficient external drainage: their waterlogging hydromorphy is of petrographic origin. Topomorphic Vertisols are found in the Gondo Valley on the right bank of the Sourou River. They develop

on clayey alluvium. Lithomorphic Vertisols are mainly located in the western part of the Gondo Plain, on the left bank of the Mouhoun River around Ouessa. The mineral richness of these soils is high: they have a high chemical fertility potential, but their structure is very often the real limiting factor of their fertility, posing the problem of tillage. Water has a double role in the fertility of these soils, usually through its excess (waterlogging), sometimes through its lack; in vertisols with solonetzic facies, poor drainage is the limiting factor of fertility. Finally, alkalinization aggravates the problem of water in vertisols, sometimes making them almost totally impermeable.

- **Mull soils in tropical regions**

They are represented by brown eutrophic tropical soils; they have a soft humus, well bound to the mineral matter, with an absorbent complex well saturated with alkaline earth bases. They develop quite widely in the Bougouriba and Bambassou basins and in the Mouhoun loop.

- **Soils with sesquioxides and rapidly mineralized organic matter**

These are the tropical ferruginous soils. We can especially distinguish the tropical ferruginous soils with little leaching on aeolian sands, which form an almost continuous belt in the Sahelian and Sahelio-Sudanian zones. Modal afacies, they can be cultivated when there is sufficient rainfall: their sandy texture gives them special physico-chemical properties and limits their use to crops adapted to light soils. The ferruginous soils with low leaching and little differentiation are generally reserved for grazing. The leached tropical ferruginous soils occupy the southern part of the Mouhoun basin towards Dapola. They are very rich in individualized iron sesquioxides, characterized by their red color.

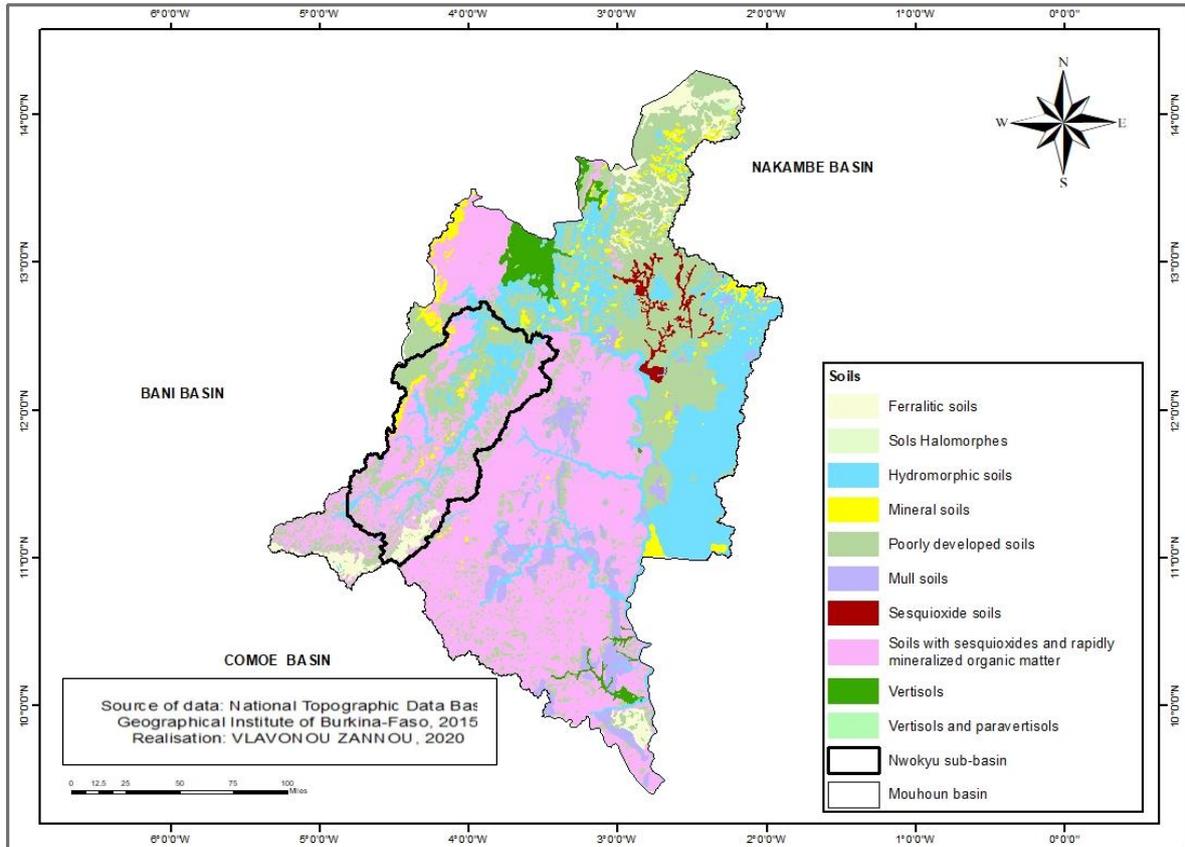
- **Ferrallitic soils**

They are characterized by low exchange capacity, low amount of exchangeable bases and generally low to very low saturation and acidic pH. They are mainly found west of Bobo Dioulasso.

- **Mineral hydromorphic soils**

Whose more or less prolonged waterlogging results in various manifestations in the color profile in relation to the reduction of iron and manganese. This type of soil is found in the Mouhoun valley, downstream of the Sourou, in the northwest of the basin, i.e. on the left bank

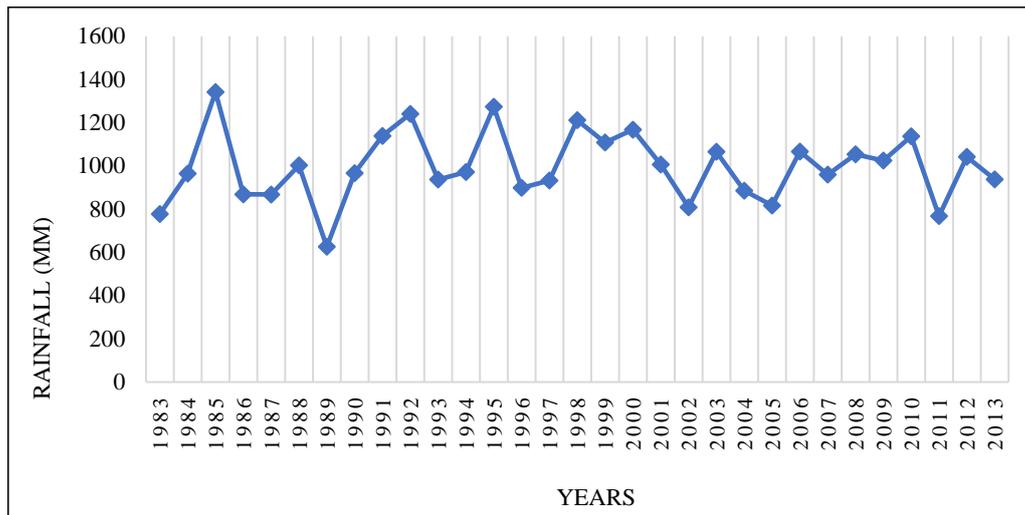
of the Mouhoun upstream of the loop, in the region of Lake Barn Impacts of climate and development on the hydrological regime of the Mouhoun (Ndiaye B., 2003)



**Figure 5:** Map showing the different soil types in the Mouhoun basin

### 3.6 Rainfall in the Mouhoun basin

Due to its geographical location, the study area enjoys a Sudanese type climate with an average annual rainfall of over 900 mm. Over the last fifty years, there has been a decline in annual rainfall in the 1970s and 1980s and an increasing trend over the last two decades (figure 6).

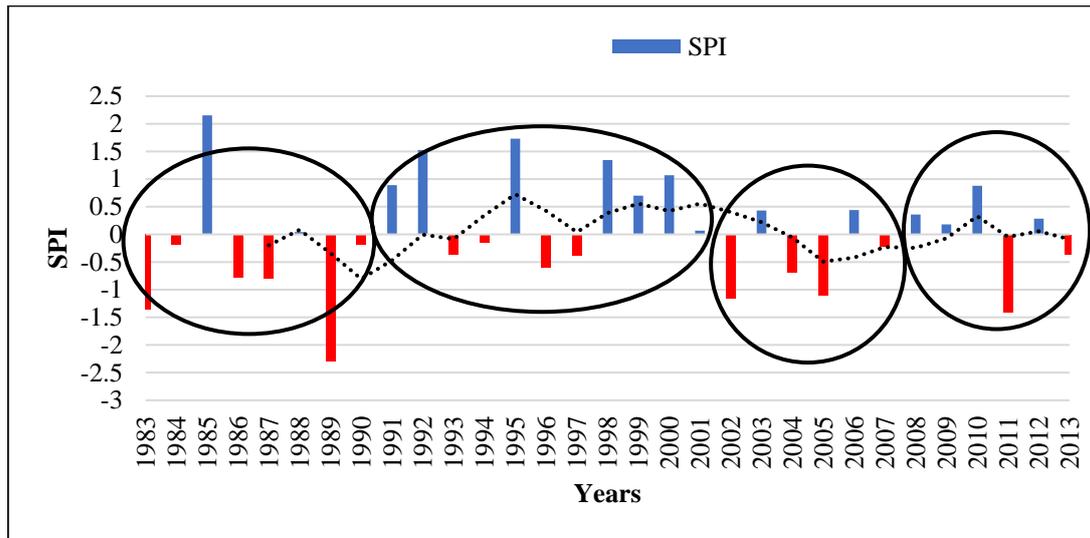


**Figure 6:** Interannual variability of rainfall in the Mouhoun basin (Bobo-dioulasso station)

To analyze the annual variability of rainfall and to characterize the rainfall evolution in the study area, we used the standardized precipitation index (SPI), which is generally used to determine the severity of the drought (McKee et al., 1993). We used it in this work to characterize dry and wet years during the 1983-2013 study period. The SPI is the difference between the precipitation in year  $i$  ( $P_i$ ) and the mean precipitation ( $P_{mean}$ ) relative to the standard deviation ( $\sigma$ ). The results obtained for this index over the period 1983-2013 are shown in figure 7, which confirms the rainfall variability described above. This rainfall is marked by its irregularity, which is manifested by significant interannual fluctuations. There is an alternation of wet and dry years.

Four phases have been identified in the temporal evolution of rainfall in the study area. The first phase is marked by rainfall deficits and concerns the period 1983 to 1990. The second phase is characterized by rainfall surpluses and concerns the period 1991 to 2001. Thus, from the year 1991, the study environment experienced a long period of humidity, the indices being relatively positive. Nevertheless, a few deficit years were recorded. This is the case for the years 1993, 1994, 1996 and 1997, which were characterized by a moderate drought ( $0 > SPI > -1$ ).

The third period (2002-2007) is in deficit and characterized by a dominance of drought years. The last period (2008-2013) is characterized by interannual variations in rainfall volume. Rainfall anomalies are identified during this last sequence. The year 2011, for example, is a year of severe drought and is found in a series of years of moderate humidity.



**Figure 7:** Standardized Precipitation Index

The following table shows the frequency distribution of the years according to the SPI classes. It highlights wet and dry episodes.

**Table 1:** Frequency of Years by SPI Classes

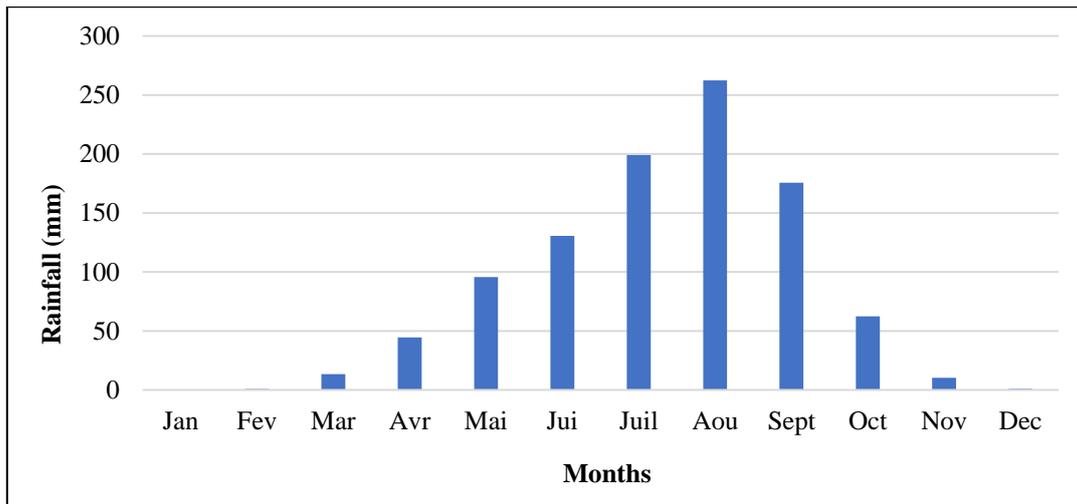
Station	NY	EH	HH	MH	nY	MD	HD	ED
Bobo-Dioulasso	30	1	4	9	1	11	4	1

Source : Data processing 2020

**SPI:** Standardized Precipitation Index; **NY:** Number of years; **HE:** Extreme Humidity; **HH:** High Humidity; **MH:** Moderate Humidity; **nY:** normal Year; **MD:** Moderate Drought; **HD:** High Drought; **ED:** Extreme Drought

In summary, the wet sequences (14 years) are lower than the dry sequences (16 years). However, the last two decades have been wetter than the 1980s. Similar results had been obtained in West Africa by several authors such as Le Barbe et al. 2007 and Le Lay and Galle 2005.

The analysis of rainfall evolution at monthly time steps (figure 12) allowed for climate zoning. The rainfall regime is a uni-modal regime characterized by a rainy season (April to October) and a dry season (November to March). The wettest months are June, July, August and September.



**Figure 8:** Monthly rainfall pattern in the Mouhoun basin (Bobo-Dioulassa station)

### 3.7 Development factors

- *Population*

According to the 2006 General Census of Population and Housing, the population of Burkina Faso, with a population growth of 3.1% per year, was 14,017,262, 51.7% of whom were women. It is characterized by its extreme youthfulness: 47% of the population is under 15 years of age, 67% under 25 years of age and 33.2% of young people are between 15 and 35 years of age. This population is estimated in 2016 at 19,034,397 inhabitants (NISD, 2009).

- *On the socio-economic level*

The economic activity of the regions making up EC-Mouhoun is differentiated: for the Hauts Bassins region, the contribution of the primary sector is equivalent to that of the tertiary sector; together these two sectors contribute half of the region's GDP. The Boucle du Mouhoun, Center-West and South-West regions are predominantly agricultural; more than 50% of their GDP is generated by the primary sector. The contribution of the North and Cascades regions to EC-Mouhoun is essentially related to the primary sector.

- *The Human Development Index (HDI)*

The Human Development Index changed very little in the different regions of the basin between 1991 and 2001, except in the Boucle du Mouhoun and Southwest regions, which saw a significant improvement, with their HDIs rising from 0.176 to 0.296 and from 0.164 to 0.267

respectively between 1991 and 2001. By way of comparison, the national HDI was estimated at 0.300 in 2001 and 0.302 in 2002.

### **3.8. Water balance and uses in the Mouhoun basin (reference year 2010)**

#### **3.8.1. Water balance**

The basin's renewable water resources are estimated at about 5.8 billion m<sup>3</sup>/year on average. As for surface water, it amounts to an average of 3.8 billion m<sup>3</sup>/year (4.7 billion m<sup>3</sup>/year including groundwater transfer). Surface water is stored in nearly 260 reservoirs with a total capacity of 806 Mm<sup>3</sup>, including 600 Mm<sup>3</sup> for the Sourou reservoir alone. The remainder is divided among reservoirs of limited capacity. Total surface water withdrawal is estimated at 1 billion m<sup>3</sup>/year, of which 30% is withdrawn for irrigated agriculture and 63% is lost by evaporation from water bodies.

Groundwater is abundant (on average nearly 2 billion m<sup>3</sup>/year of renewable resource). They contribute about 900 Mm<sup>3</sup>/year to the basic flow of rivers, mainly at the level of springs (Mouhoun Water Agency, 2014).

#### **3.8.2. Water uses in the basin**

- ***Drinking water supply***

Drinking water supply in the Mouhoun basin is provided by the National Water and Sanitation Office (ONEA). The total withdrawal was nearly 16 Mm<sup>3</sup> in 2010, 75% of which was for the city of Bobo-Dioulasso alone. The average rate of access to drinking water in rural areas in the Mouhoun basin was around 59% in 2011, varying from over 75% in some communes to less than 35% in others. In general, the improvement in access rates to drinking water is limited by the high population growth rate.

- ***Water for irrigation***

The irrigation potential is 206,000 ha, with a total of nearly 20,000 ha of hydro-agricultural developments, including 7,000 ha of irrigated perimeters; 7,000 ha of lowlands developed under partial control and 6,000 ha of small-scale pump irrigation. Irrigated agriculture downstream of dams is dominated by rice cultivation. Market gardening and maize are cultivated in the off-season, particularly on areas where double rice cultivation cannot be practiced due to insufficient water resources, and by a large number of small farms pumping directly into the rivers. Irrigation withdrawals are estimated at just over 300 Mm<sup>3</sup>/year, mainly from surface water.

- ***Water for animal husbandry***

Breeding is one of the main activities carried out in the basin. It is of the traditional extensive type. The total number of livestock is estimated at nearly 3 million Tropical Livestock Units in 2012, representing a water requirement of about 54.4 million m<sup>3</sup>/year. Watering of livestock is most often done by direct access to surface water points (rivers, lakes, ponds, reservoirs) and secondarily from wells and boreholes.

- ***Fishing***

It is practiced in the river network, flood plains and water reservoirs of EC-Mouhoun and contributes 53% (5,300 t) to the total volume of fish caught by fishing in Burkina Faso. Fish farming is practiced in cages and pens on about fifty developed sites, but production is still poorly controlled.

- ***Water demand for gold panning***

This demand is met by direct withdrawal from existing water points without much consideration for other uses, which can cause tensions due in particular to the early drying up of the water points.

- ***Water for industry***

The industrial activities concern the fields of food processing, textile industry; mechanics and metallurgy; chemistry and its derivatives; paper and packaging industry. The most important industries are mainly supplied by groundwater from private boreholes.

- ***Water for the craft industry***

Traditional well water and surface water are generally used for artisanal activities. In urban areas, crafts also use the drinking water supply network.

- ***Water for civil engineering***

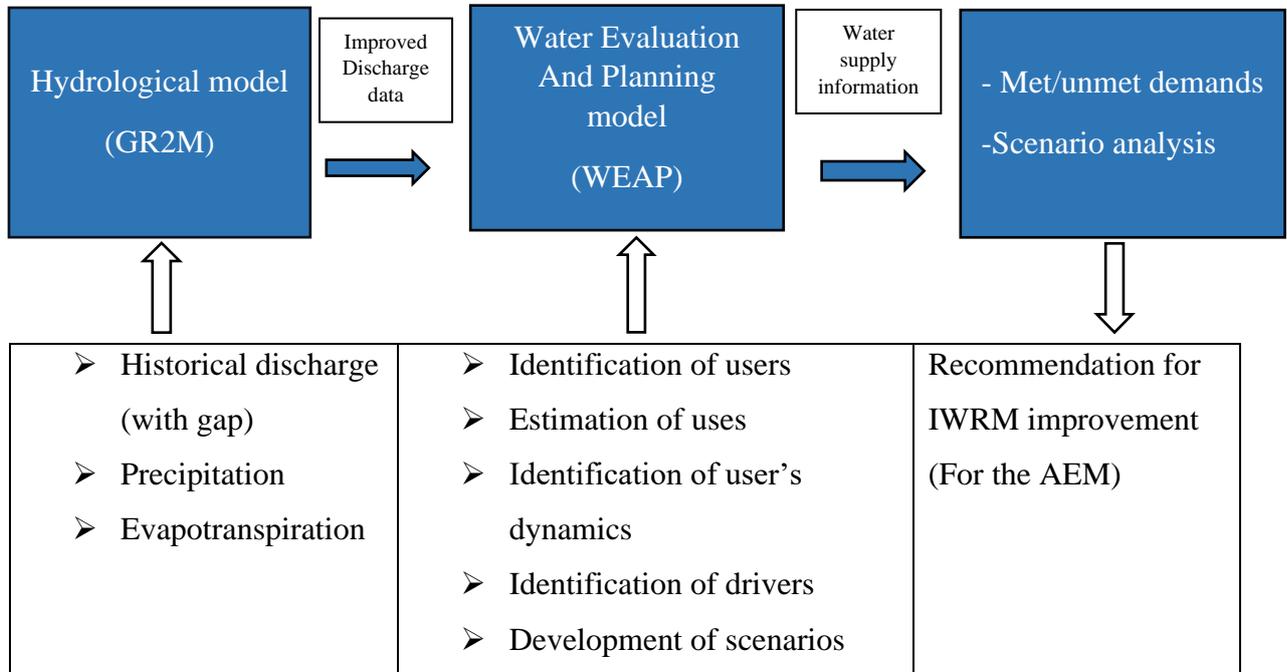
Civil engineering works can have a significant impact on the water resources of this basin. The construction of the Samendeni dam is an element that we will take into account in our study. Indeed, this hydroelectric dam was inaugurated by the President of Burkina Faso at the end of November 2019. It has a total capacity of 1.05 billion m<sup>3</sup> and will produce 2.6 MW of electricity. In addition, the dam will encourage fishing activities and irrigation in the

community. Overall, water needs for civil engineering, limited in time to the duration of the works, are currently estimated at 0.5 Mm<sup>3</sup>/year (Mouhoun Water Agency, 2014).

## CHAPTER FOUR

### 4. RESEARCH METHODOLOGY

Two models are used in this work, GR2M and WEAP. The overall methodology of the work is developed in this schematic diagram :



**Figure 9** : Schematic diagram of the methodology

#### 4.1. APPLICATION OF GR2M

##### 4.1.1. Data used

Three types of data were used in the rainfall-runoff modeling exercise, namely monthly precipitation, monthly potential evapotranspiration (ETp), and monthly discharge.

##### *a- Climatic data*

Climatological data such as precipitation was taken from the KMNI Climate Explorer database at <http://climexp.knmi.nl/selectstation.cgi?id=someone@somewhere>. For relative humidity, wind speed, vapor pressure and solar radiation, their data have been uploaded from <https://globalweather.tamu.edu/pubs>. These data concern the Bobo-Dioulasso station and the archived values for this station are monthly series.

**b- Historical discharge data**

The flow data are from the Nwokuy hydrometric station. This station is located at 12.5278 North Latitude and -3.55 East Longitude. The series of data taken spans over 1989-2013 and is extracted from the database of the General Directorate of Water Resources of Burkina Faso.

**4.1.2. Methods of analysis**

**4.1.2.1. Calculation of Potential Evapotranspiration (ETp)**

Since 1950, several formulas have been developed to estimate potential or reference evapotranspiration (FAO, 1998). They are classified into four groups according to the parameter used (temperature, solar radiation, relative humidity, wind). These climatic factors affect crop transpiration and plant matter production. Because the measurement of ETp in the field is complex, several authors have developed formulas for its estimation, including Hargreaves' (1985), Thornthwaite's (1948), and Penman-Monteith's (1994) formulas. In our study, we used the ETO Calculator which takes into account the variables temperature, solar radiation, relative humidity and wind speed and calculates ETp following Penman-Monteith's equation.

**4.1.2.2. Hydrological modelling with GR2M**

**a- Description of the model**

A schematic diagram of the structure is given in figure 9.  $P_k$  is the monthly rainfall in month  $k$  and  $E$  is the average potential evapotranspiration for the same calendar month. The equations governing the model are as follows:

**- Production**

The production function of the model is based on a soil moisture monitoring reservoir. A part  $P_s$  of the rain  $P_k$  will be added to the  $S_k$  content in the reservoir at the beginning of the time step:

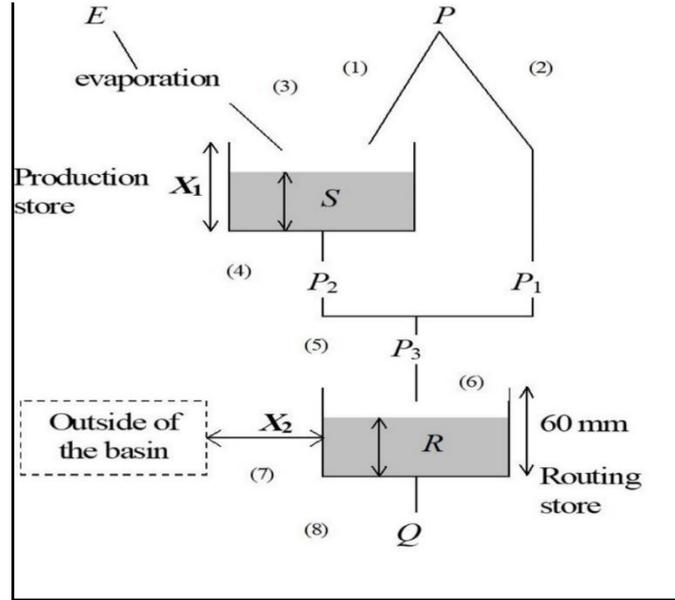
$$P_s = \frac{X_1 \left( 1 - \left( \frac{S_k}{X_1} \right)^2 \right) \cdot \tanh \left( \frac{P_k}{X_1} \right)}{1 + \frac{S}{x_1} \cdot \tanh \left( \frac{P_k}{X_1} \right)}$$

The parameter  $X_1$ , tank capacity, is positive and expressed in mm. The excess rainfall,  $P_1$ , is given by :

$$P_1 = P - P_s'$$

and the content of the tank is updated:

$$S' = S_k + P_s$$



**Figure 10:** Diagram of the structure of the GR2M model (Mouelhi et al.,2006)

Due to evapotranspiration, a quantity of  $E_s$  is taken from the tank:

$$E_s = \frac{S' \cdot \left(2 - \frac{S'}{X_1}\right) \cdot \tanh\left(\frac{E}{E_1}\right)}{1 + \left(1 - \frac{S'}{X_1}\right) \cdot \tanh\left(\frac{E}{X_1}\right)}$$

$E$  is the average potential evapotranspiration for the calendar month in question. The level  $S'$  becomes  $S''$ :

$$S'' = S' + E_s$$

#### - *Percolation*

The soil moisture monitoring tank is then emptied according to  $P_2$  percolation :

$$P_2 = S'' \cdot \left\{ 1 - \left[ 1 + \left( \frac{S''}{X_1} \right)^3 \right]^{-1/3} \right\}$$

and its  $S_{k+1}$  level, ready for next month's calculations, is then given by:

$$S_{k+1} = S'' + P_2$$

#### - *Routing and exchange with the non-atmospheric exterior*

The total amount of water  $P_3$  reaching the routing tank is given by:

$$P_3 = P_1 + P_2$$

The level  $R_k$  in the tank then becomes  $R'$ :

$$R' = R_k + P_3$$

A groundwater exchange term F was imposed by the data from the many basins used.

Ignoring this opening to the non-atmospheric exterior leads to a considerable decrease in the model's efficiency. F is then calculated by :

$$F = (X_2 - 1)R'$$

The X<sub>2</sub> parameter is positive and dimensionless. The level in the tank becomes:

$$R'' = X_2 \cdot R'$$

The tank, of fixed capacity equal to 60 mm, drains to give the flow rate Q<sub>k</sub> according to the following equation:

$$Q_k = \frac{R''^2}{R'' + 60}$$

The content of the tank is finally updated by:

$$R_{k+1} = R'' - Q_k$$

**b- Parameters**

In the context of integrated water resources management (IWRM), the simulation of monthly mean flows from rainfall (Rainfall) and potential evapotranspiration (ET<sub>o</sub>) is necessary and requires a relatively small number of parameters (two parameters X<sub>1</sub> and X<sub>2</sub>):

- a soil reservoir which governs the production function and which is characterized by its maximum capacity X<sub>1</sub>, corresponding to the water retention capacity of the soil.
- a gravity water reservoir that governs the transfer function characterized by an underground exchange coefficient X<sub>2</sub>.

On a large sample of watersheds, the values given in table 2 are obtained.

**Table 2:**Parameter values of the GR2M model obtained on a large sample of watersheds

Parameters	Median	90% confidence interval
X <sub>1</sub> (mm)	380	140 -- 2640
X <sub>2</sub> (-)	0.92	0.21-- 1.31

**c- Model calibration and validation**

To test the capacity of the GR2M hydrological model to reproduce the flows of the Nwokuy sub-basin, the following steps are taken:

- Calibration period: this involves calibrating the model over the period 1989 to 2001 and determining the model parameters  $X_1$  and  $X_2$ .
- Validation period: the aim is to validate the model over the period 2010 to 2013 by maintaining the same parameters  $X_1$  and  $X_2$ .

The calibration parameters  $X_1$  and  $X_2$  were set using the solver. The Solver is a tool that allows the optimization of parameters  $X_1$  and  $X_2$ . It is a macro programmed on an Excel sheet, therefore easy to manipulate, and whose purpose is to minimize the difference between the observed value and the simulated value. The operating principle of the Solver is based on the calculation of the difference between the observed flow and the simulated flow. The value of the sum of the squares of the deviations is then reduced (see equal to zero) by the solver to obtain the right combination of calibration  $X_1$  and  $X_2$  allowing a better fit of the model.

**d- Evaluation of the quality of the model**

The general principle of performance analysis is to compare the calculated flows with the observed flows. The performance of hydrological simulations and regional climate model bias corrections are thus evaluated based on a number of criteria. Within the framework of this research, two criteria were retained for the evaluation of the model: the Nash-Sutcliffe criterion and the  $R^2$  determination coefficient.

**e- The Nash-Sutcliffe criterion (or Nash criterion)**

$$NSE = 1 - \frac{\sum_{i=1}^n (Q^{obs} - Q_i^{sim})^2}{\sum_{i=1}^n (Q^{obs} - Q_i^{mean})^2}$$

With  $Q^{mean}$  the average observed flow,  $Q^{sim}$  the calculated flow,  $Q^{obs}$  the observed flow and  $n$  the number of observations.

A NSE value of 0.5 for a comparison of daily flows is considered an acceptable value in some hydrological studies (Zhang, et al., 2013; McCloskey, et al., 2011; Moriasi, et al., 2007).

**f- The coefficient of determination  $R^2$**

$$R^2 = \left[ \frac{\sum_{i=1}^n (Q_{i,obs} - \bar{Q}_{obs})(Q_{i,calc} - \bar{Q}_{calc})}{\left[ \sum_{i=1}^n [(Q_{i,obs} - \bar{Q}_{obs})^2]^{0,5} \sum_{i=1}^n [(Q_{i,calc} - \bar{Q}_{calc})^2]^{0,5} \right]} \right]^2$$

The value of  $R^2$  describes the proportion of the variance of the observed flows to the simulated flows. Authors such as Moriasi, et al (2007) suggest that any  $R^2$  value greater than 0.5 for daily flow comparisons is an acceptable threshold in hydrological simulation.

**4.2. APPLICATION OF WEAP**

**4.2.1. Acquisition of the software**

The choice of software used in this study is based on the availability, accessibility and flexibility of the parameters that make it up and that allow the exploitation of a wide range of collected databases. The acquisition of the data to be simulated is the primordial step in the modeling process. The WEAP (Water Evaluation And Planning) software can be downloaded free of charge from the website: <http://www.weap21.org>. Activation of the model requires a valid license with a user name and registration code. A free license was granted to us in the framework of this study.

**4.2.2. Structure of the model**

WEAP has five main display modes: Mapping, Data, Results, Block Diagrams, and Notes.

**a- Map**

This display contains Geographic Information System (GIS) based tools for easy system configuration. Objects (such as request nodes, demand nodes, and holds) can be created and placed in the system by selecting, dragging and pasting items from a menu. Image (raster) or vector files obtained from ArcView or other standard GIS tools can be added to the schematic as a background. Data and results from any node can be quickly accessed by clicking on the relevant object.

**b-Data**

Data display allows creating variables and relationships, and enter assumptions or projections using mathematical expressions and dynamic relationships with Excel. It is in this window that you can enter all the data you want to simulate.

### ***c-Results***

The results interface allows a detailed and flexible display of the model outputs in graph, table or schematic form. You can choose the types of results you want to see such as: water demand or needs, flow requirements, coverage rate etc... While choosing the year, scenarios, and branches that we want to present.

### ***d-Synoptic diagram***

In this display, key indicators in the system can be highlighted for quick viewing. You will have an overview of all the results you wish to see simultaneously.

### ***e-Notes***

The "Note" display provides a place to document data and assumptions. Useful information about the different branches that have been entered can be noted.

## **4.2.3. Principle of operation**

The WEAP model is accompanied by a tutorial that facilitates understanding and guides the user through the wide range of applications that can be covered by WEAP. WEAP applications typically include several steps. Since our study is concerned with modeling, we will outline the steps below.

### ***a-Creation of a new study project***

It is the first step in WEAP modeling. Next, the boundary of the area to be represented during the project is selected. An image or vector GIS map can be added to the project area. This map can be used for system orientation and construction and for refining the project boundary. It will also be used as background for the component drawings required to perform the simulation.

### ***b- Definition of general parameters***

It is necessary to define the general parameters of the modeling including the years (beginning and end of the modeling), the time steps, the units and the period for which the scenarios will be generated. The start year corresponds to the current state of the project. It is chosen to serve as the base or reference year for the model and all information systems.

### ***c-Creation of key assumptions***

Key assumptions are key assumptions are data ready to be used by the user which help as mains conditions for the analysis such as domestic water use, water requirements for demand sites, monthly percentage of water use, population growth rate, etc. Its use is especially valuable when the model has a large number of similar elements. They are created in the "Data" view. Its advantage is that scenarios can be created to vary this consumption without having to edit each of the demand sites but simply by changing the value of the key assumption.

### ***d-Introduction of the elements in the cartography***

During this step, the articulating elements of the modeling are drawn such as: the river, the demand sites, connection of the site with a supply (river or groundwater), return flow link etc...

### ***e-Entry or data entry for each element***

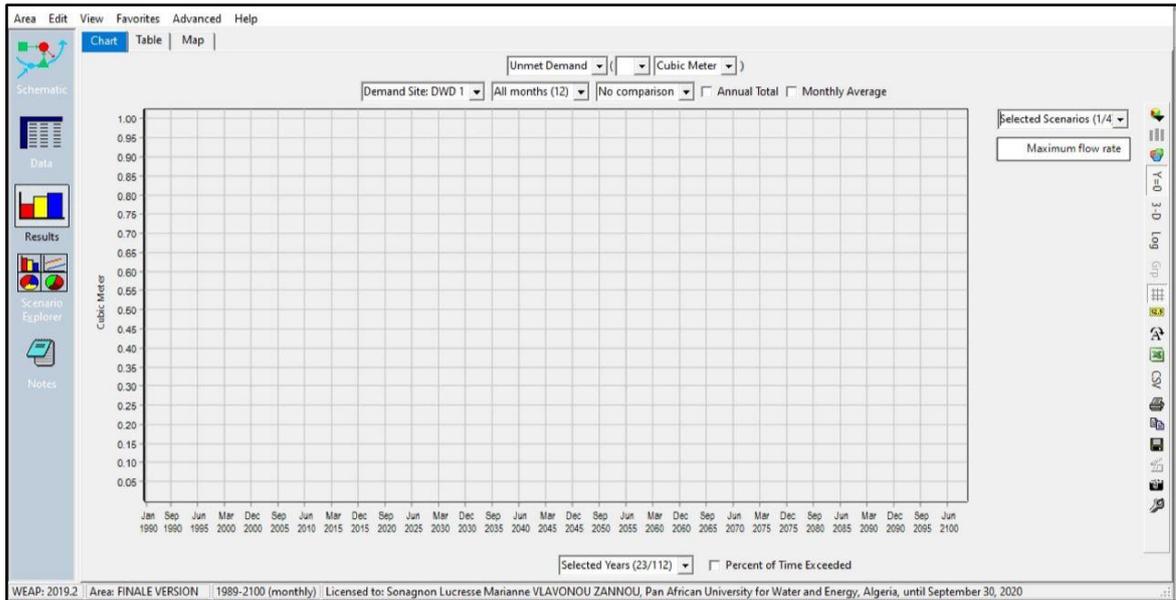
To enter the data concerning the elements, you can either:

-click the right mouse button on the item and choose the option "Edit data" or any other action from the context menu;

-switch to the "Data" view by clicking on the "Data" symbol and select the item in the data tree and enter the data.

### ***f-Run the model and display the results***

To see the results, run the model and then go to the "Results" window to start the calculations. This will calculate the model for the scenario generated by using the data at the current state for the specified time period of the project. More results such as water demand, distributed water, recovery, unmet demand, etc. can be seen. The results display window is shown in figure 9:



**Figure 11:** WEAP model results display window

#### 4.2.4. Presentation of data

Most of the data used here are collected from a study carried out in July 2014 by the Mouhoun Water Agency in the framework of the elaboration of the master plan for water development and management of the Mouhoun basin. As said previously, the whole Mouhoun basin was not taken into consideration for the modeling but rather the upper part of the basin (Mouhoun upper downstream called Nwokuy).

- **Demand Sites**

The data entered in the request sites are:

- The level of annual activity that determines the demand such as agricultural area, number of domestic and industrial water users, etc.
- Annual water consumption or level of water consumption per unit of activities;
- The monthly change or monthly share of annual demand;
- The rate of consumption or percentage of input flow consumed.

**Table 3:** Demand sites with their respective information

Demand site	Annual activity level	Annual water use rate	Monthly variation	Consumption
Population (1989 à 2013 / taux d'accroissement de 3%) Pop Vouhoun 3 Pop Siou Pop Pandi Pop Kou Pop Kouhoun Pop Vouhoun 6 Pop Mouh_ta	100,511 hab 193,481 hab 86,346 hab 605,880 hab 45,349 hab 101,267 hab 651,125 hab	16.42 m <sup>3</sup> /hab/year based on the fact that the daily water use is 45l/hab (ONEA, 2015)	Proportional to the number of months	20%
Irrigation IRR 1 IRR 2 IRR 3 IRR 4 IRR 5 IRR 6 IRR 7	449.17 ha 675.75 ha 280.79 ha 403.33 ha 276.16 ha 472.10 ha 507.14 ha	15,000 m <sup>3</sup> /ha /year	January 12.5% February 12.5% March 12.5% April 12.5% May 12.5% June 0% July 0% August 0% September 0% October 12.5% November 12.5% December 12.5%	70 %

#### 4.2.5. Modeling with WEAP

Before starting the modeling, it is necessary to parameterize the model according to the objective to be achieved.

##### *a- Cartography: Creation of the Nwokuy sub basin Model*

The first step is the creation of the new project. To do this, use the option "New project" in the main menu "Project" and name the project "Nwokuy Watershed", then select the outline of the study area on the world map that appears. At this point, it is essential to add a GIS layer to the area, which is used as a background to plot rivers, demand sites etc. The following figures show the world map and the map of the Nwokuy sub-basin with the river systems.

##### *b- General parameter settings*

In WEAP, the general parameters are: years and time steps, in which the year of the current state is added as the base year for modeling. In this study, the year 1989 is chosen as the year of current accounts and scenarios are constructed from the data entered in that year. The modeling is projected to 2100. The default time horizon is therefore changed to 1989-2100.

##### *c- Digitization of project elements*

After setting the general parameters, we move on to the digitization of the elements, i.e. the introduction of the elements making up the project scheme such as the Mouhoun river, the demand sites (water demand, irrigation), and the introduction of data for each element.

- *Input of river flow data*

Table 4 shows the different monthly variations in mean minimum and maximum rainfall flow (1989-2013) that have been inserted:

**Table 4:** Monthly variation of rainfall flow in the Nwokuy sub-basin (1989-2013)

Flowrate (m <sup>3</sup> /s) Months	Min	Min/2	Average	Max
January	14.586842	7.2934211	26.6348916	43.7091803
February	11.3045776	5.6522882	20.7506158	34.5926318
March	9.38641773	4.6932086	17.6061381	29.0248394
April	7.98449252	3.99224626	18.0516747	33.8481409
May	10.1710863	5.08554314	21.7093481	41.5620887
June	12.9650011	6.48250053	28.7355532	62.5817305
July	19.1010047	9.55050237	46.270756	85.457285
August	30.6012082	15.300601	80.8398218	156.308965
September	42.3071152	21.153556	89.4755353	162.095874
October	35.2551576	17.627578	69.7814638	107.200464
Novelmberr	24.9313918	12.465699	48.100849	83.3417609
December	19.2644945	9.63224727	34.91243	58.2442273

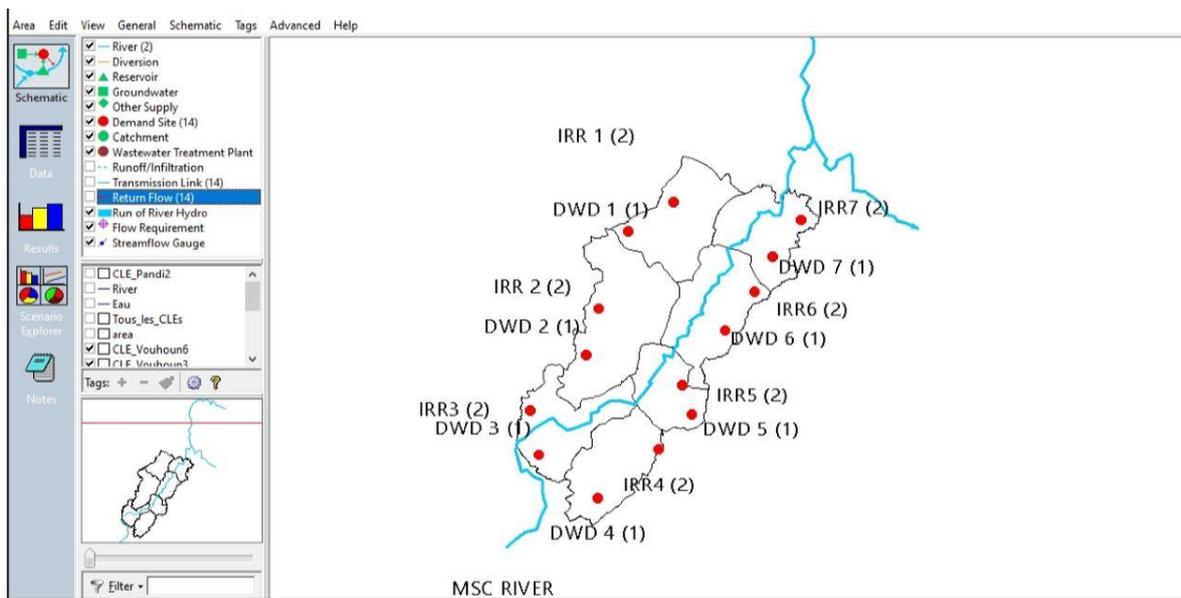
According to the acuity of the problems of development and management of water in sub-basins, aquifers, rivers, urban agglomerations and structures, it was set up in accordance with the Master Plan for Water Development and Management of the Mouhoun Competence Area of the Mouhoun, the Local Water Committees (LCW). Their main vocation is the local management of water resources. The Nwokuy sub-basin is subdivided into seven LWCs. At the level of each LWC, two demand sites were considered in this study, namely irrigation and drinking water consumption, making a total of 14 demand sites. The demand sites are added in the "schematic" view. The only resource considered in this study is water from the Mouhoun river. The table 5 shows the local water committees in the Nwokuy basin and their demand sites:

**Table 5:** Names of local water committees in the Nwokuy sub-basin and their demand sites

Local Water Committees	Domestic Water Demand	Irrigation
Vouhoun 3	DWD 1	IRR 1
Siou	DWD 2	IRR 2
Pandi	DWD 3	IRR 3
Kou	DWD 4	IRR 4
Kouhou	DWD 5	IRR 5
Vouhoun 6	DWD 6	IRR 6
Mouh-ta	DWD 7	IRR 7

- *Creation of request sites and data entry*

Figure 10 shows the sites of demand for irrigation and domestic water requirements:



**Figure 12:** Creation of demand sites

The data inserted for domestic water requirements and irrigation are those given in table 3.

There are two main seasons in Burkina Faso, the dry and the rainy season. The dry season runs from October to May and the rainy season from June to September. Thus, irrigation generally covers only eight months of the year.

- ***Transmission link and return flow***

It is a question of determining how a demand is met and this has been accomplished by connecting the river to each demand site. The return flow is created to model the wastewater coming from the demand sites. This waste water is piped directly to the river. However, it should be noted that not all of the water entering the sites is returned to the river, some is consumed, and some infiltrates into the ground or evaporates.

- c- Creation of key assumptions***

Three main hypotheses are created:

- The use of domestic water;
- Water needs for irrigation
- The population growth rate.

With respect to population growth, the population of each local water committee is assigned a growth rate with the rate defined by the key assumption "population growth rate". This growth is applied in the reference scenario and is 3%. The population in 2015 is 1,783,959.

- d- Creation of scenarios***

The modelling of domestic and irrigation water demand for the 14 sites is based on the creation of five.

- Reference scenario***

It is established from the current account, into which all the basic data is entered to simulate the evolution of the system without intervention. For the current study, the reference scenario covers the year 1989. It simply reflects a projection of current trends without major changes, and serves as a point of comparison for other scenarios in which changes in the system data can be achieved.

- Minimum flowrate scenario***

This scenario is inherited from the reference scenario. It is used here the minimum flow data to make a future projection in order to understand how domestic and irrigation water needs evolve in a deficit year. It covers the year 1990 to 2100.

***- Average flowrate scenario***

In this scenario, the average flow rate is used for the future projection to understand how domestic and irrigation water requirements change in a normal year. It covers the year 1990 to 2100.

***- Maximum flowrate scenario***

The same exercise is done but with the maximum flows between 1990 and 2100.

***- Samendeni Scenario***

In the last scenario, the Samendeni dam, which is a dam located upstream of the Nwokuy watershed, will be taken into consideration. It was inaugurated in November 2019 with a total capacity of 1.05 billion m<sup>3</sup>. This last scenario named "Samendeni scenario" will allow to see if the water needs will be covered if the minimum flow of the basin is reduced by 50%. It also covers the period from 1990 to 2100.

## CHAPTER FIVE

### 5. RESULTS AND DISCUSSION

#### 5.1. Modeling with GR2M

The application of GR2M in the Nwokuy sub-basin was carried out based on the values of observed monthly rainfall (mm), Reference Evapotranspiration (ET0) and observed monthly runoff water (mm).

##### 5.1.1. Result

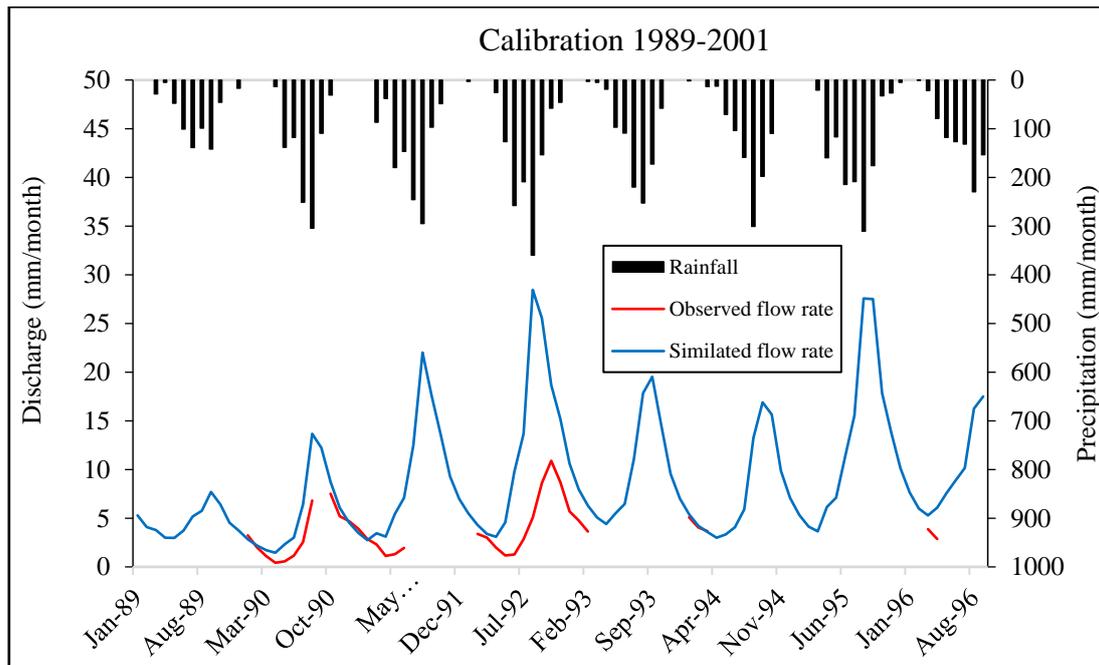
###### *a- GR2M model calibration*

The model calibration was carried out with the series from 1989 to 2001, using the solver in Excel to optimize parameters  $X_1$  and  $X_2$ . During the calibration phase, the suggested full ranges of parameters  $X_1$  and  $X_2$  (as proposed by Cemagref) were used until an optimum value of the Nash criterion and the coefficient of determination between the simulated flows and the observed flows were obtained. The calibration results are presented in the following table:

**Table 6:** Calibration results (1989-2001)

$X_1$ (mm)	$X_2$ (mm)	Nash-Sutcliffe (Q)	Nash-Sutcliffe ( $\sqrt{Q}$ )	Nash-Sutcliffe (ln Q)	Bilan	$R^2$
10.14	0.76	50.51%	56.18 $\mu$	56.27%	100.53	0.3794

The analysis of this table reveals that the calibration of the parameters gives satisfactory values for the Nash criterion. As for the coefficient of determination, expressing the intensity of the relationship between the observed and simulated flows, it can be considered unsatisfactory (0.3794). This poor model performance at calibration is related to the high interannual variability of the climate in the study area. The calculation of the Standardized Precipitation Index in the session of the study area presentation shows that over the period from 1989 to 2013, climate variability is very pronounced. There are six dry years (1989, 1990, 1996, 1993, 1994 and 1997) and seven wet years (1991, 1992, 1995, 1998, 1999, 2000 and 2001). In addition, there is a severe lack of data in the study area. The distribution of these flows at monthly time steps is shown in figure 13.



**Figure 13:**Hydrographs observed and simulated by the GR2M model over the period 1989-2001

The analysis of figure 13 shows a sawtooth pattern of observed and simulated flows alternating seasons of high and low flow discharges consistently with the rainfall pattern in the sub-basin. The months of August and September have the highest monthly flows. The dynamics of the simulated flows follows the same pattern as that of the observed flows, but there is a slight overestimation of the simulated flows (calibration balance equal to 100.53).

***b- Validation of the GR2M model***

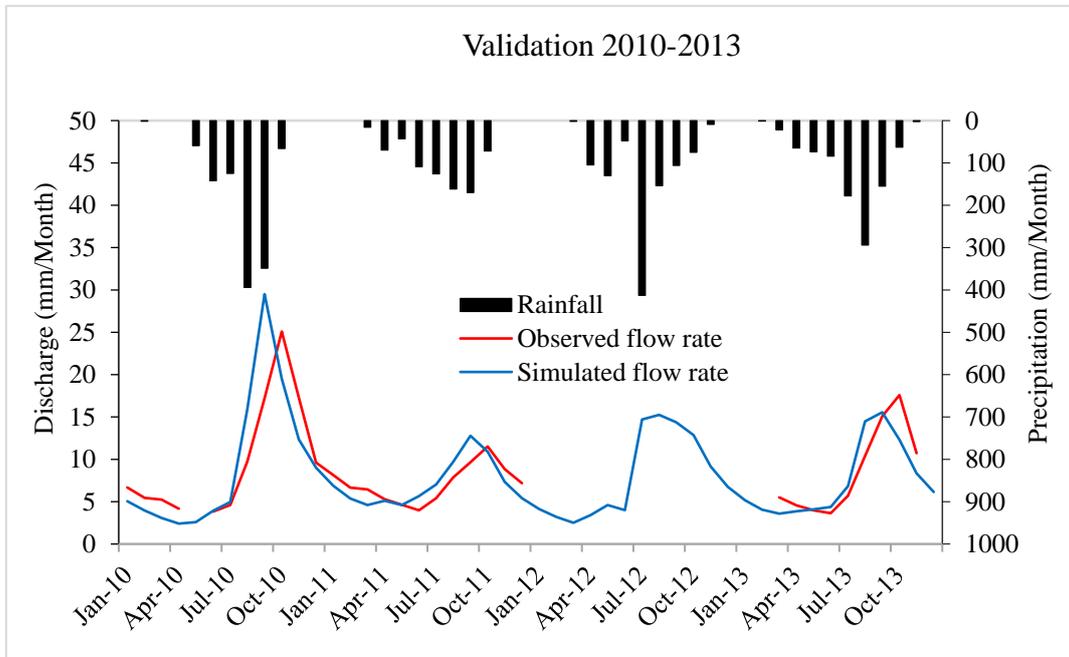
The model validation was done over the 2010-2013 period. The results of this validation are presented in table 7:

**Table 7:**Validation results (2010-2013)

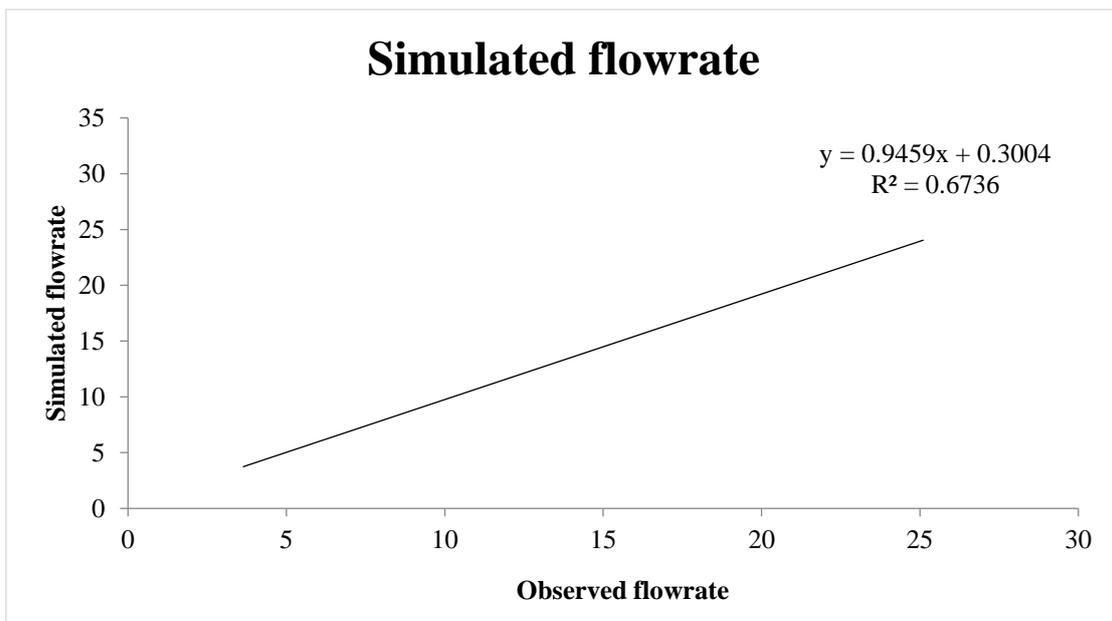
X <sub>1</sub> (mm)	X <sub>2</sub> (mm)	Nash-Sutcliffe (Q)	Nash-Sutcliffe (√Q)	Nash-Sutcliffe (ln Q)	Bilan	R <sup>2</sup>
8.75	0.92	68.1%	69.2%	67.5%	97.5%	0.67

The analysis of figure 14 shows a similar dynamic as well as a good fit between simulated and observed flows over the period 2010-2013. Plotting the simulated against the simulated flows (figure 15) gives a coefficient of determination (R<sup>2</sup>) equals 0.67. This

discrepancy between observed and simulated discharges can reasonably be attributed to important gaps in the series of observed flow obtained at the Nwokuy station. However, this value of the coefficient of determination is acceptable and reflects an association between the observed and simulated discharges.



**Figure 14:** Hydrographs observed and simulated by the GR2M model over the period 2010-2013



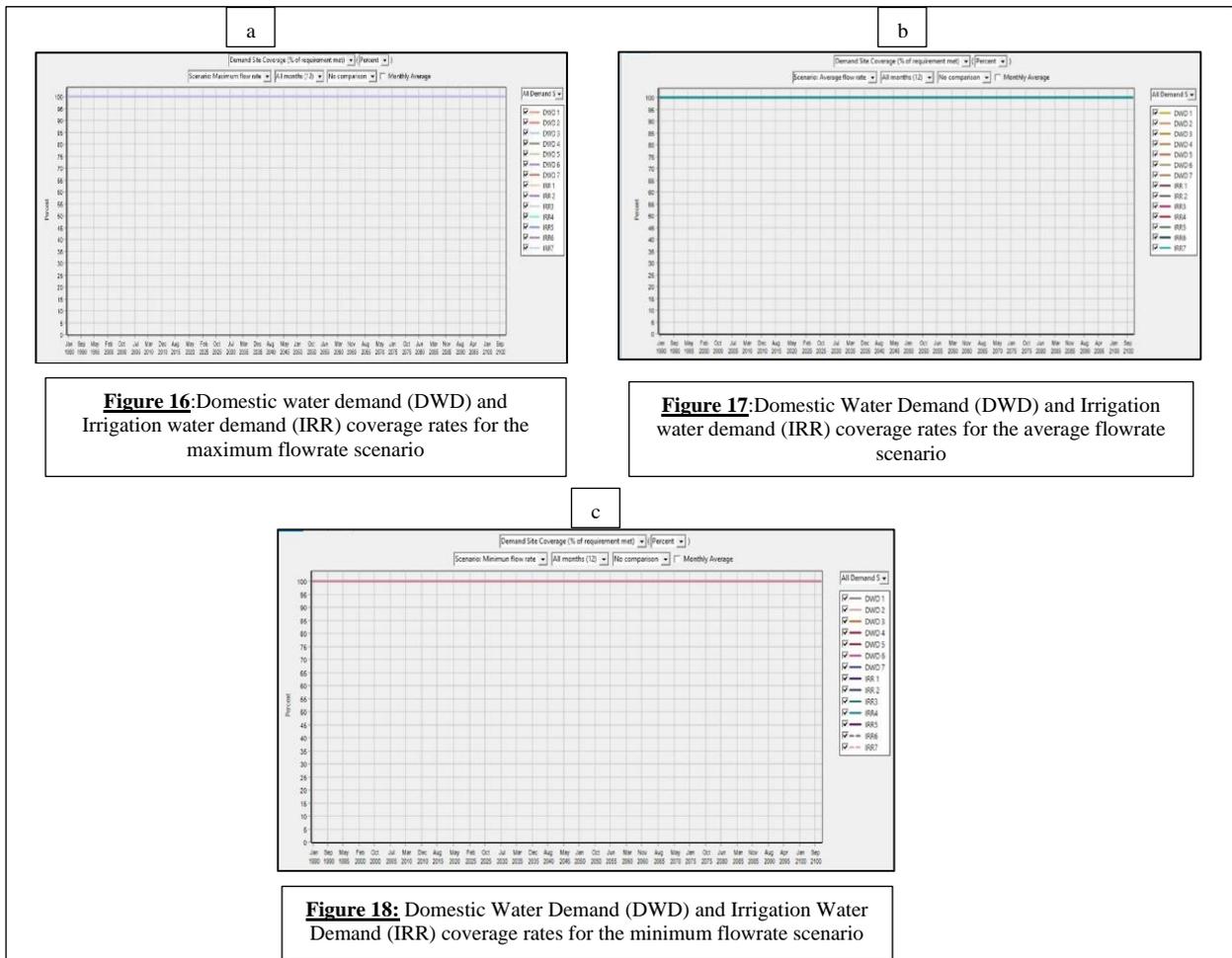
**Figure 15:** Result of the validation by graphical correlation between observed flowrate and simulated flowrate by the GR2M model on monthly data

The GR2M model overall gives satisfactory results (Moriassi et al. 2007). The next step will be to use the flow data simulated by the GR2M model as input data for the WEAP model.

## 5.2 WEAP Modeling

### 5.2.1. Water coverage of sites

Figures 16, 17 and 18 present the water coverage rates for domestic needs and irrigation of the Local Water Committees for the different scenarios (maximum flow rate, average flow rate and minimum flow rate). Indeed, future projections show that for irrigation and domestic needs, the coverage rate is 100% for all demand sites in the Nwokuy sub-basin until year 2100. These results show that even in a deficit year where the river flow rate is minimal, domestic and irrigation water needs are met for the seven LWCs. This abundant availability of resources can be explained by the importance of flows in the Nwokuy sub-basin. According to the Ministry of Water, Hydraulic Works and Sanitation (2104), the interannual and seasonal variability of flows is high in the Mouhoun basin. In a wet decennial year, the total volume would reach nearly 7.2 billion m<sup>3</sup>; in a dry decennial year, the total volume would drop to 2.5 billion m<sup>3</sup> and in a median year the total volume would be about 4.1 billion m<sup>3</sup> /year.



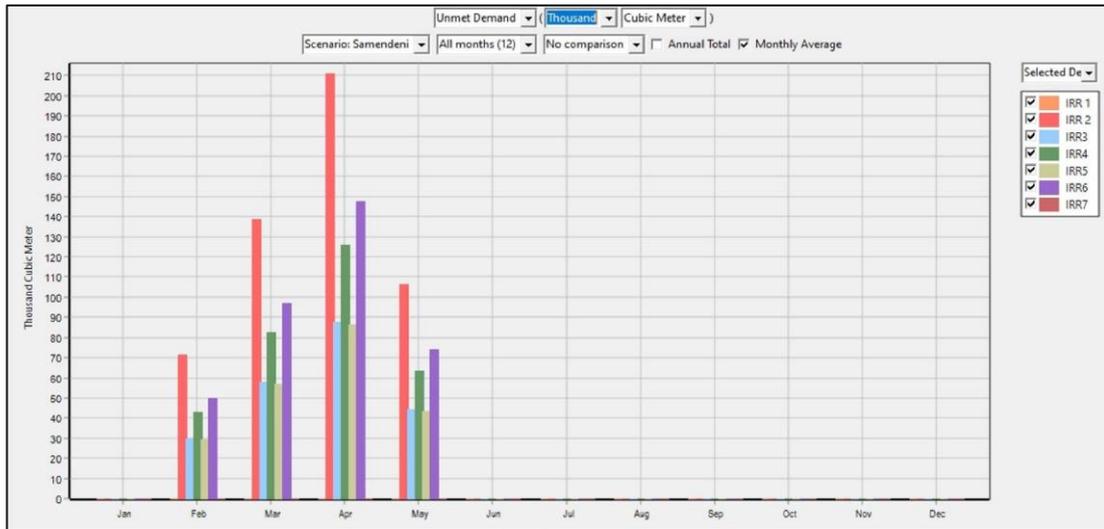
## 5.2.2. Unsatisfied demands

### 5.2.2.1. Water requirement for irrigation

Unsatisfied demands are only experienced under the Samendeni scenario. All demand sites observe an unsatisfied demand under this scenario. For irrigation, supply problems start in 2080 and gradually evolve until 2100 (figure 19). The IRR 2 site corresponding to the LWC of Siou is the most affected with a deficit of 5.05 million cubic meters of water in the year 2100 and the IRR 5 site corresponding to the LWC of Kouhou is the least affected with a deficit of 2.07 million cubic meters of water in the year 2100. Unsatisfied demands are experienced in the months of February, March, April and May (figure 20) corresponding to the low flows period. The highest unmet demand is recorded in April with a deficit of 210.96 thousand cubic meters. The construction of the Samendeni dam may be the main cause of the decrease in water availability in this scenario. This unsatisfied demand could be accentuated by factors such as climatic constraints.



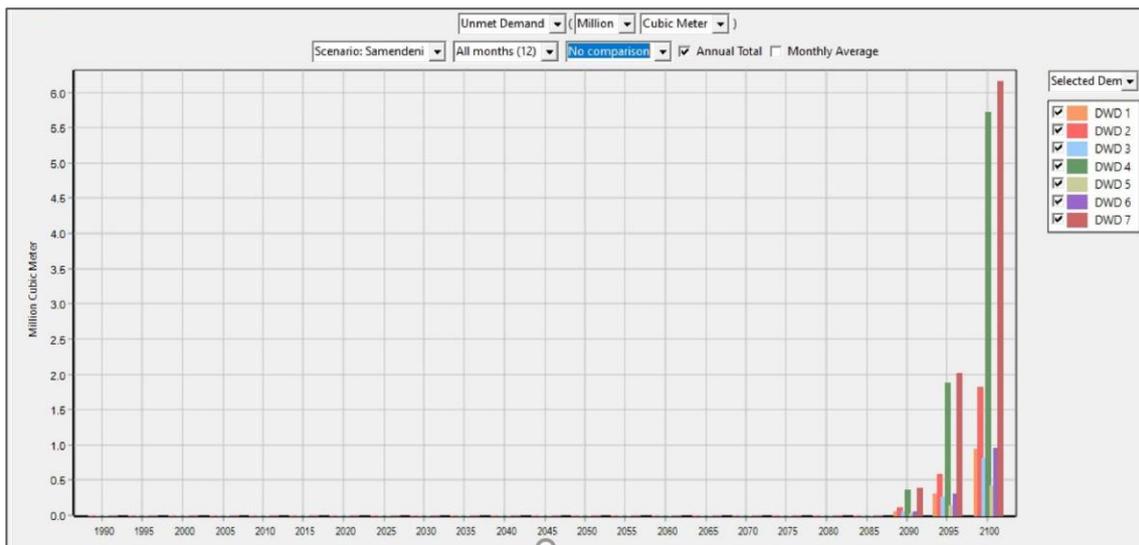
**Figure 19:** Unmet irrigation demand graph for Samendeni scenario



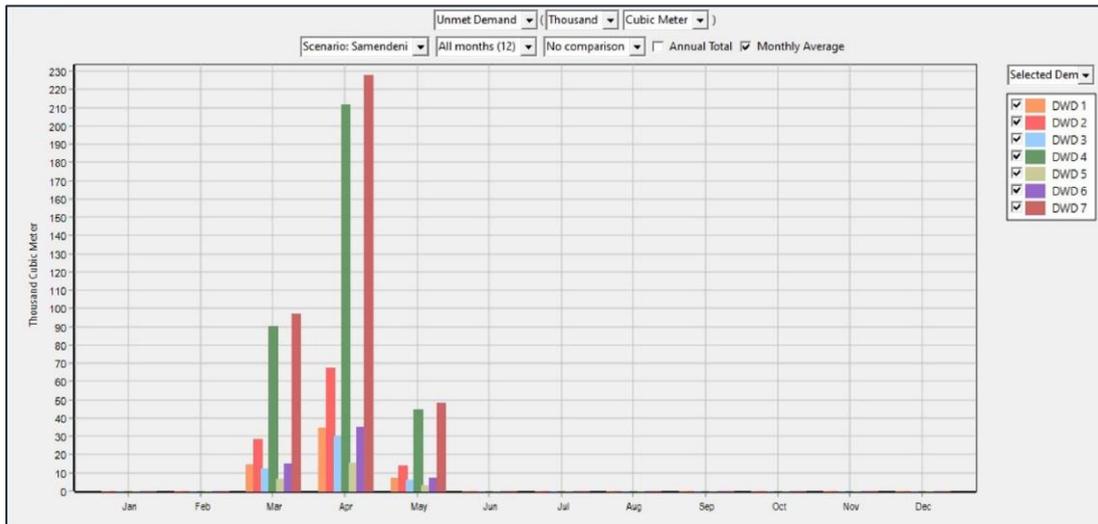
**Figure 20:** Graph showing months affected by unmet demand for irrigation for the Samendeni scenario

**5.2.2.2. Domestic water requirement**

For domestic water needs, unmet demand begins in 2090 and gradually evolves (figure 21). The DWD 7 site corresponding to the Mouhoun-Ta LWC is the most affected with a deficit of 6.16 million cubic meters of water in the year 2100 and the DWD 5 site corresponding to the Kouhou LWC is the least affected with a deficit of 424.58 thousand cubic meters of water in the year 2100. As for irrigation, unsatisfied demands for domestic water are experienced in March, April and May (figure 22). The largest unsatisfied demand is in April with a volume of 294.41 thousand cubic meters.



**Figure 21:** Graph showing months affected by unmet demand for irrigation for the Samendeni scenario



**Figure 22:** Graph showing the months affected by unmet demand for domestic water for the Samendeni Scenario

Studies by the General Directorate of Water Resources of Burkina Faso and Moktar (2017) on the Sourou basin show a downward trend in rainfall and an increase in evapotranspiration at the Bobo-Dioulassou station. Thus, in a context where the climate is dry, problems of availability and satisfaction of water needs could arise. These results agree with those of Moktar (2017) according to which problems related to water availability could occur from 2021 to 2053 with a water deficit of 34.25% in a very dry climate. However, there is a considerable difference between the years. This could be due initially to the number of uses of water considered by Moktar (2017) in his study. In the current study, water for animal husbandry, water for gold panning, water for industry and water for civil engineering have not been taken in consideration. Only water for irrigation and water for domestic uses have been taken in consideration. The second point could concern the percentage of consumption considered (100% for all water uses considered), whereas in our current study, 20% of consumption was considered for domestic water needs and 70% for irrigation water needs.

## **CHAPTER SIX**

### **6. STRATEGIC GUIDELINES FOR THE MANAGEMENT OF WATER RESOURCES IN THE MOUHOUN BASIN**

#### **6.1. Integrated water management at the watershed level**

Integrated management is a mode of management that includes the interests, resources and constraints of all the actors involved in the same field and in the same environment. This avoids having each party consider only its own concerns and responsibilities when making decisions. In the case of water resources, it is a question of planning, developing, distributing and managing the optimal use of the resource, from the qualitative and quantitative points of view. This includes the management of quantitative risks such as droughts, shortages, floods, etc. This management concerns many actors including public authorities, farming companies and inhabitants. Integrated water management therefore takes into account all the uses and users that have an impact on water resources. It provides an overall vision and knowledge of the effects of activities on water resources and the various uses of water. When water uses and water-related activities are considered in isolation, the effect on the resource may seem negligible. However, when they are considered together, the impact can be major. Thus, integrated water management at the watershed level is important because it is a management method that considers all activities that have an impact on water resources within a watershed. It makes it possible to take into account the capacity of the watershed to support the various uses of water and to obtain a global vision in order to preserve the resource and the uses of water for future generations.

Although only two major uses of water were considered in this study (water for domestic use and water for irrigation), the results show that a more rational use of water resources and the promotion of allocation among the different users on a priority basis will allow the satisfaction of basic human needs and avoid water shortages in the long term. In addition, integrated water management at the watershed level has other advantages such as:

- Bringing together the users and stakeholders of water resources working in the same watershed so that they can work together on the uses to be favored and the actions to be undertaken;
- Using public and private funds judiciously by promoting a more efficient coordination of the actions undertaken by the various stakeholders of the territory;

- Reconcile sometimes conflicting uses between the preservation of ecosystems and economic development activities;
- Develop water resources on environmental, social and economic levels; Encourage public participation in the decision-making process;
- Call on the leadership of local stakeholders;
- Adopt a common vision to address water issues (diffuse pollution, flow management, access to water, etc.).

## **6.2. National Water Policy in Burkina Faso**

Today in Burkina Faso there are many policy documents and strategies adopted in various development sectors to guide actors in the medium and long term. Some of these policies and strategies have close links with the water sector: this is the case of the National Water Policy. It is a sector reference whose general objective is to contribute to the sustainable development of the country by providing appropriate solutions to water-related problems in a water resource management approach. Its specific objectives are diversified. We have among others:

- Satisfy in a sustainable way the water needs, in quantity and quality, of a growing population, in a physical environment particularly affected by climate change;
- Improving governance of the water sector through sustainable financing;
- Promote research and capacity building of stakeholders and the promotion of regional cooperation on shared water.

However, there is always a need to review the number of years covered by the policies and strategies adopted. As the results of our study show, some problems may only become apparent if projections are made over 50 years or more. Hence the need for a strategy that extends over several years (beyond 50 years).

## **6.3. Sectoral policy for the mobilization and management of water resources in Burkina-Faso**

This policy aims to meet water needs for all uses in a context of climate change. Burkina Faso's sectoral policy works to ensure that the availability of the resource is sustainably ensured; the freshwater needs of users and aquatic ecosystems are sustainably met; and finally, drinking water needs are sustainably met (Government of Burkina Faso, 2018).

### **6.3.1. Ensuring sustainable water availability**

The aim is to increase surface water storage capacity to 6,732 million m<sup>3</sup> in 2027 and the number of new dams to be built to 46 in 2027. The number of dams to be rehabilitated to 157 in 2027 and the rate of functionality of infrastructures to 73.40% in 2027. The achievement of this objective is achieved through the following actions:

- Construction and rehabilitation of water resource mobilization works;
- Maintenance and upkeep of water resource mobilization structures;
- Coordination and monitoring of the implementation of water resource mobilization actions;

### **6.3.2. The freshwater needs of users and aquatic ecosystems are met on a sustainable basis**

The prospect is to increase the proportion of surface water reservoirs; to set up and operationalize water policies. To this end, it is a matter of carrying out:

- Strengthening the political, legal and financial frameworks for water resource management;
- Strengthening the capacities of the Water Agencies, Local Water Committees and other stakeholders;
- Improvement of the National Water Information System;
- Research and development in the field of water;
- Protection of water resources.

### **6.3.3. Drinking water needs are met on a sustainable basis**

The aim is to increase the national rate of access to drinking water to 95% in 2027, the rate of functionality of drinking water supply facilities in rural areas to 100%, and finally the rate of functionality of modern water points in rural areas (boreholes) to 100% in 2027. To achieve these objectives, it will be necessary to:

- Facilitate access to drinking water;
- Improve the management of the public water service and;
- Strengthen the institutional framework.

## **6.4. Mobilization of water resources in the Mouhoun basin**

### **6.4.1. Mobilization strategies**

Surface water flows are concentrated over a relatively short period of the year. The development of uses will require actions to increase the availability of surface water during the

dry season. As for groundwater resources, it seems that they could be further developed not only for the needs of PWAs but also for other uses. Based on the principles of IWRM, the following strategies for mobilizing water resources are considered:

- to promote the development of local facilities that take into account the expectations of users at the grassroots level, adapt as well as possible to all natural conditions and take into account local socioeconomic specificities;
- to give priority to multiple-use surface water mobilization works (irrigation, fishing, watering, etc.) rather than reserved use works (hydroelectricity);
- to favor the storage of surface water in areas characterized by a low level of losses through evaporation and infiltration. These areas are generally located in the southern part of the basin;
- to promote actions that encourage the recharge of water tables by infiltration of surface water.

#### **6.4.2. The economic stakes**

- Support to associations and groups of irrigators at the base;
- Improvement of the capacities and technicality of irrigators;
- Improvement of the efficiency of irrigated perimeters;
- Improvement of water and land management within the framework of small-scale pump irrigation and promotion of small-scale family irrigation;
- Valorization of water in lowland developments, reconciling the interests of different users and respecting the natural environment;
- Extension of hydro-agricultural developments;
- Taking into account water needs and pollution risks related to mining activities;
- Taking into account water needs and pollution risks related to industrial, artisanal and civil engineering activities;
- Development of the tourist potential.

#### **6.4.3. Governance issues**

The search for better water governance requires capacity building of management, planning, regulatory and control structures in various areas such as training, working procedures, technical and scientific equipment, research and development. The most advanced technical instruments (modelling, satellite imagery) are not yet used on a daily basis and are in reality mastered only by a few managers in general. Within the framework of the action plan for

integrated water resources management, a partial assessment of the needs for capacity building of the public administration has been undertaken and suggested courses of action. However, no such information is available on the capacity building needs of other actors (NGOs and sector associations, private sector, etc.). In addition to this:

- The continued operationalization of the LWCs;
- The elaboration, adoption and monitoring of the Water Agency's multi-year intervention program;
- The evaluation of the impacts of IWRM actions at the Mouhoun basin scale;
- Information and communication activities concerning the Water Agency and IWRM;
- Involvement of stakeholders at the grassroots level in water resource management;
- Involvement of local authorities in water management;
- The application of regulations.

#### **6.4.4. Fight against water wastage in the Mouhoun basin**

Despite of the perception of water abundance in the Mouhoun basin and particularly in the Nwokuy sub-basin which served as a modeling area, results show that water shortages could be experienced from the year 2080. Thus, awareness raising on water saving is necessary for the preservation of the resource. The aim of awareness raising is to sharpen the population's awareness of water issues and to bring target groups such as farmers in the Mouhoun basin to collaborate in the successful saving and protection of water. This will be achieved through the use of the most efficient irrigation techniques, which are likely to increase production and decrease the amount of water to be supplied.

### **Conclusion**

Burkina Faso's water policy considers that water is an economic good, a scarce and vulnerable resource and must be protected both quantitatively and qualitatively. The management of water must be based on common decisions and agreements between the different actors and users. Indeed, several bodies have been created in recent years to reinforce this policy at the level of river basins. Capacity building of actors at all levels, rigorous monitoring of the resource, awareness raising on water saving, all supported by financial investment can help to better manage water resources.

## **GENERAL CONCLUSION**

The Mouhoun basin is one of the five watersheds of Burkina-Faso. Its hydrographic network is dense and is made up of major rivers. It is about 1,000 km long in Burkina Faso and has nine main tributaries and 27 sub-basins. According to the Mouhoun Water Agency (2014), the balance of surface water resources amounts to an average of 3.8 billion m<sup>3</sup>/year. The analysis of climatic variability has enabled to characterize the rainfall evolution in the study area. The results obtained for the calculation of the Standardized Precipitation Index over the period 1983-2013 show four phases in the temporal evolution of rainfall. The first phase is marked by rainfall deficits and concerns the period 1983 to 1990. The second phase is characterized by rainfall surpluses and covers the period 1991 to 2001, while the third phase (2002-2007) is a deficit and is characterized by a dominance of drought years. The last period (2008-2013) is characterized by interannual variations in the volume of rainfall. It is deduced that wet sequences (14 years) are inferior to dry sequences (16 years). However, it is noted that the last two decades have been wetter than the 1980s.

Within the framework of our study, the Nwokuy sub-basin (Mouhoun upper downstream) was considered as a modeling area. The rainfall data were retrieved from the Bobo-Dioulasso station and the flow data are from the Nwokuy station. Two models were used, the GR2M model to fill the gaps in the observed discharge time series and the WEAP model which entered the simulated flows obtained from the GR2M. The application of the GR2M hydrological model provided a time series of uninterrupted flow. The flow thus generated has a certain degree of uncertainty that should not be neglected, but it is reasonable to use it in view of the acceptable performance of the hydrological model. The objective of using the WEAP model is to simulate the evolution of domestic and irrigation water needs in the Nwokuy basin by 2100. Four scenarios have been developed: minimum flow scenario, medium flow scenario, maximum flow scenario and the Samendeni scenario. The results show that the domestic and irrigation water needs in the basin up to 2100 are fully met for the minimum flow, medium flow and maximum flow scenarios. This means that in a deficit, normal or surplus year, the water needs for the two targeted uses will be satisfied until the year 2100. The application of scenarios using the WEAP model shows that in both deficit and wet years, water demands are covered for irrigation and domestic use in a reasonable future. However, a major anthropogenic action such as the construction of the Samendeni dam could in a more or less distant future lead to cases of unsatisfied demand, especially for irrigation water. For the last scenario, it has been noticed that

for irrigation, problems of availability start in 2080 and gradually evolve until 2100 and for domestic water needs, unmet demand starts in 2090 and gradually increases until 2100

The application of a good sectoral water management policy will delay this unsatisfied need, but also the strengthening of the capacities of the Water Agency and Local Water Committees of the Mouhoun basin. The development of educational programs and information and awareness campaigns on water saving is necessary. This will allow an improvement in water use, in order to minimize waste and reduce overall consumption while maintaining the social benefits of water.

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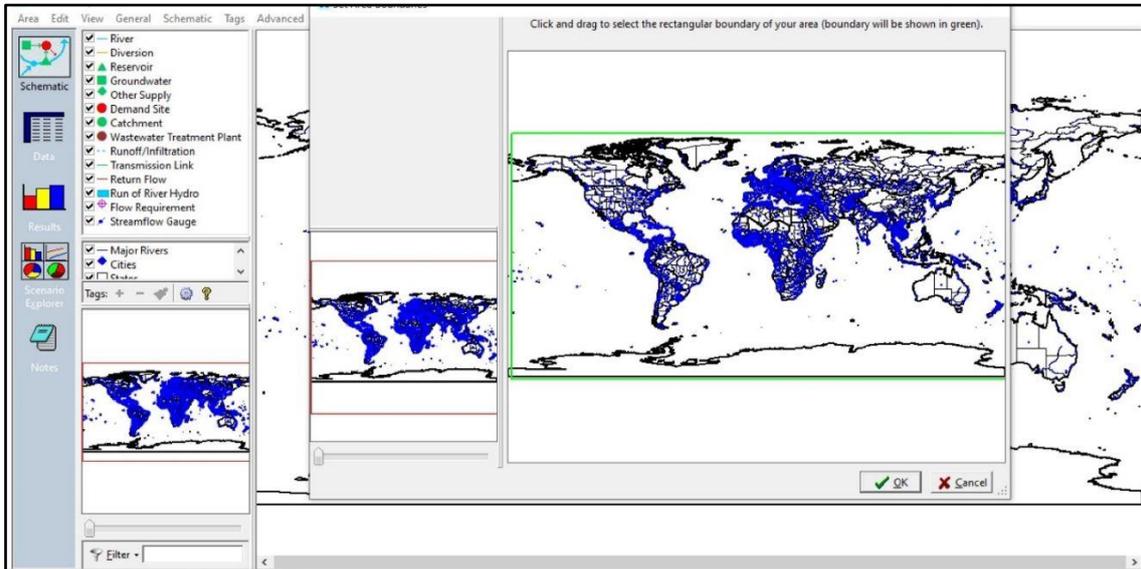
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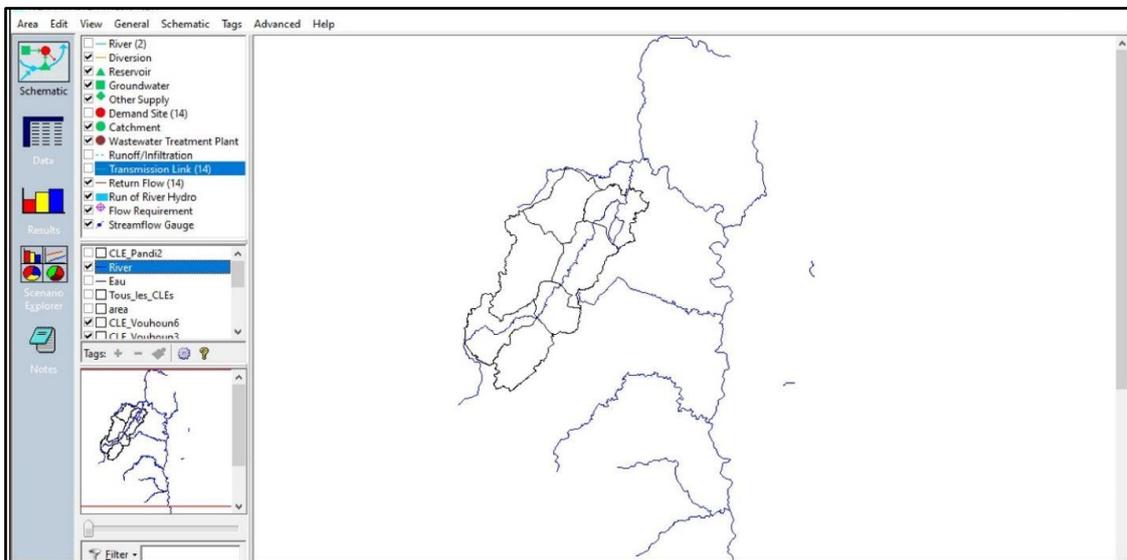
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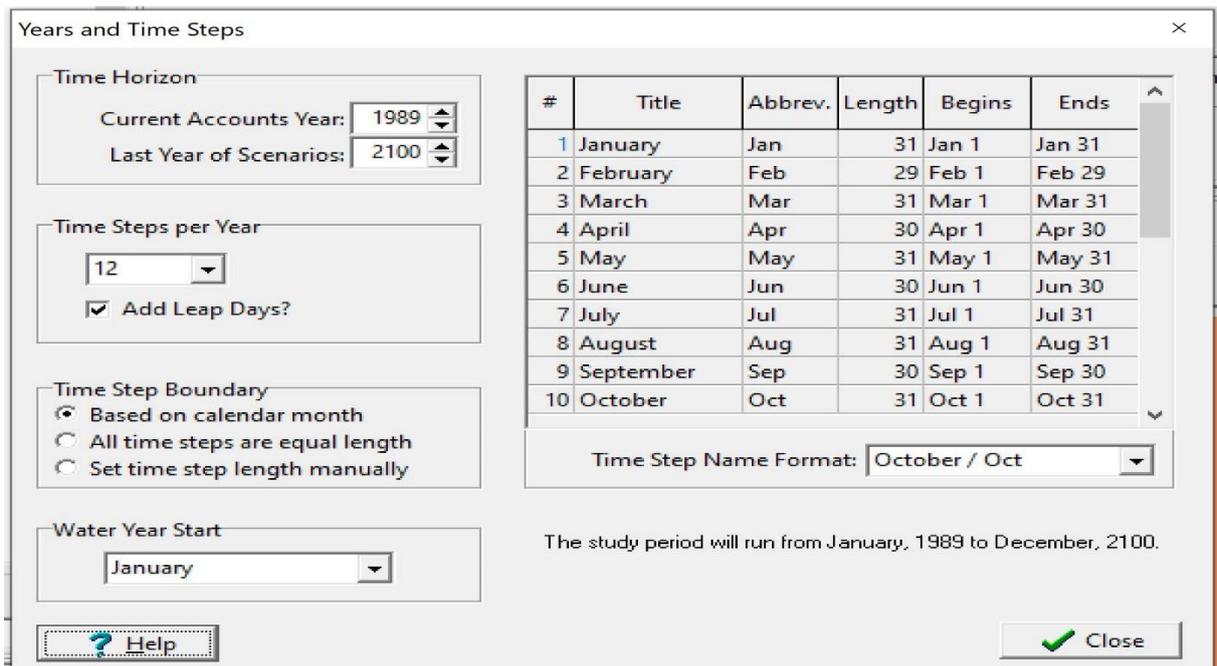
APPENDIX



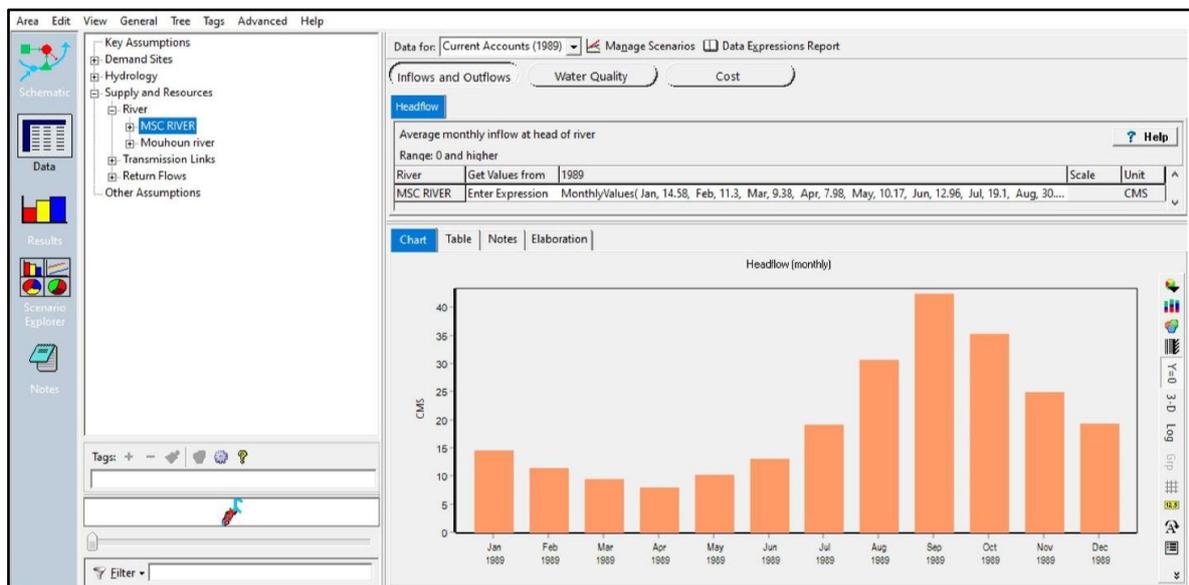
**Appendix 1:** The map of the world



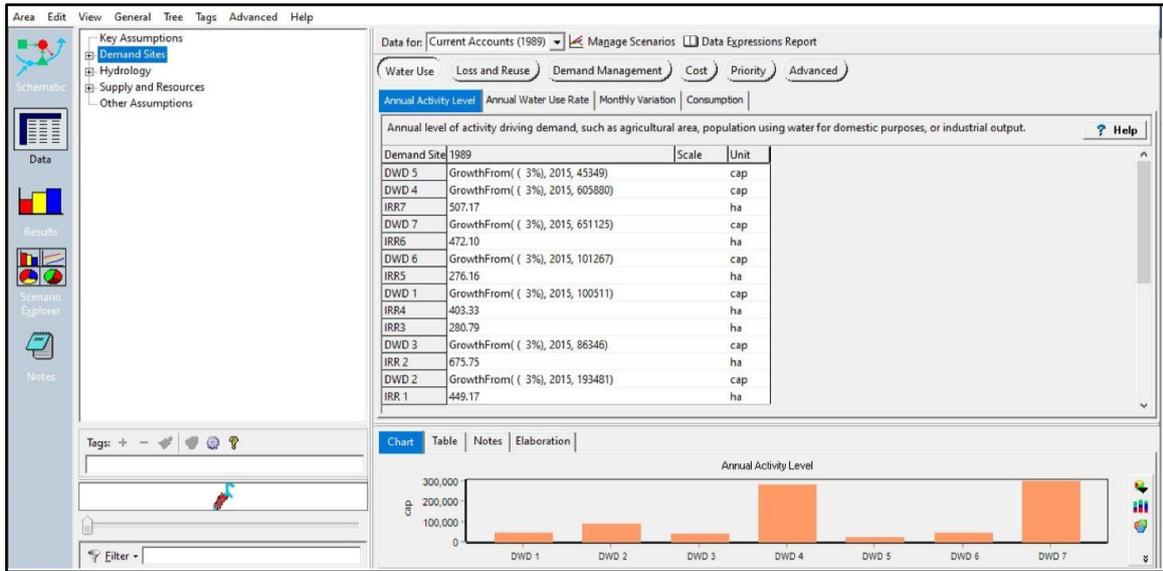
**Appendix 2:** Map of the Nwokuy sub-basin with the river system



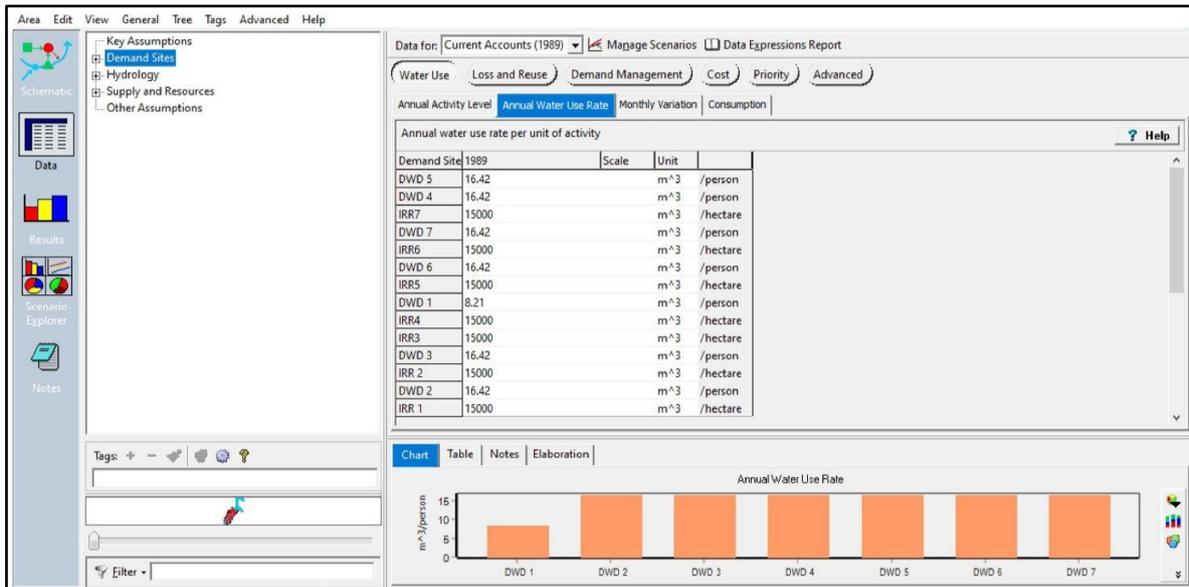
**Appendix 3: Window** for setting years and time steps



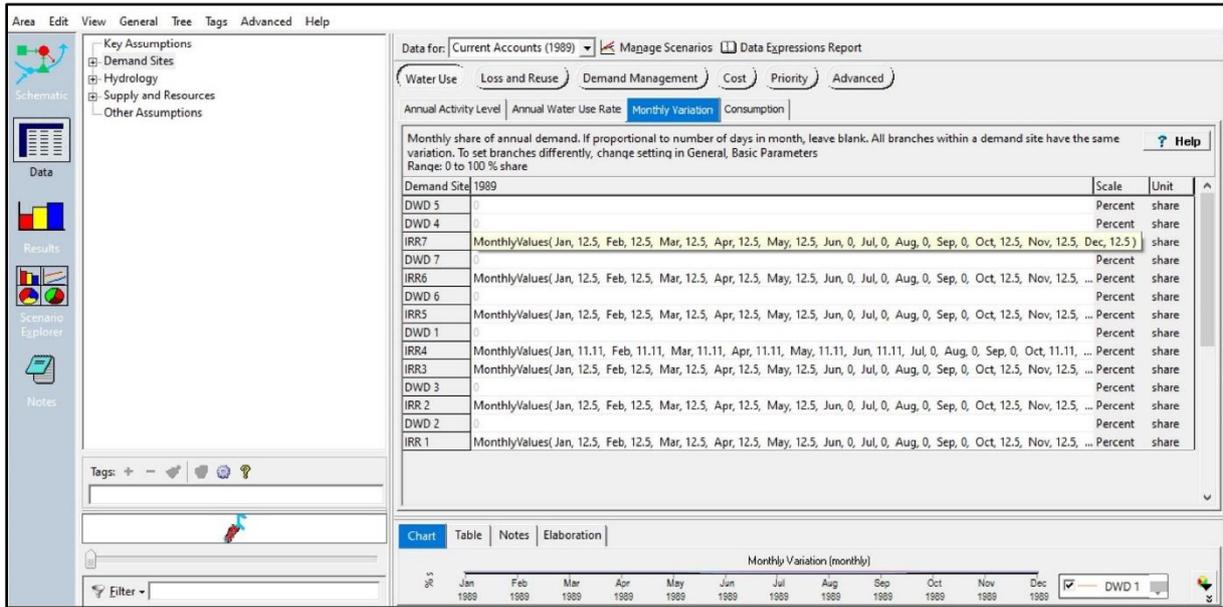
**Appendix 4: River data entry** for the current account



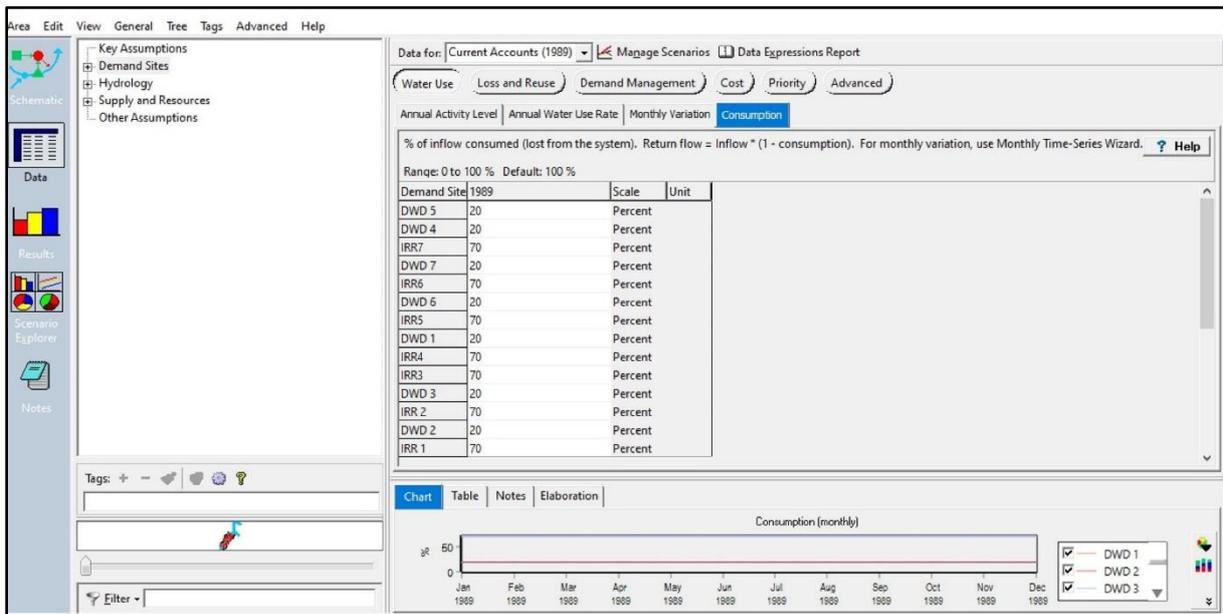
**Appendix 5:** Annual activity level data (current account)



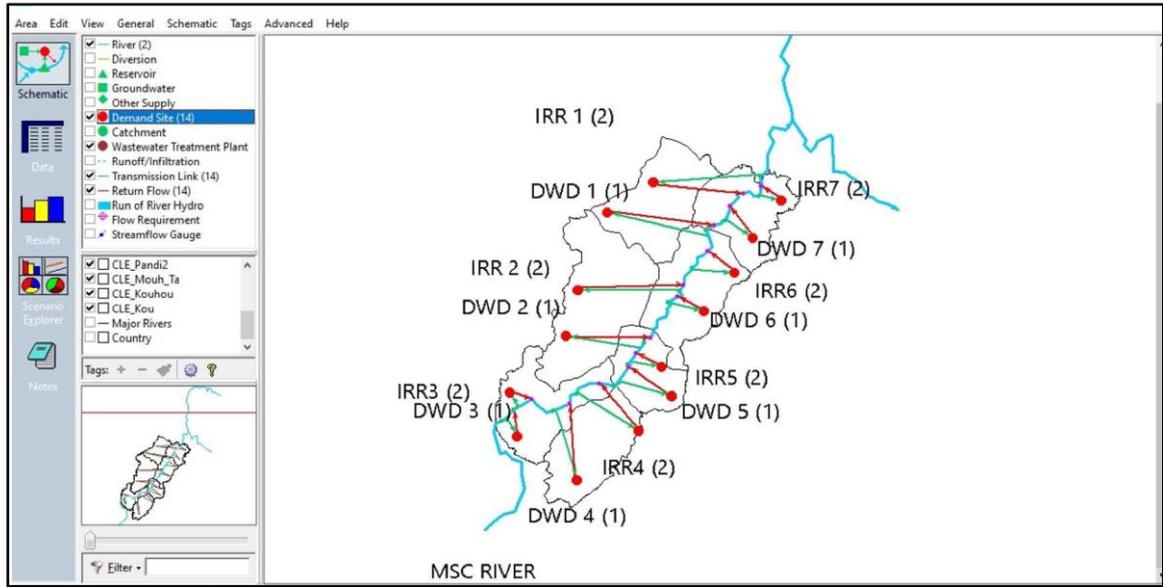
**Appendix 6:** Annual water use rate (current account-1989)



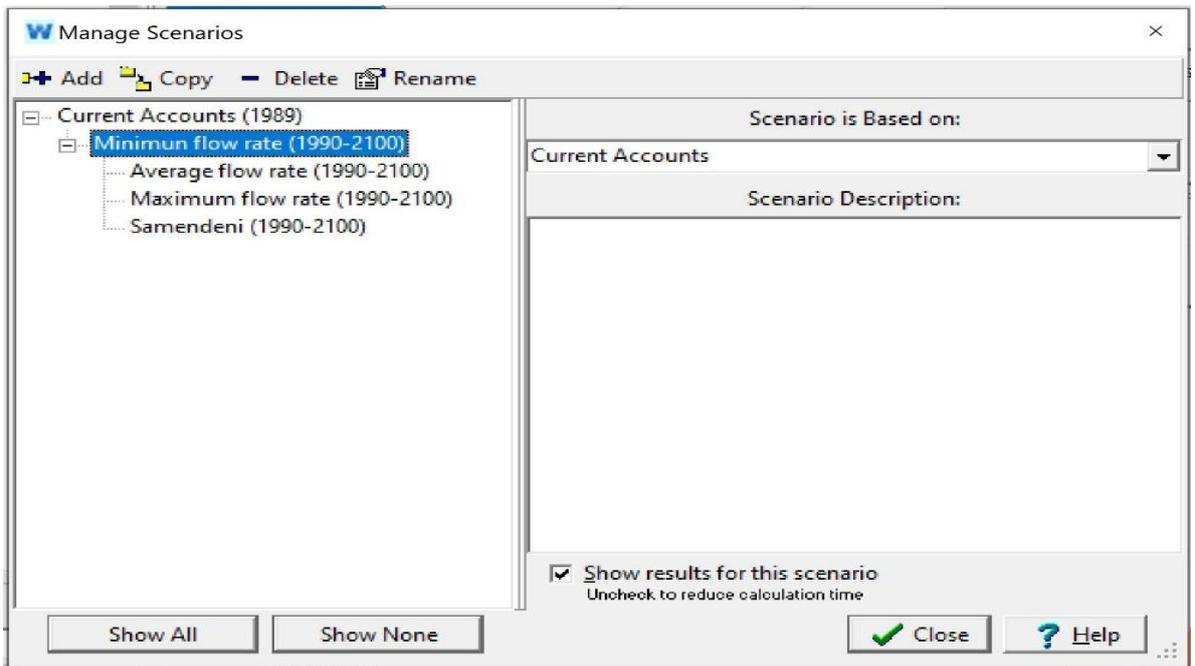
**Appendix 7:** Monthly variation data (current account)



**Appendix 8:** Consumption rate (current account)



**Appendix 9:** Transmission link and return flow



**Appendix 10:** The different scenarios constructed