MODELING A SAHELIAN WATER RESOURCE ALLOCATION UNDER CLIMATE CHANGE AND HUMAN PRESSURE: CASE OF LOUMBILA DAM IN BURKINA FASO.

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Dedication

This thesis is dedicated to:

- *My deceased Father,* ***Sibiri Emile BONTOGHO*** *who educated me to never give up despite what the situation looks like.*
- *My mother Georgette BONTOGHO/OUEDRAOGO who took care of my kids during my stay abroad. Thank you for your prayers.*
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Kabore/Bontogho T. Patricia Emma

In research, the success is in details.

ABSTRACT

Alike most of West African countries, Burkina Faso is facing water resources availability issues. The water scarcity resulting from the rainfall decline of the 1970s is ongoing and represents one of the most challenging problems to tackle for the populations in this area of the world. Despite the implementation of adaptation measures mainly through realization of dams, water availability is still a crucial issue. Consequently, populations still lack safe water for multiple purposes. This seems to be exacerbated by the worst impact of climate change which would impose great change in climate variability as projected by several studies. Indeed, as climate change is inherently linked to the hydrological cycle, it may cause significant alterations in water resources. Nonetheless, despite the seriousness of water scarcity problems and its negative consequences on populations, information is still lacking to understand the past and future climate trend and their impact on the future water availability and demand. Therefore, there is a need to understand those processes in a view of adaptation planning. To model water allocation under climate change and human pressure in an ungauged basin, the Loumbila dam which plays a great role in Ouagadougou´s water supply system is taken as a case study to reconstitute inflows, simulate actual water allocation and predict monthly water allocation under different climate change scenarios.

For these purposes, an assessment of the past climate variability in the basin was drawn. Then, the dam water balance was estimated and the water allocation was assessed. Four major conclusions are drawn from this thesis. By applying R-climdex and Instat, various indices were calculated based on an approach recommended by the World Meteorological Organization (WMO). Four indices related to precipitation (PRCPTOT, RX1day, CWD, CDD) and other four related to temperature (TXx, TNn, CSDI, WSDI) were selected. The first key findings of this study on the climate variability are that in general the intensity and frequency of extreme precipitation and temperature events are increasing. The total precipitation is decreasing at a change rate of -2.05 while the maximum one day precipitation is increasing at a change rate of 0.35. The rate of change in CWD is -0.01 and the rate of change in CDD is about 0.59.

The rainfall season is becoming shorter and the occurrence of dry spells is also increasing with dry spells length varying between 5 and 35 days. The change rate in temperature indices is 0.03, 0.02, 0.06 and 0.28 respectively for TXx, TNn, CSDI and WSDI. By setting up a second set of software (ARC GIS) and models (CROPWAT, GR2M and Yates) to estimate the dam water balance, the results show the reconstitution of the dam inflow, the market gardening area and the crops water requirement. It was found that the market gardening around the dam occupied an area of 177ha. Finally, a serial number of sensitivity analysis with the water allocation model (WEAP) under RCP_8.5 and RCP_4.5 scenarios was done. RCMs data bias correction was set up based on delta change method used by Lettenmaier and Gan (1990). The assessment of water needs shows an upward trend of water supply meaning that this site will experience great challenges in the future. The unmet demand for different demand site will increase in the future due to the decrease in water availability and increase in water demand.

Key words: Water resources, climate change, climate variability, human pressure, ungauged basin, sustainable water allocation, RCMs scenarios, Massili basin.

RESUME:

A l'instar de la plus part des pays de l'Afrique de l'Ouest, le Burkina Faso fait face à la rareté des ressources en eau depuis la baisse de la pluviométrie des années 1970. Malgré la mise en œuvre de mesure d'adaptation, notamment à travers la réalisation de barrages, l'eau garde toujours son caractère 'rare' dans le contexte sahélien. En conséquence, de nombreuses personnes ne disposent pas d'assez d'eau pour satisfaire leurs besoins quotidiens. Cette situation se trouve exacerbée par les effets néfastes du changement climatique qui perturbent la variabilité du climat comme démontrés par des études précédentes. Néanmoins, en dépit de la gravité des problèmes de disponibilité de la ressource en eau et de ses conséquences négatives sur la population, peu de recherches ont été investies pour comprendre les tendances passées et futures du climat et leur impact sur l'offre et la demande en eau pour les futures générations. Cependant, il s'avère primordial de comprendre ces processus en vue d'assurer une planification durable de la ressource.

Afin de modéliser l'allocation de l'eau dans un contexte de pression climatique et anthropique pour un bassin versant non jaugé, le réservoir de Loumbila qui joue un important rôle pour l'approvisionnement en eau potable de la ville de Ouagadougou est pris comme site d'étude pour reconstituer les débits d'entrée, simuler la répartition actuelle de l'eau et prévoir l'allocation mensuelle à l'horizon 2050 sous différents scénarios de changement climatique.

A ces fins, une évaluation de la variabilité du climat passé a été élaborée. Ensuite, le bilan d'eau du réservoir a été estimé. Enfin, l'allocation de l'eau a été simulée en utilisant un modèle de distribution hydrologique. Quatre grandes conclusions sont tirées de cette thèse. En effet, en appliquant R-climdex et Instat, plusieurs indices ont été estimés en se référant sur une approche recommandée par l'Organisation Mondiale de la Météorologie (OMM). Quatre indicateurs pluviométriques (PRCPTOT, RX1day, CWD, CDD) et quatre autres indicateurs de températures (TXx, TNn, CSDI, WSDI) ont été sélectionnés.

Les principaux résultats de cette étude sur la variabilité du climat relatent qu'en général, l'intensité, la fréquence des précipitations, les températures et l'occurrence des événements extrêmes sont en augmentation. La saison des pluies est de plus en plus courte avec des poches de sécheresse de plus en plus fréquentes variant de 5 à 35 jours (1960-2012).

La précipitation totale décroit a un taux de 0.25 tandis que la quantité de pluie maximum enregistrée en une journée est en baisse de 0.35. Le nombre de jour pluvieux diminue de 0.01 tandis que le nombre de jours de poches de sécheresse augmente de 0.59. Les indices de températures connaissent une augmentation de l'ordre de 0.025 à 0.27.

L'application de CROPWAT, ARC SIG, GR2M et Yates a permis d'estimer les composantes du bilan hydrique à savoir les débits à l'entrée du barrage, l'étendue des cultures maraîchère et la quantité d'eau nécessaire pour ces cultures. Il ressort de ces analyses que le maraichage autour du barrage occupe une superficie de 177 ha.

Enfin, une série d'analyse de sensibilité avec le modèle d'allocation de l'eau (WEAP) sous les scenarios RCP_8.5 et RCP_4.5 a été effectuée. Les bias des données du RCM ont été corrigés avec la méthode des delta-change défendu notamment par Lettenmaier et Gan (1990). Les évaluations des besoins en eau pour les différents usagers montrent une tendance à la hausse, ce qui signifie que ces sites connaîtront de grands défis dans l'avenir car la demande non satisfaite des différents sites va augmenter en raison de la diminution de la disponibilité en l'eau.

Mots clés: ressources en eau, changement climatique, variabilité climatique, pression anthropique, bassin versant non jaugé, allocation de l'eau, scénarios, Massili.

Lists of Publications

Papers

1. **Kabore/Bontogho, P.E**.; Ibrahim, B.; Barry, B.; Helmschrot, J. (2015a): Intra-seasonal variability of climate change and peasant perception in central Burkina Faso. International Journal of Current Engineering and Technology (IJCET) 5 (3): 1955-1965.
2. **Kabore/Bontogho, P. E**.; Nikiema, M.; Ibrahim, B.; Helmschrot, J. (2015b): Merging historical data records with MPI-ESM-LR, CanESM2, AFR MPI and AFR 44 scenarios to assess long-term climate trends for the Massili Basin in central Burkina Faso. International Journal of Current Engineering and Technology (IJCET) 5 (3): 1846-1852

Posters for workshop

1. **Kabore/Bontogho, P.E**.; Ibrahim, B.; Barry, B.; Helmschrot, J : Intra-seasonal variability of climate and peasant perception of climate change in central Burkina Faso. *(American Geophysical Union Fall meeting 2014).*
2. **Kabore/Bontogho, P.E**.; Ibrahim, B.; Barry, B.; Helmschrot, J : Assessing Land Management Changes and Population Dynamics in Central Burkina Faso in Response to Climate Change. *(American Geophysical Union Fall meeting 2015).*

Contribution to newletters

1. Jorg Helmschrot; Heou Maleki Badjana, Emma Patricia Kabore/Bontogho: Land cover change and it implication for the sustainable management of West African water resources. *Newsletter of the Global Land Project . November 2015.*

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ACRONYMS AND ABBREVATIONS

AEN: Nakambe water agency/ Agence de l'eau du Nakambe

BMBF: German Ministry for Education and Research

CESCR: Committee on Economic, Social and Cultural Rights

CCMA: Canadian Centre for Climate Modeling and Analysis

CRU: Climate Research Unit

DGRE : Direction Générale des Ressources en Eau/ Agency of Water Resources

DGM: Direction Générale de la Météorologie/ agency of Metereology

FAO: Food and Agriculture Organization

GEO: Group on Earth Observation

GIS: Geographical Information System

GCM: Global Circulation Models

IIASA: International Institute for Applied Systems Analysis.

IGB: Institut Geographic du Burkina / Burkina Geographical Institute

IPCC: Intergovernmental Panel on climate change.

JGCRI: Joint Global Change Research Institute

NAPA: National Adaptation Programme of Action

MPI: Message passing interface

NCDC: National Climatic Data Center

ONEA: National water and Sanitation Company

PNUE/ UNEP: United Nations Environment Programme

UNCSD: United Nations, Commission on Sustainable Development

UNFCCC: United Nations Framework Convention on Climate Change

UNWWAP: United Nations, World Water Assessment Programme

USAID: United States Agency for International Development

RSME: Root Square Mean Error

SEI: Stockholm Environment Institute

SRP: Small Reservoirs Project

WEAP: Water Evaluation and Planning System

WMO: World Meteorological Organization

WUE: water use efficiency

WWF: World Wildlife Fund

1. CHAPTER 1: GENERAL INTRODUCTION

1.1. Introduction

Water as backbone of all socio-economic development sectors such as industry, agriculture, livestock and hydropower is fundamental to life. The Earth is called the blue planet due to the fact that it is covered by water: about 70 % of the earth surface is covered by water in oceans and only 3% of this percentage represents freshwater. According to GEO (2003), the useable fraction represents about 200 000 km^3, less than 1% of freshwater and only 0.01% of all water on the earth. Africa seems to have important water resources. Indeed, Africa has many big rivers such as the Congo, Nile, Zambezi, Niger, Limpopo, Orange, Senegal, and Lake Victoria. However according to WWF (2000), Africa is the second driest continent after Australia, and millions of Africans suffer from water scarcity throughout the year. By 2025, twelve countries would be limited to 1,000–1,700 m^3 /person/yr, and the population at risk of water stress could be up to 460 million people, mainly in western Africa (UNEP/GRID-Arendal, 2002). These estimates are based on population growth rates only and do not take into account the impact of climate change on water resources.

Climate has a great influence on hydrological cycle which characterizes the availability of water resources. Consequently, climate change will have considerable impacts on hydrological cycle, thus affecting those depending on water resources (Bates et al., 2008). The effects of climate and environmental change are likely to exacerbate water stress in Africa over the next five decades and this could generate conflicts over water, mainly in arid and semi-arid regions.

IPCC (2007) defines climate change as any change in climate over time, whether due to natural variability or as a result of human activity. Climate change refers to a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change might result from natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC, 2014). Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The globally averaged combined land and ocean surface temperature data as calculated by a linear trend, show a warming of 0.85 (0.65 to 1.06) °C, over the period 1880 to 2012, when multiple independently produced datasets exist. The total increase between the average of the 1850–1900 periods and the

2003–2012 periods is 0.78 °C(0.72°C to 0.85°C), based on the single longest dataset available (IPCC, 2013). This phenomenon affects the entire world and “Africa is the most vulnerable region to climate change, due to the extreme poverty of many Africans, frequent natural disasters such as droughts, floods, and agricultural systems heavily depend on rainfall” (IPCC, 2001). Fourteen countries in Africa are already experiencing water stress; another 11 countries are expected to face the same situation by 2025 at which time nearly 50 percent of Africa’s predicted population of 1.45 billion people will face water stress or water scarcity. Further studies (Magadza, 2000; Pachauri and Benedick, 2000; Kashyap, 2004) emphasized this aspect by stating that climate change may impose additional stress on water quantity and quality, especially in developing countries. Nearly all regions of the world are expected to witness a net negative impact of climate change on water resources and freshwater ecosystems (IPCC, 2007). From the late 1960s, the Sahelian region has experienced chronic below average annual rainfall although a return to wetter conditions has been observed in the last two decades in some areas of West-Africa (Lebel et al., 2003). Many studies show that the rainfall decline since 1970 across the Sahel has had a significant impact on runoff in the region in most cases by reducing flow (Bricquet et al., 1997; Mahé et al., 2000) and in a few cases by increasing flows (Pouyaud and Le Barbé, 1987) depending on the nature of the drainage network and the geology. Other studies have shown that the type of land use has a great impact on runoff generation (Fournier et al., 200 4).

One objective of the United Nations Millennium Development Goals (MDGs) is to significantly increase the access to safe water in many physical and economical water scarce countries but many countries still have water problems. Burkina Faso for instance is classified among the countries which will experience water stress by 2025 (UNEP, 1999). This has led to the early adaptation and implementation of the Integrated Water Resources Management (IWRM) policy since 2009. Indeed the implementation of Integrated Water Resources Management (WBGU, 2007) by the Global Water Partnership (GWP) aims at insuring sustainable water sharing in the countries and constitute by this fact an adaptation strategy to climate change. Despite these policies and Sahelian countries willingness to cope with water scarcity, water allocation still constitutes a great challenge for basins water agencies, mainly in ungauged basins where the lack of hydrological and climatic data impede to water resources knowledge. Therefore equitable and sustainable water sharing between users in ungauged basins proved to be challenging, moreover in the context of climate change.

WEAP, the Water Evaluation and Planning system, as one of many different IWRM models, is an exemplary application linking supply and demand site requirements. Allowing scenario analysis, changes in supply and demand structures can be simulated discovering potential shortages and the effects of different management strategies (Yates et al., 2005). Furthermore, models help revealing the question whether water shortages are caused by physical or economic constraints. Referring to the opening quotation where States as well as public and private actors are obliged to ensure water security for all people, IWRM and its models are a useful tool to improve water management practices and increase water security (WBGU, 2007). Enhancement of water supply in developing countries using integrated water management will help achieving the MDG target number '7.C' which demands to halve between the proportion of people without sustainable access to safe drinking water and basic sanitation by the horizon 2015.

This study is part of the general problematic of water management or allocation in a context of climate change and data deficiency (climatic and hydrological) which constitutes a huge impediment for decision in the framework of surface water resources management. Within a context of water scarcity and competition between multiple users, this study is a contribution to an integrated management of water resources in ungauged basins in general and in particular for the Loumbila reservoir basin in Burkina Faso. Water resources allocation in ungauged basins under climate change and human pressure occurs as part of multidimensional investigations that bring together wide unknown parameters. To reach this objective, it is necessary to develop a better understanding of how the past climatic and hydrologic system behaved. Then the estimation of unknown parameters to run WEAP model will be assessed (irrigation area, irrigation need and headflow). Thus the thesis will proceed as follows: the first part will present the main objectives of the research. In the second part, the characterization of the Loumbila basin is carried out. The third part will examine the dam water balance and the water allocation under climate change scenarios. Finally the water resource modeling will be carried out and the impacts of the different climatic scenarios will be assessed.

1.2. Background and motivation

Due to the over use of available water resources, it has become very important to define appropriate allocation of water resources for planning and management of Loumbila water resources. Scarce water resources and growing competition for water will reduce its availability for water supply and irrigation. At the same time, the need to meet the growing demand of vegetables to satisfy the population of Ouagadougou will require increased vegetables production from less water. Achieving greater efficiency of water use will be a primary challenge for the near future and will include the employment of techniques and practices that deliver a more accurate supply of water to crops. In this context, deficit irrigation can play an important role in increasing water use efficiency (WUE).

1.3. Problem statement

Water availability is a growing global concern (UN, 2012) and many rivers are affected by water scarcity and quality issues. As a Sahelian country, Burkina Faso since the rainfall decline in 1970 is experiencing water resources availability issues mainly due to climate change and anthropogenic actions. To cope with this problem, more than 1700 dams were built throughout the country (Boelee et al., 2009). A study realized by the Ministry of water and agriculture shows that the number of dams is around 1806 nowadays (MAH, 2012) and half of the dams were built between 1974 and 1987. This period coincides with the period of drought in the 1970s occurred in West Africa (Cecchi et al., 2009b). Unfortunately, most of the dams are undergoing problems such as siltation and pollution leading to a reduction of storage capacity and this is detrimental for the users.

The Loumbila dam situated within the Massili basin at around 16km from Ouagadougou (Burkina Faso capital) between the longitudes 12°31'9" N and Latitude 1°22'14" W, is facing the same problems. This dam was constructed in 1947 to serve the purpose of Ouagadougou water supply. Later on, many activities such as irrigation were developed and the dam has experienced growing water extractions from the anarchical water gardening and urban uses. Therefore despite the improvement of both rural population economies, the above activities are reducing the dam water availability. Thus, as mentioned by the Clean Stream Environmental Services (2005), activities within a catchment affect both the physical attributes as well as the chemical constituents of the water body and therefore also affect the biotic integrity of the community. The Loumbila dam is experiencing growing water extractions from agriculture and urban uses combined with emerging demands for environment protection which are increasing competition for scarce water resources. In addition, the Intergovernmental Panel on Climate Change (IPCC, 2014) has indicated that Climate-induced longer and more frequent droughts will continue to challenge existing water resources especially in southern and western Africa. Climate change is expected to result in severe water stress over much of the African continent (Millar, 2007). Burkina Faso is classified among the countries which will experience water stress by 2025 (UNEP, 1999). Thus, the dam is facing both climatic (change in rainfall and temperature variability) and human-induced pressure (increase water need for water supply and irrigation) which are jeopardizing the water availability. Consequently the water management still constitutes a great challenge for the Nakanbe water agency and the National agency for water and sanitation which are in charge of the dam management. This situation is emphasized with a lack of hydrological and climatic data as Loumbila dam is located in an ungauged basin. Sustainable water resources allocation is the main challenge in the Massili basin. Therefore the equitable and sustainable sharing of water resources between users in ungauged basins proved to be very challenging in the context of climate change. However, sustainable management is complicated by persistent droughts, extreme variation of the occurrence and distribution of water resources, high population growth, absolute poverty and desertification. Thus, knowledge on the future water availability and water needs prove to be necessary for a successful water management

The Water supply of Ouagadougou is insured by the Loumbila dam, the Ziga dam and three dams in the city of Ouagadougou. The Loumbila dam constructed in 1947 was the main source of Ouagadougou town until 2004 with the construction of the Ziga dam. In 2015, the Loumbila dam contributed to 30% of the capital water supply.

According to Burkina Faso's Ministry of Water and Environment (MECV, 2000), total water demand could increase from 110 million m^3 in 1975 to 1,200 million m^3 in 2025. Thus even if the Loumbila dam provided nowadays 1/3 of the water supply, it is not excluded that Loumbila dam water resources would be more solicited for water supply. Therefore the integrated management of this water body as advocated by the principles of IWRM is very important and very challenging. But, how to manage water resources when there is no information on certain parameters of the dam such as the inflow, the discharge and the water extracted for various activities?

1.4. Objectives of the study

The general objective of this thesis is to model water allocation for a Sahelian small reservoir in response to the challenge of managing ungauged basins under climate change and human pressure by applying climatic and hydrological models. To this end the following specific research objectives were planned to be pursued:

- To assess Massili basin climatic variability, peasant perception on climate change and their link to climate variability;
- To estimate Loumbila dam water balance;
- To model Loumbila dam water resource allocation under some climate change scenarios.

1.5. Hypothesis and questions

The main hypothesis is that the Loumbila dam reservoir will undergo climate and human pressure which will threaten the water availability. Some questions rise under these probable conditions:

1- What is the climate variability trend within the Massili basin over historical period? At which level farmers in the basin are aware of climate change?
2- How to estimate the dam water balance?
3- What will be the future impacts of climate change on water availability in the Loumbila dam?

1.6. General Methodology of the study

The originality of the study is highlighted by the evaluation of water allocation in a context of ungauged basins where water resources are under the pressure of climate change conditions and population growth. The approach is based on five activities:

- Literature review and data collection.
- Characterization of climate variability in the watershed
- Socio-economic survey taking into account farmer's perception.
- Hydrological models simulations under climate scenarios.
- Assessment of water availability by 2050 horizon.

1.7. Thesis structure

This thesis is organized in seven chapters spread within two parts. The first part is organized in four (04) chapters. Chapter one (01) focuses on the generalities and presents the objectives, problem statement and methods of the study. Chapter two (02) presents the literature review. The third chapter (03) describes the study area and present the data used for the study. The chapter four (04) assesses the climate variability and farmers' perception on climate change. A critical analysis of the trend in term of rainfall and temperature was done to best apprehend the impact of climate change on the study area. In chapter five (05), the water balance is estimated. This involves the calibration and validation of GR2M, Yates and CROPWAT models. The second part of the thesis gathers the last two chapters (6 and 7). The former concentrates on the estimation on water demands, unmet demands and discusses the future water availability under social and climate change scenarios by 2050. Chapter seven (07) gives some recommendations and perspectives to the study.

2. CHAPITER II: LITERATURE REVIEW

Researches on water resources have a long scientific history and have been investigated for many decades. But research is still ongoing and nowadays integrates water allocation, climate change and modeling. This chapter intends to review the relevant topics in term of water allocation under climate change. To achieve this, literature related to climate change and water allocation will be examined. Therefore a literature review on climate change and variability will be first presented. Then, review on water resources allocation will be carried out to give an idea about the ways of dealing with water allocation worldwide.

2.1. Climate change and climate variability

Climate variability refers to variations in the mean state of climate statistics (standard deviations, the occurrence of extremes, etc.) on all temporal and spatial scales beyond those of individual weather events. Variability may result from natural internal processes within the climate system (internal variability) or from variations in natural or anthropogenic external forces (external variability). Climate change refers to change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer (IPCC, 2014). This usage differs from that in the Article 1 of United Nations Framework Convention on Climate Change (UNFCCC), where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods. Climate variability refers to the climatic parameter of a region varying from its long-term mean. Every year in a specific time period, the climate of a location is different. Some years have below average rainfall, some have average or above average rainfall. Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC, 2014). The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. Climate change may affect the Sahelian region of Africa through severe variations in rainfall, water shortage and low agricultural yield. This should amplify drought risks and evaporation, and reduce agricultural productivity and a 10% drop in rainfall is expected by 2050 (IPCC, 1997). In addition, climate change will probably result in higher temperatures as a 1.4-1.6^{0}C rise is expected by 2050 (IPCC, 1997), potentially increasing the risk for forest fires or bushfires. The IPCC fourth assessment report states that global average surface temperature has increased by 0.74 ± 0.18^{0}C in the last century and is projected to increase by another 1.1–6.0^{0}C in this century (IPCC, 2007b). Long-term impacts on the regional economy are not well-known yet, but damages alone exceed US$ 130 million.

Burkina Faso is experiencing severe impact of climate change and is listed as one of the priority countries of the World Bank's Disaster Risk Management (DRM) team for 2009/11 DRM/CC (2009). The recent impact of climate change in Burkina is illustrated by the severe floods of September 2009 which affected more than 150,000 people in Ouagadougou. From the many studies carried out on climate variability in Burkina Faso (Diello, 2007; Ibrahim et al., 2012; Zampaligre´, 2013; Ibrahim et al., 2014), it could be highlighted that decreasing precipitation with rising temperatures, will cause more damage to agriculture in Burkina Faso. Studies on climate change in Burkina Faso show in general worrying trends from temperature and precipitation projections. Indeed, according to CEEPA (2006), farms in Burkina Faso will lose 72% of their net revenue as a result of increasing temperatures and 84% as a result of decreasing precipitations by 2050.

2. Water resources availability

West Africa is facing water availability challenges due to increasing population, climate change and its variability, poor water resources management and inappropriate land use practices. For instance, due to the close link between water resources and climate, a shift in global climate change has serious implications for water resources and regional development (Riebsame et al., 1994). According to Sharma et al. (1996), eight countries in West Africa were suffering from water stress or scarcity in 1990; this situation is getting worse as a consequence of rapid population growth, expanding urbanization, and increased economic development. In 2000, about 300 million Africans risk living in a water-scarce environment. Moreover, by 2025, the number of countries experiencing water stress will rise to 18 affecting 600 million people (World Bank, 1995), thus, many countries will shift from water surplus to water scarcity as a result of population changes alone between 1990 and 2025, using a per capita water-scarcity limit of 1,000 m3.yr-1 (UNEP, 1999). The World Water Forum which involved private institutions, regional organizations, non-governmental and public authorities in order to evaluate and monitor water resources management is a result of international awareness on water related challenges highlighted in Dublin statement (ICWE, 1992).

3. Water resources allocation

- **definition and concepts**

Importance of water resources to human being requires its sustainable allocation mostly in a context of climate change where water availability is under pressure. Water allocation refers to a set of possible mechanisms to distribute water resources/water rights among a varying number of possible users. Such a process of water allocation sets out how, by whom, and on what basis decisions are made over who will be entitled to abstract water (FAO 2003; FAO 2004 a), or "whereby an available water resource is distributed to legitimate claimants and the resulting water rights are granted, transferred, reviewed, and adapted. Hence, water allocation processes generate a series of water rights governing the use of water... " (WWF 2007). Within a country, water allocation may be implemented at small to large (local to basin) scale. Whatever the scale adopted for the allocation, the allocation mechanisms within any country can be regarded as a unique system for sharing the available water across the known sources of demand as highlighted by the World Bank (1997). Generally speaking, water rights, or water use rights, define the extent to which a water user has access to water resources or "the right to take and use water subject to the terms and conditions of the grant" (FAO 2003).

Sustainable water allocation should consider three key principles: equity, efficiency and sustainability (UNESCAP, 2000). Equity means that water resources within a river basin should be fairly shared by all of the stakeholders. Efficiency concerns the economic use of water resources with respect to minimizing costs and maximizing benefits. Under sustainability, water is utilized economically both now and in the future such that the environment is not harmed. However, it is not easy to fulfill all the three principles or goals for a water allocation problem at the basin scale. The sustainability involves the availability for future generations.

The main goal of sustainable water allocation is to ensure (based on rules and procedures) water resources sharing between various competing sectors of society by taking into account the availability, and the priorities of present and future water needs. Consequently, talking about the issue of water allocation involve knowledge on past, present and future water availability and demands.

- **Example of water resources allocation in Burkina Faso**

Article 14 of the 1991 constitution of Burkina Faso states that natural resources belong to the people and should be used for improving their living standards. Recognition of water as a public good is thus enshrined in the constitution itself. However, the water resources management was sector-based, meaning that each water demand sector mobilized the quantity of water needed without taking into consideration neither the other users, nor the long term impact of water withdrawal on ecosystem. This has led for instance to occurrence of conflicts mainly between farmers and breeders. The United Nations-led Johannesburg World Summit on Sustainable Development (WSSD) of 2002, for instance, declared that all countries should "develop integrated water resource management and water efficiency plans by 2005" (United Nations, 2002, Article 26). Based on the summit declaration, Burkina Faso has put in place several policies and institutional mechanisms to insure sustainable water resources management (MAHRH, 2003) such as the adoption of a national IWRM action plan (PAGIRE) and the establishment of basin agencies (Nakambe, Mouhoun, Comoe) and 30 local water management committees (Comités Locaux de l’Eau, or CLE). The stated purpose of the CLE is to take responsibility for managing water at sub-basin level.

3 CHAPITER III: PRESENTATION OF THE STUDY AREA AND THE DATASET

3.1. Presentation of the study area

3.1.1. Geographical description

The Massili basin, a sub-basin of the Nakanbe watershed is situated in central Burkina Faso, between the longitude: 1°15’-1°55’ West and the latitude 12°17’- 12°50’ North.. The basin covers an area of 2612 km^2 with a perimeter of 218 km. Figure 1 shows the outline of the catchment with the major river system, rain and discharge gauges.

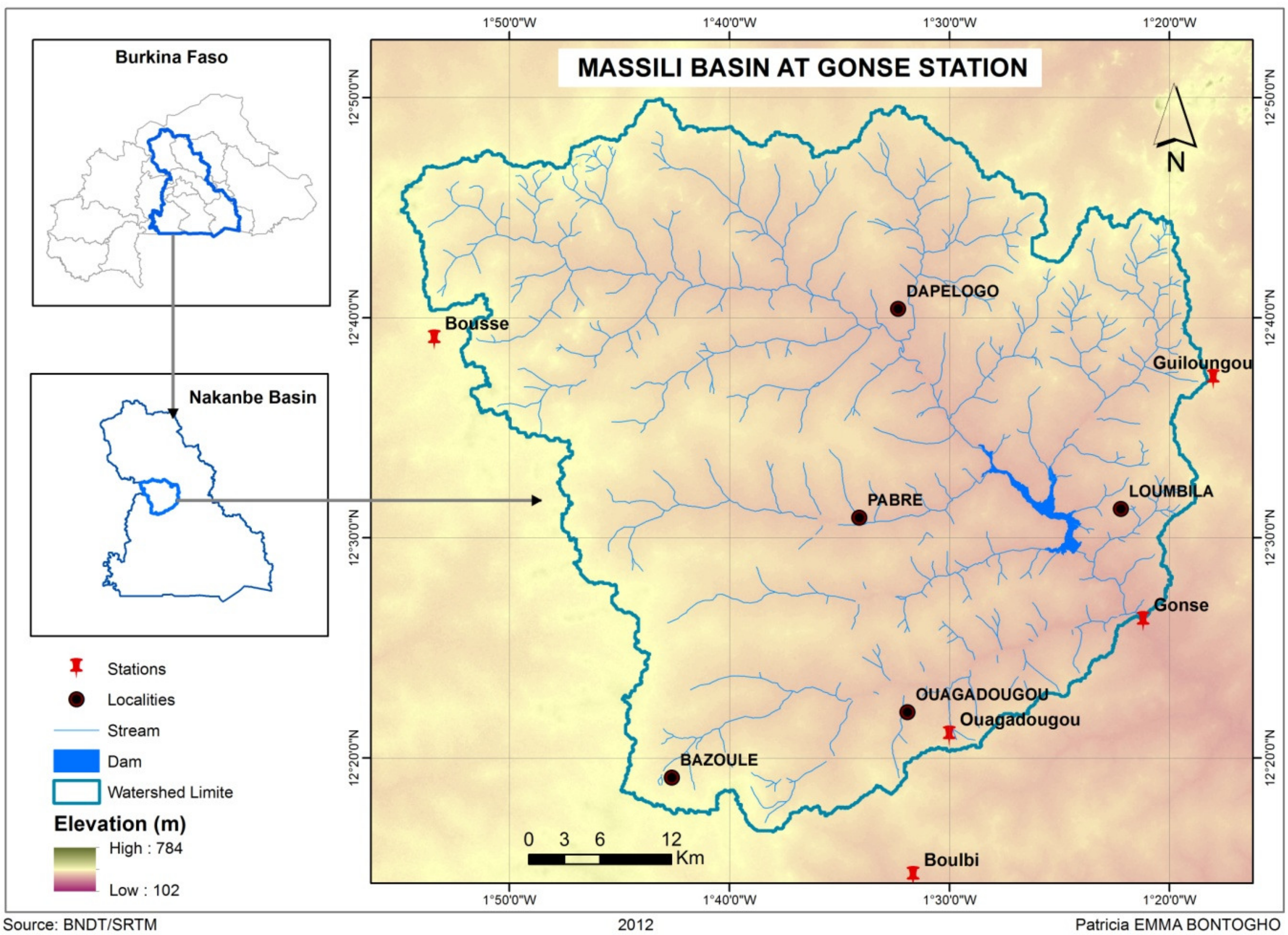


Figure 1: Location of the Massili basin at Gonse station

Administratively this watershed lies on three (03) provinces: Kadiogo, Oubritenga and Kourweogo. Owing to the fact that the limit of the watershed does not fit the administrative limits, only one hundred and eight (108) localities of the three provinces are included in the watershed (figure 2).

Source : BNDT 04/2013 Patricia Emma BONTOGHO

Figure 2: Localities of the Massili basin at Gonse station.

3.1.2. Description of the land use and the land cover in the basin

According to FAO (1997) **,** Land cover (LC) refers to all the natural and manmade features that cover the earth's surface, whereas land use (LU) refers to the human activity that is associated with a specific land unit, in terms of utilization, impacts or management practices. In 1999, FAO/UNEP defined Land use as the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it. Thus land use is defined as the human function of a given area while land cover is the physical surface of the land. Therefore, human activity has a strong impact on spatial land cover patterns due to the close link between land use and land cover (LULC). The mixing of the concepts of LCLU has been present for at least the last 25 years (Anderson, 1976) and has become so prevalent that classification of 'pure' LC is rare even when this is the stated objective (Di Gregorio and Jansen, 2000; Janssen, 2008) . Accurate and up-to-date information on land cover is required for applications, including land resource planning, studies of environmental change and biodiversity conservation. Knowledge on LULC trend is important as it is one of the most important factors that affect water balance components in a watershed and may be involved in hydrological processes. For instance, Mahé and Paturel (2009) demonstrated that the joint effect of climate change and human activities on land cover is responsible for an increase of the runoff coefficients in some of the West African Sahelian Rivers since the 1970s. Mahe et al. (2005) have revealed that in the Nakanbe basin, the runoff is increasing due to the decrease in vegetation.

In order to analyze the Massili basin LULC dynamics and spatial pattern over time, a set of three remote sensing satellite scenes were acquired for the years 1990 (Landsat5 TM), 2002 (Landsat 7 ETM+) and 2013 (Landsat8 OLI/TIRS) from the Global Land Cover Facility's (GLCF) website, http://glcf.umiacs.umd.edu/index.shtm (table 1). Landsat images were used because of its cost effectiveness and availability to the scientific community. All the datasets were geo-rectified into UTM projection and WGS 84 Zone 30 North. False color composite images were produced using several band combinations. For instance bands 2, 3, 4, were used to produce the false color composite RGB 4-3-2 with Landsat 7 (ETM+) and Landsat 5 (TM). However with Landsat 8 (OLI/TIRS), it is RGB 5-4-3 that were used to get the same false color composite needed. In addition, a field survey was conducted in 2014 to collect ground-truth information based on 08 plots in the study area in order to confirm the current changes. In the field, the land cover types were observed and recorded and a GPS was used to capture coordinates of each sample point. In addition to the LULC assessment, Land cover change was related to population dynamics trough Kendall correlation analysis applying SPSS software package. As the limit of the watershed does not respect the administrative limit, assessment of the watershed population is complex and is assumed to be the sum of each locality population from the census of 1985, 1996, 2006 and 2013.

Table1: Images source and description

Images	Spatial Resolution	Path/Row	acquisition Date	Number of scene	Source
Landsat5 TM +	30m*30m	195/051	21/10/1990	1	U.S.Geological Survey
Landsat7 ETM+	30m*30m	195/051	21/10/2002	1	U.S.Geological Survey
Landsat8 OLI->TIRS	30m*30m	195/051	27/10/2013	1	U.S.Geological Survey

3.1.2.1. Image classification

The satellite images were pre-processed and subset to the study area. Digital image classification involves the process of assigning pixels in an image to land cover classes. Maximum Likelihood Classification method (object-oriented classification method) was used to classify each of the three Landsat images using ENVI4.7 software. Base on the visual interpretation of the images and the field survey, six LULC classes were identified for the 1990, 2002 and 2013 images and mapped Vegetation is mainly covered by Gallery Forest, Tree and Shrub savannas and farm. Differences between classes are in general significant for 2002 and 2013 images. Then, the classified images were converted in vector format in ENVI 4.7 and exported into ArcGIS. Thereafter each land use type was delineated, its area and proportion to the total area was computed. Based on the developed land use maps, change analysis was carried out using post classification comparison in GIS. Finally, derived land use changes were compared with census data in order to explore links between population dynamics and the land use changes**.**

3.1.2.2. Assessment of the classification accuracy

Classification accuracy is mandatory and must be checked prior to the use of satellite images data for LULC assessment. The classified images were validated using ground data regions of interest developed during the classification stage. In addition, overall accuracy and Kappa coefficient method was applied within the framework of this study. The total accuracy is defined as the ratio of the number of correctly classified pixels in a class to the total number of correctly classified pixels in all classes and is expressed as:

$$\mathbf{OA= \frac{1}{\mathit{N}} \Sigma P_{ii}\ (01)}$$

OA= overall accuracy, N= the number of experimental pixels, ΣP_{ii}= the sum of principal diagonal elements of the error matrix. Kappa coefficient is also used because of some downsides of total accuracy. Kappa coefficient describes the similarity between what on land (land truth) and what on paper (Richards, 1999). Kappa coefficient is calculated from Equation:

$$\boldsymbol{Kappa = \frac{Po-Pc}{1-Pc}} \quad \mathbf{(02)}$$

With P_0 observed correctly, Pc expected agreement. Accuracy assessment carried out on these results revealed that an overall classification accuracy > 90% and a kappa coefficient of >0.9 were achieved for all classifications. Accuracy coefficient values are globally high for the basin. Indeed, for the Massili basin Kappa coefficient is around 0.94 for both Landsat7 and Landsat 8 in 2002 and 2013. Table 2 shows the details about the accuracy coefficient. Thus, Kappa results showed that the classification is reliable according to the method proposed by Janssen (2008).

Table 1: Images classification overall accuracy and Kappa coefficient values in2002 and in 2013.

Satellite sensor	Overall Accuracy (%)	Kappa
Landsat5 TM	95.6	0.94
Landsat7 ETM+ (Enhanced Thematic Mapper)	95.6	0.94
Landsat8 OLI-TIR	95.9	0.94

3.1.2.3. Assessment of Land use/land cover change in Massili Basin

The classified digital image (figure 3) highlights the clear shift in land use/land cover in the Massili basin. Indeed from the analysis of the 1990, 2002 and 2013 land use, it can be underscored that the vegetation is dominated by farm, tree, shrub savannas and gallery forest. The most extensive land use in the study site was the farm.

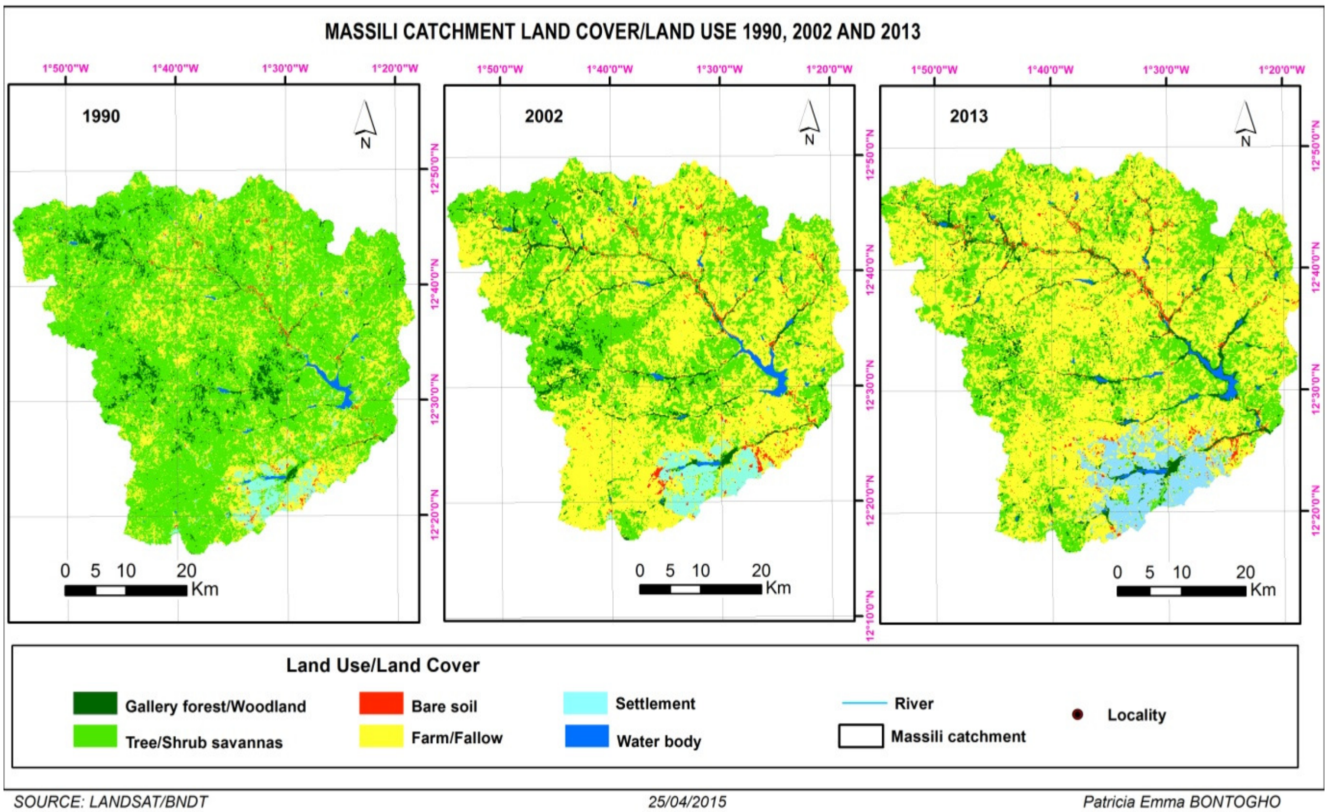


Figure 3: Massili basin Land use, Land cover 1990, 2002 and 2013

The quantification of LCLU change in the Massili basin is given in Table 2. Figure 3 shows the classification results obtained for the three dates (1990, 2002 and 2013) in the Massili watershed. In 1990, the Massili watershed landscape was dominated by tree/shrub savannah (69%, 1802.28 km^2), Farm/Fallow was representing 22%, Gallery forest (4%), Settlement (3%), Bare soil (1%), Water bodies (1%). In 2002, the major landscape was Farm (54%). Tree/Shrub savannas were reduced to 36% while the Gallery Forest was decreased to 1% of the basin area. In 2002 more than 5% of Shrub Savannah was converted into farm. The situation has also slightly changed in 2013 with an increase of the area devoted to farm/fallow and settlement at a rate of 3% and Gallery forest has increased to 4%.

The changes in land use are in agreement with a notable increase in population. The analysis of census data showed that the number of inhabitants increased from 338 inhabitants per km^2 in 1990 to 1150 inhabitants per km^2 in 2013. As shown by statistical analysis (Kendall correlation tau=0.9), there is a close relation between both dynamics. The figures 4 depicts the trend of LULC according to population growth. It could be underscore that the increase of population was accompanied by a great decrease of three/shrub savannah. In addition, Farm/Fallow was increasing in parallel to population growth. The settlement also is following the trend of the population growth.

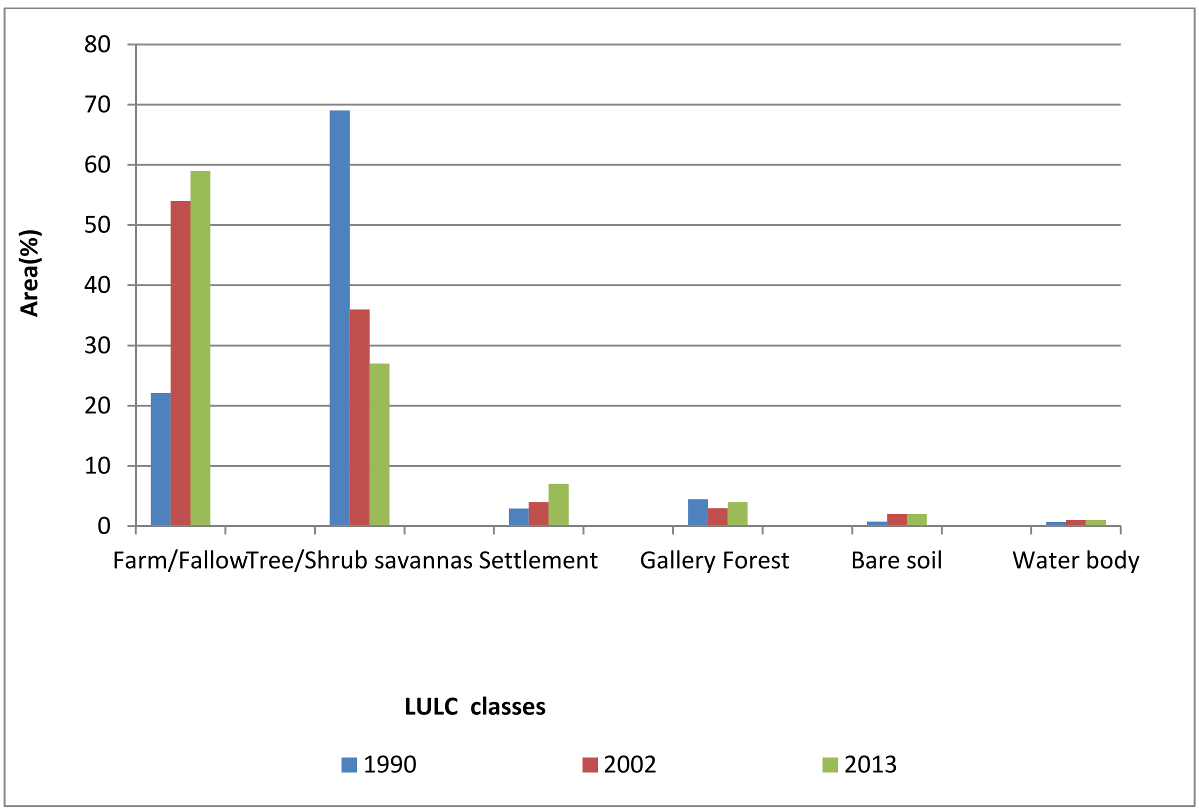


Figure 4: Evolution of Land covers types and their relative percentage in Massili basin

The analysis of census data showed that the number of inhabitants increased from 338 inhabitants per km^2 in 1990 to 1150 inhabitants per km^2 in 2013. As shown by statistical analysis (Kendall correlation tau=0.9), there is a close relation between both dynamics. Figures 5 depict the trend of LULC according to population growth. It could be underscore that the increase of population was accompanied by a great decrease of three/shrub savannah. In addition, Farm/Fallow was increasing in parallel to population growth. The settlement also is following the trend of the population growth.

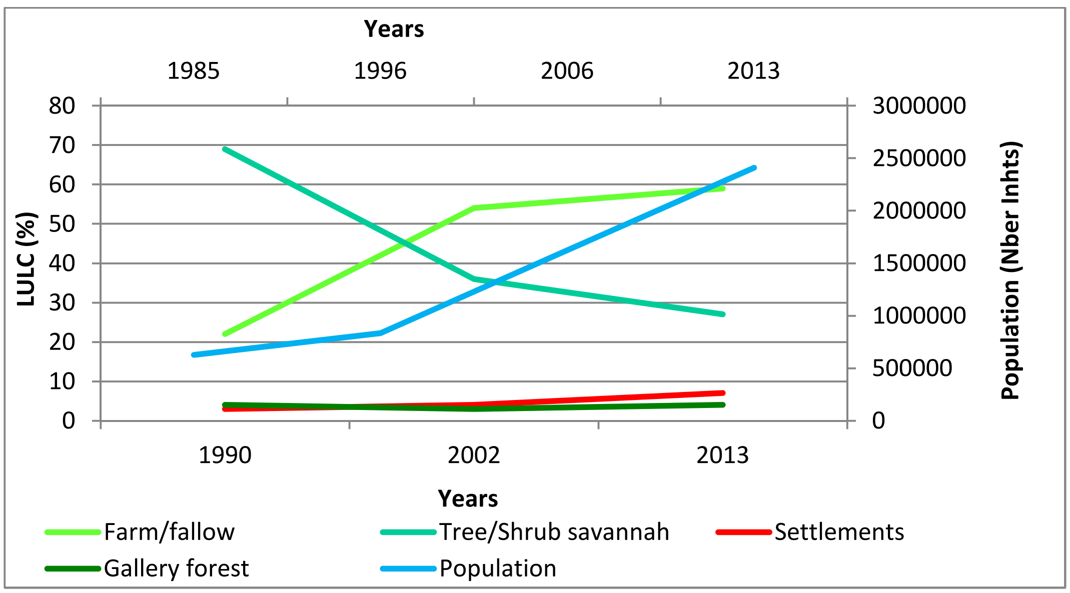


Figure 3: Trend of LULC according to the population.

3.1.3. Geology, soils classification and hypsometric curve

➢ Geology and soils classification

In general, there exist two geological components in Burkina Faso (SAWADOGO, 1994): a crystalline and Precambrian part and a sedimentary part of superior Precambrian age. About 80% of the country area is covered by the first group. The Massili basin is characterized by the crystalline and precambrian and the following groups could be found: the granite-migmatite nucleus (which covers a great area of the basin), the Volcano-sedimentary epimetamorphic and the plutonic rock. According to Dubreuil et al. (1972), the plains are more important than valley. The deteriorated formations could be explained by the presence of lateritic breastplate. Dubreuil et al. (1972) established a map indicating that the upstream basin of Ouagadougou is dominated by lateritic breastplate whilst the sub basin of Loumbila is characterized by: brut inorganic soils, granite, laundry tropical ferruginous soils very gravelly on eroded materials, clay laundry tropical ferruginous soils, the inorganic hydromorphic soils.

The Massili watershed is characterized by breastplate mounds and some emergent granite rock formations, which mark their crests. The basin is flat (slope ≤ 2 ‰) and the main type of soil is eutric regosol (52%). The eutric gleysol is the second big sequence of soil covering around 36% of the basin. The vertigos are less representative in term of percentage (0.3 to 0.8%). Table 3 shows the major types of soil in the watershed according to FAO classification.

Table 2: Soil types and their relative percentage in Massili watershed

Soil classes	**Vertic cambisol**	**Ferric lixisol**	**Eutric gleysol**	**Lithic leptosol**	**Eutric regosol**	**Vertisol mazieutric**
Percentage (%)	0.3	3.3	36.1	6.9	52.6	0.8

The image classification is the process of assigning individual pixels or groups of pixels to thematic classes (Richards, 1999). The soils map of the study area resulting from FAO image classification approach is presented in Figure 6.

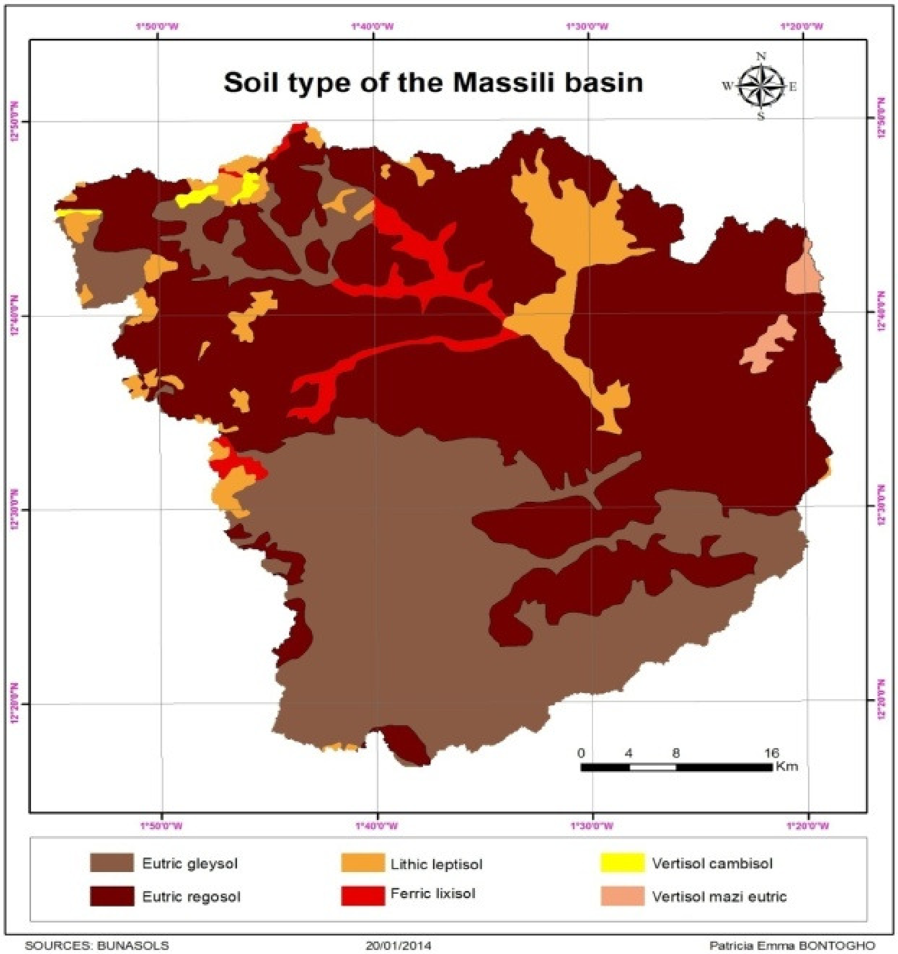


Figure 4: Soils type of Massili basin at Gonse station

- **Hypsometric properties of Massili basin**

Hypsometric analysis (area-altitude analysis) is the study of the distribution of horizontal cross-sectional area of a landmass with respect to elevation (Strahler, 1952). Hypsometric curve is also an essential tool to measure and represent the form of a watershed and its evolution owing to the close link between watershed morphology and hydrological curves. Indeed, Watershed hypsometric curve gives a general synthetic view of the watershed relief. Hypsometric curve represents the repartition in term of percentage of the watershed surface (which is above the corresponding altitudes) versus the altitude. Thus, a hypsometric curve is essentially a graph that shows proportion of land that exists at various elevations, by plotting relative area against relative height. The hypsometric curve plays a key role in watershed characterization in the sense that it constitutes a tool for the comparison of watersheds or of different sections of a watershed. Moreover, the average amount of precipitation over the watershed can be estimated by using hypsometric curve. Finally, hydrographic network, hydrologic and hydraulic behavior can be determined through the analysis of the hypsometric curve. Indeed, hypsometric curve determine the type and rate of processes that shape a given natural drainage basin. Hypsometric analysis describes the distribution of horizontal cross-sectional area of river morphology with respect to elevation (area-altitude analysis). The Morphology of a river basin plays a primary role in the dynamics of surface and subsurface water runoff generation. The percentage hypsometric curve (area-altitude curve) relates horizontal cross-sectional area of a drainage basin to relative elevation above basin mouth. Thus the estimation of the watershed hypsometric curve gives detailed on the morphology of the watershed.

This section aims at drawing the hypsometric curve of the Massili basin. In order to generate the hypsometric curve of the basin areas DEM are imported in ARCGIS 10 environment. This was realized by deriving hypsometric data from the 30 meter ASTER DEM. SRTM DEMs were downloaded via internet to extract Massili basin river SRTM DEM and altitude. These curves have been used to infer the stage of development of the drainage network and to differentiate between tectonically active and inactive areas (Keller and Pinter, 1996).

Figure 7 shows the results of hypsometric curve for the Massili river basin. In the graph, ordinate values represent altitude, expressed as elevation above sea level, and abscises values represent cumulative frequency or areas under given contour intervals around watersheds or summit points. Being a summation of area intervals per altitude, the region under a hypsometric curve therefore represents the amount of rock between a river outlet and the erosion surface. Strahler (1952) refers to it as the hypsometric integral. The shape of a hypsometric curve changes from concave-convex to concave as the basin reaches the equilibrium (mature) stage. The figure shows a concave hypsometric curve characterizing the Massili basin as old or at an erosional stage. Approximately more than 50% of area lay at elevations above 310m. The basin river hypsometric curve indicates flat watershed expressing medium hydrological processes.

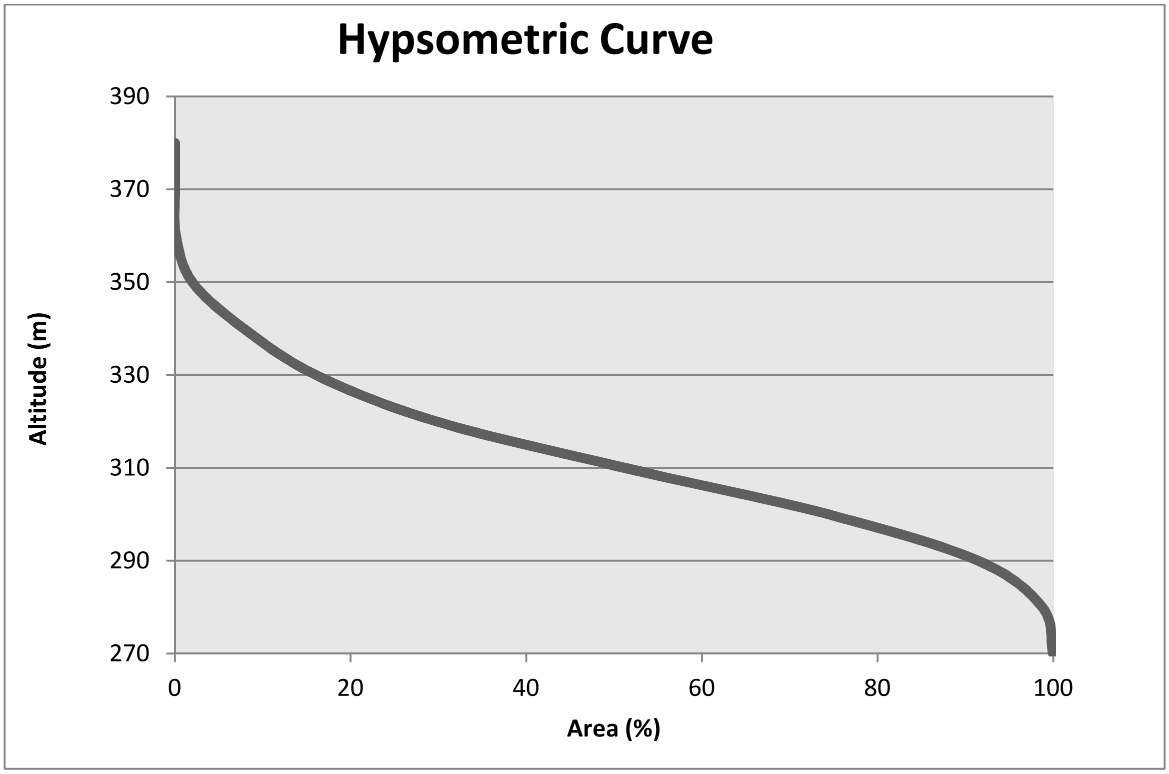


Figure 5: Hypsometric curve as obtained for Massili River.

3.1.4. Hydro-climatic context

3.1.4.1. Hydrology of Massili basin limited at Gonse station

The hydrology of the Massili basin at Gonse can be located within two referential watersheds. At the national scale, this basin is a sub-basin of Nakanbe basin and at the international scale hydrology, it is worst noting that Massili basin is part of the trans-boundary Volta basin**.** The Massili basin limited at Gonse station is located between the longitude 1°15'-1°55'W and the latitude 12°17'-12°50'N. This watershed covers an area of 2612 km^2 and is composed by many little basins. The most important sub basins are: Donse basin (175km^2), Pabre basin (210km^2), Kamboince basin (125 km^2), Ouagadougou basin (350 km^2) and Loumbila basin (2120 km^2). The altitude of the area varies between 250 and 350 m**.** This basin involves many irrigation perimeters. The basin derived its name from the Massili River, one of the Nakanbe river (White

Volta) right banks. This tributary originates at 12 km from the North of Bousse (a village at 50 km from Ouagadougou). Before Loumbila, the Massili flows at 20 km at the East of Ouagadougou and it is joined by many temporary tributaries with Koulohoko and Bandatengakoui as the most important. The Massili and its tributaries drain the water of tree department of Oubritenga province: Ziniare, Bousse and Ouagadougou. Thus, this temporary river flows across the capital of Burkina Faso draining various type of pollution (agricultural, industrial and domestic) coming from the anthropogenic activities of the town. The Massili is characterized by a rainfall-evaporation regime with high runoff in summer and low runoff in winter.

- **The water bodies within the basin.**

The main water bodies within the basin are the Loumbila dam (42 million m^3) which provides Ouagadougou water supply, the Donse dam, the Kamboince dam, the Pabre dam and the series of three dams in the city of Ouagadougou: the dam n°1, n°2, n°3. The particularity of the Massili basin is that this basin is site to the first dam of Burkina Faso which is the dam of Pabre located at about 15 km from the capital and created by the white Missionary. The series dams were created in 1963 for the capital water supply. From 1955 to 1971, the series dams were the main source of water supply of Ouagadougou. Nowadays those dams have a storage volume of 6.87 Mm^3 (MAHRH, 2002).

The Loumbila dam (12°29 N, 01°24 W) was constructed in 1947 on the Massili River (Nakambe tributary) and has a volume of 42, 2Mm^3 (Dembele, 2006). It is located at around 20 km from the capital at the Northern East of the capital (Figure 1). The dam was completed in 1947 across the Massili River to serve the purpose of Ouagadougou water supply but there has been water withdrawal from the system for other purposes such as public work and irrigation. The volume of the reservoir was originally 30 Mm^3 at a level of 278.48 m with a surface area of 16.30 km^2 extending over a length of 11 Km. Nowadays the dam has a volume of 42Mm^3 and is used for multiple purposes: water supply, irrigation and public work. The following table summarizes the main features of the Loumbila dam.

Table 4: Characteristics of Loumbila dam features

Loumbila dam features		
Important dates	1947	Creation
	1956	First rebuilding
	1970	Second rebuilding
	1992	Record of the maximum peak discharge (800 m^3/s).
	2004	Increase of the dam storage at 42 Mm^3
	2010	Third rehabilitation of the dam
Reservoir	Basin of the dam	2120 km^2
	storage volume	42 Mm^3
	Surface area	1500 ha
	Depth	6.5 m
	Initial water level	276.00 m
	Bottom level	272.79 m
	Top of dead storage	274.00 m
	Dam crest level	280.00 m
	Flood contole zone	278.50 m
	Spillway bottom level time series (optional)q	278.93 m
	Bottom outlet capacity time series (optional)	50.00 m

The figure 8 shows a picture of Loumbila dam.

Figure 6: Loumbila dam

- **Water use and management**

The primary purpose of the Loumbila Dam was to provide safe water to the capital. Thus the main consumptive water use of Loumbila dam is Ouagadougou water supply followed by informal irrigation and municipality's purposes. The total water withdrawal from the dam can not be estimated due to the irrigation potential. Indeed due to the anarchical development of the market gardening around the dam, the monitoring has been failed leading to a lack of data on the irrigation water withdrawal ; a attempt to estimate the irrigation potential will be presented

Within the framework of this study. No specific studies have been conducted to establish the percentage of the land affected by market gardening around the dam.

The major irrigated crop is tomato in 2012. Other frequently produced crops include cabbage, okra, peppers, aubergine, cucumber and onion. Water use efficiency at conveyance and field levels is low since no concerted efforts have been made to address the problem of water losses.
The National Water and Sanitation Agency (ONEA) is the main institution in charge of Loumbila dam control. However, this agency exercises management functions over the water body and the quality of water retrieved for water supply only. Thus since the market gardening activity is informal, its management is dialed by the farmers and once can imagine the weak level of water use efficiency and high level of water pollution since no concerted efforts have been made to address the problem of water losses , pesticides and fertilizers uses. Nonetheless, the positive impact of this activity includes improved access to cereals (rice) and vegetables, hence better nutrition to some national and boundary extend. Indeed, some vegetables from Loumbila market gardening are exported toward boundary countries such as Ghana and Togo. Therefore, the incomes from this activity help many rural families. Nonetheless, this informal irrigation contributes to the pollution of the water resources as confirmed by a study realized by Cecchi et al. (2004) showing high water turbidity and the presence of sediments which may constitute a based for proliferation of cyanobacteria.

3.1.4.2. Climate conditions

Burkina Faso has three climatic zones: the Sahelian zone in the north receiving less than 600mm average annual rainfall; the north-sudanian zone in the center receiving an average annual rainfall between 600 and 900mm; and the south-sudanian zone in the south with an average annual rainfall in excess of 900mm. The Massili basin is characterized by an annual rainfall varying according to the season with a long dry season period and a short rainy season.

Analysis of figure 9 shows annual mean temperature varying between 27° C and 30° C.

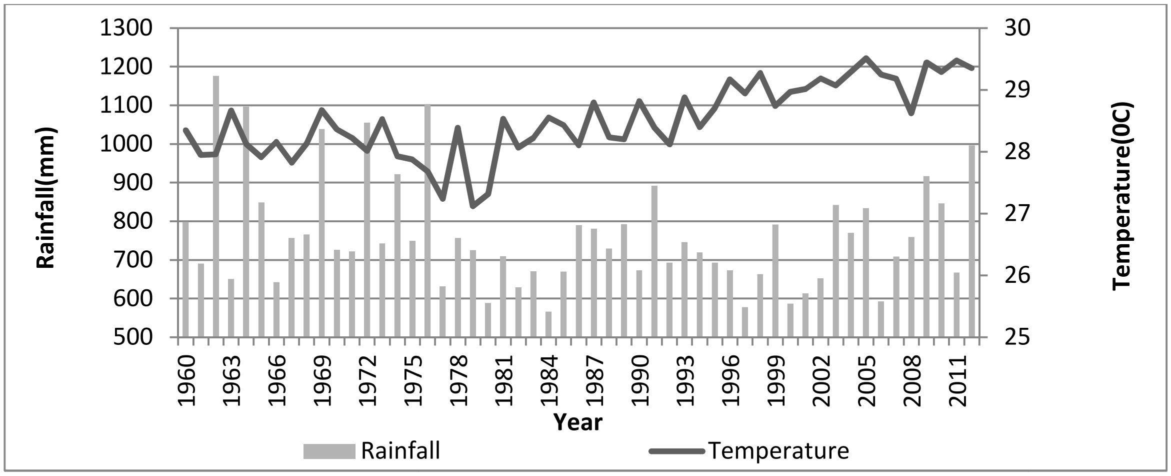


Figure 7: Annual rainfall and temperature from 1960 to 2011 in Massili basin

The Standardized Precipitation Index (SPI) is a tool developed for defining and monitoring drought based on the cumulative probability of a given rainfall event occurring at a station. High SPI value (closer to 3) is interpreted as heavy precipitation event over time period specified, medium SPI value (approximately = 0) characterized normal precipitation event over time period specified and low SPI value (closer to -3) shows low precipitation event over time period specified. Figure 10 relates the SPI trends in Massili basin.

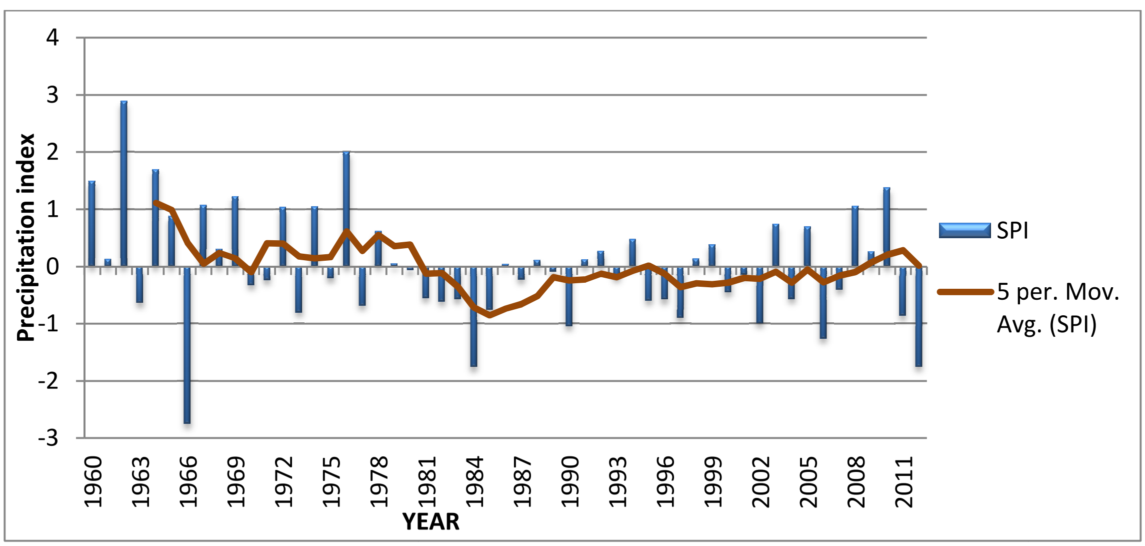


Figure 8: Standardized precipitation index from 1960 to 2011 in the Massili basin at Gonse station

3.2 Presentation of the dataset

This section presents the data collected in the framework of this study. This thesis is mainly based on observed and simulated source of data. Importance of data in research required their secure, flexible storage and management. Despite the importance of data storage for research, few data storage models have been implemented in Africa. An information system called Massili River Basin Information System (MRBIS) was developed in partnership with the Department of Geoinformatics at the Friedrich Schiller University of Jena (Germany) to facilitate the data use. Massili River basin information system (MRBIS) is a web-based data management and analysis platform with limited access to all data used in the framework of this study. The MRBIS contains data for Massili basin at daily time step (rainfall, temperature and discharge). The MRBIS is implemented using a standard Linux web stack with Apache web server, PHP programming language, PostgreSQL database management system (http://www.postgresql.org) and PostGIS extension (http://www.postgis.org) for spatial data support. In case of no or slow internet connectivity, and for an easy distribution, MBIS may also be operated in a virtual server environment using the Virtual Box (http://www.virtualbox.org) software package. The whole system is built based on open source software, ensuring a cost-efficient deployment and operation. To generate different forms to view, search, edit and interlink datasets, XML-files are used as description layers (Kralisch and Krause, 2006). Online access to the MRBIS is possible but requires permission agreement (password require to the author).

- **MRBIS layout**

MRBIS contains four mains modules:

•**MBISts** for the management, analysis, statistical processing, gap filling and visualization of measured and simulated time series data.

• **MBISmap** for the description and visualization of vector or raster data and for linking all types of stored geometry objects (points, polygons, and layer) to metadata stored in MBIS.

• **MBISdoc** to store documents and their metadata (project related PDF documents) or to associate documents to other dataset in MBIS (images associated to a measurement station).

• **MBISsim** to store information related to the management of simulation runs on environmental models (parameter sets) as well as indicator calculation and scenario management

➢ **Time series and geo data management and processing**

Time series are imported under the rubric of new time series data module. After control of the data format, the data gaps are detected. The main functions for gaps filling involve the inverse distance weighting with elevation correction, linear regression, nearest neighbor or linear interpolation. After gaps filling, the imported time series are visualized and analyzed in terms of location, parameter type, unit, elevation, and distance to neighboring stations or calculate their correlation with other time series data considering the same parameter and unit. The stored time series data can be exported for further used in models. In addition, maps can be imported under the format of shapefile, Tiff and raster. Map plotting allows visualizing the watershed and stations. Figure 11 shows the data stored in the MRBIS.

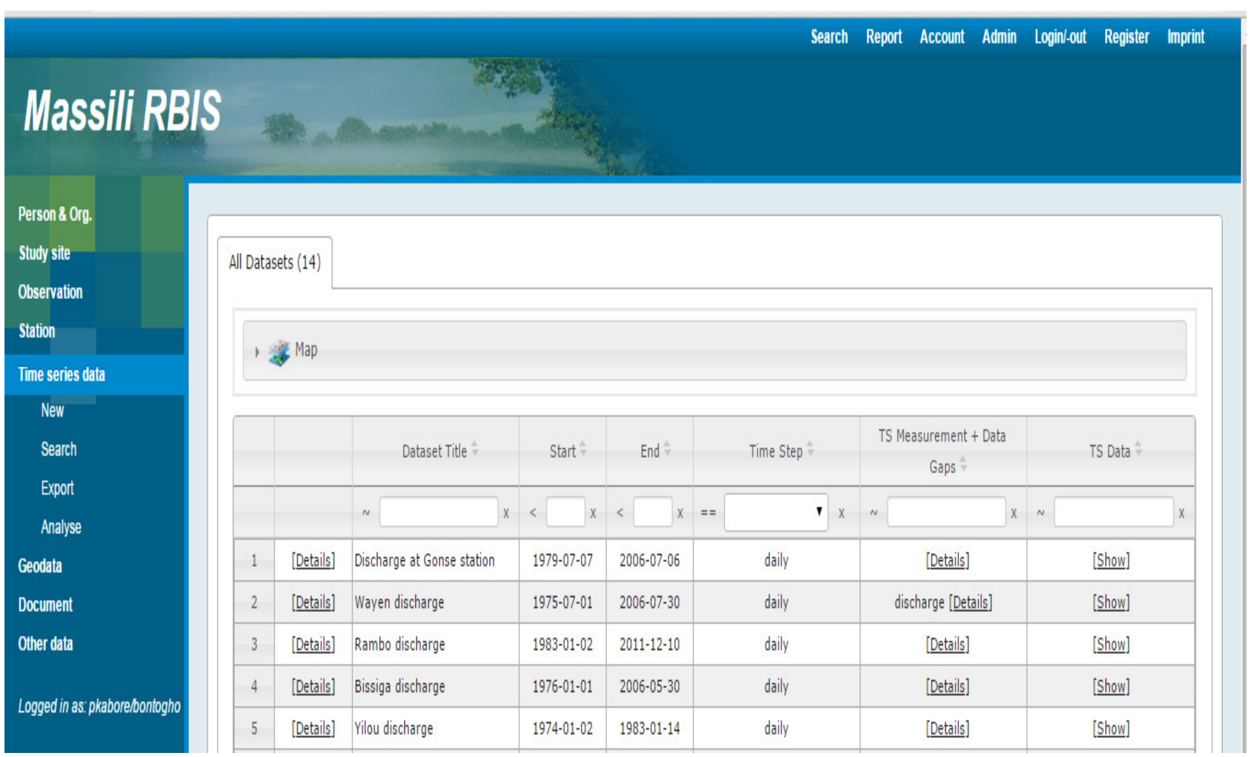


Figure 11: Massili basin climatic and hydrological dataset stored in MRBIS.

3.2.1 Type and source of data

3.2.1.1 Climatic data

Hydrological processes are influenced by climatic patterns. Indeed, the hydrological regime of Rivers is influenced by precipitation and exchange with groundwater (Anonyme et al., 2005). Thus the importance of climatic data for hydrological studies is crucial. This can be illustrated by a decrease in rainfall which will consequently lead to a decrease in river discharge and water availability. However the Massili basin has only one synoptic station located at Ouagadougou. Even though this station is representative of the basin, the presence of other data is required. To achieve this, data were retrieved from the Climate research unit (CRU). The Climatic Research Unit (CRU) was established in the School of Environmental Sciences (ENV) at the University of East Anglia (UEA) in Norwich in 1972. It is widely recognized as one of the world's leading institutions concerned with the study of natural and anthropogenic climate change. CRU aims at improving scientific understanding in past climate history and its impact on humanity, the course and causes of climate change during the present century and prospects for the future. The datasets are managed by a variety of people and projects. In addition, temperature and rainfall data for Boulbi, Bousse and Guiloungou were used. Thus two types of meteorological data were retrieved: one from the national agency of meteorology and one from CRU database

- **Meteorological and hydrological data**

The climate data sets used for this study covers a period of 51 years (1961 to 2012). Data of minimum, maximum and mean temperature, evaporation, sunshine, humidity, wind speed at daily time step from Ouagadougou and daily rainfall data from Ouagadougou, Bousse, Boulbi and Guiloungou were collected from the Direction General of National Metereology agency. Daily runoff data of Gonse station were obtained from the National Hydrological Service (DGRE) of Burkina-Faso.

Table 5: Available observed time series of rainfall, temperature and discharge.

Stations	Latitude	Longitude	Altitude (m)	Sources	Period	Variable
Ouagadougou	12°21N	01°31W	303	DGM	1961-2012	rainfall temperature
Boulbi	12°14N	01°32 W	315	DGM	1961-2012	rainfall temperature
Bousse	12°40N	01°53 W	345	DGM	1961-2012	rainfall temperature
Guiloungou	12°37N	01°18W	310	DGM	1961-2012	rainfall temperature
Wayen	12°23' N	01°05' W	252	DGRE	1975-2005	Discharge
Yilou	13°0'59 N	-1° 33' W	-----	DGRE	1973-1982	Discharge
Gonse	12°29' N	01°24' W	-----	DGRE	1975-2006	Discharge
Rambo	13°36' N	02°04' W	-----	DGRE	1983-2006	Discharge
Bissiga	12°46' N	01°09' W	-----	DGRE	1976-2006	Discharge

- **Climatic Research Unit data**

The Climatic Research Unit (CRU) provides monthly time series data set of precipitation, daily maximum and minimum temperatures, cloud cover, and other variables covering Earth's land areas for 1901 to 2012. The data set is gridded to 0.5°x0.5° degree resolution, based on analysis of over 4000 individual weather stations records (CRU, 2014). The grids were built by interpolation according to the latitude and longitude. The data used for the realization of CRU database is provided by the National agency of meteorology, the National Climatic Data Center (NCDC) and from the World Metereological Organization (WMO) and other published sources

(New et al., 1999, 2000; New et al., 2006). These datasets were processed and the datasets which were not concordant were canceled. Grids of rainfall, temperature and evapotranspiration from the period 1903-2006 were retrieved.

Rainfall and Evapotranspiration (ETP) Data at monthly time step have been collected from the Climate Research Unit (CRU). Data from CRU are under the shape of grid at monthly time step and at half degree square (0.5°x0.5°) on all West Africa. The grids have been built by interpolation according to the longitude and latitude (Spline function). Data which have been used for the production of these grids come from national's meteorological agencies, the National Climatic Data Center (NCDC), the World Metereological Organization (WMO) and others sources published (New et al., 1999, 2000). Those data have been submitted to a quality control and the stations which were not responding have been suppressed or replaced by the series average. The CRU Grid used in this study covered the period 1901 to 2009.

The rainfall grids have been built by interpolation from a hundred of rainfall post covering Mali, Burkina Faso and Côte d'Ivoire. Due to the lack of adequate data, CRU data have been used in order to do this study.

- **Regional Climate models data**

Regional Climate models (RCMs) are important tools used to provide climate data from General Circulation Model (GCM) data. The principle is based on a transfer of coarse resolution (GCM) to a higher resolution data in order to produce more detailed information (Grotch and MacCracken, 1991; Salathé, 2003; Fowler et al., 2007) for hydrological impact studies. Indeed, RCM output is used as input for regional and local climate impact models. Among the international research implemented to provide RCM data, ENSEMBLES, NARCCAP and CORDEX were used worldwide (Giorgi et al., 2009; Mearns et al., 2009; Van der Linden and Mitchell, 2009).

IPCC has implemented climate change scenarios which constitute a base for future climate change assessment. The first categories of Special Report on Emission Scenarios (SRESS) were developed in 2000 and differ from the scenarios developed in 2011 (RCPs) which are based on the estimation of Green House Gas emissions. Four family types of Representative Concentration Pathways (RCPs) were developed and each one defines a specific emissions trajectory and subsequent radioactive forcing: RCP_8.5, RCP_6, RCP_4.5, and RCP_2.6. The first Representative Concentration Pathway RCP8.5 is a scenario of a rising radiative forcing pathway leading to 8.5 W/m^2 in 2100 (Rao and Riahi, 2006; Riahi et al., 2007). The second scenario (RCP_6) is defined by the stabilization without overshoot pathway to 6 W/m^2 at stabilization after 2100 (Fujino et al., 2006; HIJIOKA et al., 2008). RCP_4.5 is related to stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100 (Smith and Wigley, 2006; Clarke et al., 2007; Wise et al., 2009). RCP2.6 is defined as a peak in radiative forcing at ~ 3 W/m2 before 2100 and decline (Van Vuuren et al., 2006; Van Vuuren et al., 2007). In order to assess the impact of climate change on water resources, two RCPs data were retrieved from AFRI-MPI-HIRHAM5 (developed at CORDEX) and AFRI-44-HIRHAM5 (developed at CORDEX) regional climate model.

The RCPs scenarios data were retrieved from the CORDEX database CORDEX-Africa Matrix RCP_4.5 and RCP_8.5, for 2001-2050, with about 50km resolution. Projections for the 2000-2050 period in minimum, maximum, mean temperature and precipitation at monthly time step for Ouagadougou station are used: RCP_4.5 runs from the Canadian Centre for Climate Modeling and Analysis, the third generation of coupled global climate model (CGCM3.1 Model, T47) and RCP_8.5 runs from the Meteo-France, Centre National de Recherches Meteorologiques, the third version of the ocean-atmosphere model (CM3 Model).

3.2.1.2 Hydrological data

- **Discharge data**

The discharge data were collected from the National Hydrological Service (DGRE). The daily time series data of six watersheds (Wayen, Gonse, Yilou, Bissiga, and Rambo) were collected. The choice of those basins was first led by the fact that most of them have known an increase of runoff coefficient during the climatic break which occurred during the years 1970 and secondly by their proximity to Loumbila watershed

- **Water Holding Capacity data (WHC)**

The Soil water holding capacity (WHC) is an important parameter for the simulation of discharges. Indeed, it represents the capacity of the soil reservoir in this model. FAO soil WHC at each grid scale (0.5°x0.5°) is available as digital soil map (FAO-UNESCO, 1974-1981) which is constituted with more than 4930 soil unities. FAO (1981) defined seven (07) classes of soils which Water Holding Capacities are determined according to the soil depth, texture, influence of parent material, seasonal flood conditions, top soil texture and other minor correcting factors. The set of soil WHC computed by Ouédraogo (2001) for the Nakanbe basin has been used to derived the WHC of the Massili, Rambo, Bissiga, Loumbila, Yilou and Wayen basin.

Table 6: Water holding capacity of Massili basin (FAO)

XG	YG	SMINPM (mm)	SMOYPM (mm)	SMAXPM (mm)	SAXTONPM (mm)
-1,75	12,75	51.32	70.59	89.77	67.92
-1,25	12,75	93.84	114.89	136.58	83.73
-1,75	12,25	69.04	88.32	107.47	69.57
-1,25	12,25	77.93	97.47	117.55	79.47

Figure 12 illustrated the spatial distribution of WHC for Massili basin.

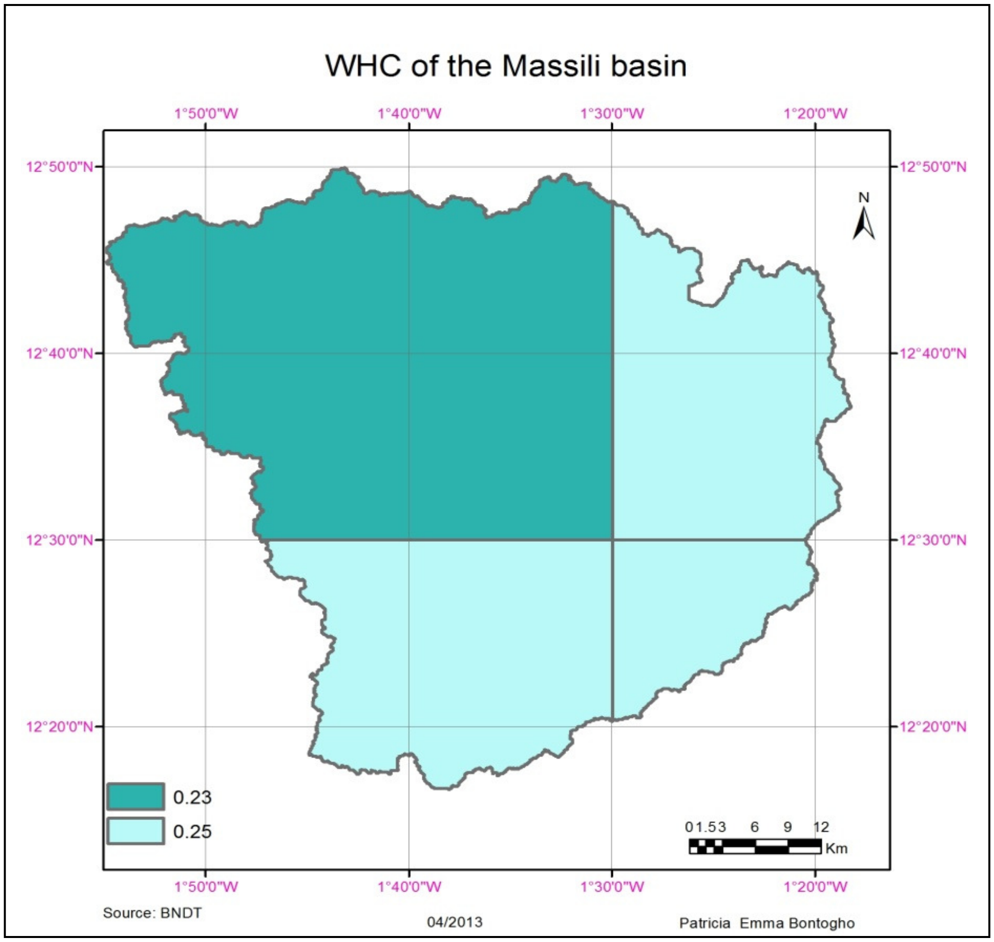


Figure 12: Water holding Capacity of Massili basin (FAO)

3.2.1.3 Geographical data

- **Shapefile**

Geographical shape file were obtained from the National Agency of geography (IGB). All the parameters listed below are used to describe the study area.

Table 7: Geographical data

Shapefile	Source
Soil	National Agency of Geography
Vegetation	National Agency of Geography
Geology	National Agency of Geography
Hydrology	National Agency of Geography
Land use	National Agency of Geography

3.2.2 Data processing

3.2.2.1 Hydro-climatic data processing

The purpose of trend analysis is to determine whether the values of a series of observed random variables increase or decrease over time by describing the amount or rate of that change. Many trend tests can be found in the literature such as Pettitt Test and Mann-Kendall which will be used for the purpose of this study. The Pettitt test is widely employed for detecting changes in hydro-meteorological time series data (Moraes et al., 1998; Ma et al., 2008; Zhang and Lu, 2009). Non-parametric Mann-Kendall test is used to detect monotonic changes in both hydrologic and climatic data of the study area. This method has been widely used to assess the significance of trends in hydro-meteorological time-series data (Moraes et al., 1998; Xiong and Guo, 2004; Kundzewicz et al., 2005; Xu et al., 2005; Bae et al., 2008; Ma et al., 2008; Ma et al., 2009; Qi et al., 2009). The Mann-Kendall statistical test has been shown to be more robust than parametric tests when dealing with skewed data and outliers in a data series (Önöz and Bayazit, 2003).

- **Description of the model**

RAINBOW is a tool for hydro-meteorological time series analysis. The data analysis can be performed under two methods (frequency analysis or homogeneity test) by selecting a Normal, Log-Normal, Weibul, Gamma, Gumbel, Exponential or Pareto distribution. The data analysis accuracy can be checked through graphical methods (Probability plot and a Histogram of the data superimposed by the selected probability function). In addition two statistical tests Chi-square and the Kolmogorov-Smirnov test) can be allied to investigate the data distribution. RAINBOW allows also to analyze time-series with zero or near zero events (the so called nil values) by separating temporarily the nil values from the non-nil values. By calculating the global probability, the nil and no-nil rainfall are combined again. When the probability distribution can be accepted, the user can view the calculated events that can be expected for selected probabilities or return periods.

- **Frequency analysis**

The Purpose of frequency analysis is to estimate the probability distribution in order to have idea about the rainfall depths from a given period. In a frequency analysis, (Snedecor and Cochran 1980; WMO, 1981, 1983 and 1990; Haan, 2002) estimates of the probability of occurrence of future rainfall events are based on the analysis of historical rainfall records. Frequency analysis of data requires homogeneous and independent data. The restriction of homogeneity assures that the observations are from the same population. The RAINBOW model offers a test of homogeneity which is based on the cumulative deviations from the mean. By evaluating the maximum and the range of the cumulative deviations from the mean, the homogeneity of the data of a time series is methods for estimating probabilities of exceedance (plotting positions) of ranked data, where r is the rank number and n the number of observations (Raes et al., 1996; Gbaguidi, 2005).

- **Spatial distribution**

The assessment of the spatial distribution of the rainfall was done from the comparison between data from two nearest stations using the method of Kendall. This method described by Doorenbos, (1976) allows also apprehending the correlation which exists between a series of data of two nearest stations. Indeed, the Kendall rank (1955) correlation coefficient evaluates the degree of similarity between two sets of ranks given to a same set of objects. This method compare a pair of data, one pair representing observations covering the same period at two neighboring stations.

- **Homogeneity test**

Homogeneous rainfall records are often required in hydrologic design as many records are not homogenous. Because of the uncertainty about possible changes; graphical methods are often used in climatology and hydrology to obtain some insights into the homogeneity of datasets. A popular tool is the double-mass curve (Searcy and Hardison, 1960) which is obtained by plotting the cumulative amounts of the station under consideration against the cumulative amounts of a set of neighboring stations. Therefore it is always necessary to test the significance of departures from homogeneity by statistical methods. Common statistical techniques in climatology and hydrology are reviewed in a publication on climatic change by the World Meteorological Organization (W.M.O, 1966).

The aim of homogeneity test is to check the deviation of historical data sets according to the mean of this series. The homogeneity of the records from the Massili basin station was investigated for the period 1960-2012 using the RAINBOW software (Raes et al., 1996). One of the tests of homogeneity (Buishand, 1982) principle is based on the cumulative deviations from the mean of a data set rejection probability of 90%, 95% and 99% (confidence level).Under the null hypothesis H_0 it is usually assumed that the Yi's have the same mean with Y_i (Y_1, Y_2, Y_n) a sequence of data.

$$\mathrm{Sk} = \sum_{k=1}^{n} (\ \mathrm{Yi} - \mathrm{Y}) \ (03)$$

Where Yi are the observations of the series and Y is the arithmetic mean of the series. If the series is homogenous, it can be expected that the value of Sk fluctuates around Zero, because there is no systematical derivation of the annual value in relation to the mean. After a scale remittance (by dividing the values of S_k versus the standard deviation of the series), RAINBOW draws the cumulative deviations in relation to the mean of the series and indicate on the same figure the lines giving the probability of homogeneity rejection.

For homogeneity assessment, annual rainfall from 1961 to 2005 of Ouagadougou, Boulbi, Boussé and Guiloungou were used. Thus a homogeneity test was applied to the climatic pattern of this station (evaporation, sunshine, wind speed, humidity). In a frequency analysis (Snedecor and Cochran 1980; WMO, 1981, 1983 and 1990; Haan, 2002) estimates of the probability of occurrence of future rainfall events are based on the analysis of historical rainfall records.

3.2.2.2 Results of data processing

Annual rainfall from 1961 to 2005 of Ouagadougou, Guiloungou ,Boulbi and Boussé were used. Table 8 reveals the correlation coefficient between the stations. The data consistency control shows that the datasets are not homogenous.

Table8: Kendall coefficient of correlation showing the heterogeneity in rainfall time series

	Ouagadougou	Boulbi	Bousse	Guiloungou
Ouagadougou	**1**	**0.161**	**0.287**	**0.425**
Boulbi	**0.161**	**1**	**0.149**	**0.224**
Bousse	**0.287**	**0.149**	**1**	**0.127**
Guiloungou	**0.425**	**0.224**	**0.127**	**1**

- **Homogeneity tests**
    - **Boulbi station**

At Boulbi station over the period 1961 – 2006, forty six (46) observations were made. The homogeneity of the data is depicted in figure 13. Boulbi rainfall data homogeneity is not rejected. Table 8 shows the frequency analysis of the data. It can be assumed that the probability to record a total rainfall of 1005.86 mm was 5% while the probability to have a total rainfall amount exceeding 586.67 mm was 90%.

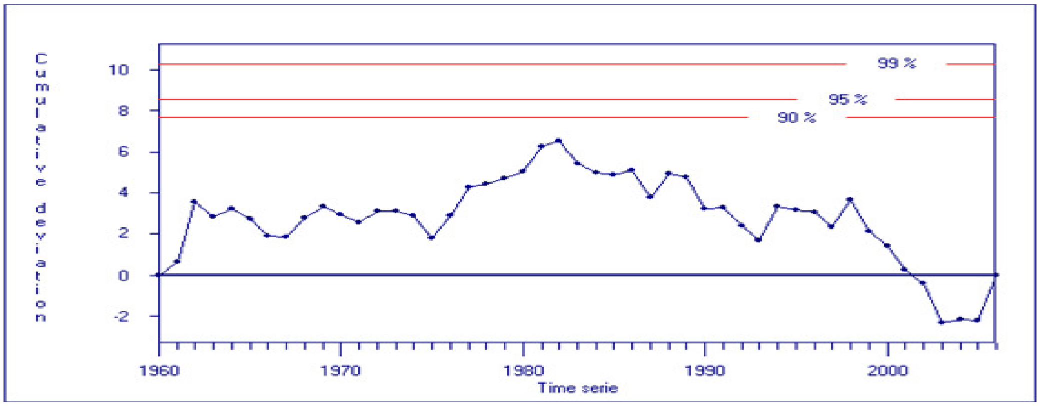


Figure 13: Cumulative deviations from the mean for the total annual rainfall (1960 – 2012) for Boulbi station.

Table 9: Analysis of frequency of Boulbi station.

Probability of exceedance (%)	Rainfall (mm)
10	953.80
30	845.28
50	770.24
70	695.19
90	586.67

- **Bousse station**

At Bousse station over the period 1961 – 2006 46 observations was made. Data homogeneity is depicted in figure 14. Bousse rainfall data homogeneity is not rejected. Table 8 shows the frequency analysis of the data. It can be assumed that the probability to record a total rainfall of 926.8 mm is 5% while the probability to have a total rainfall amount exceeding 517.1 mm is 90%.

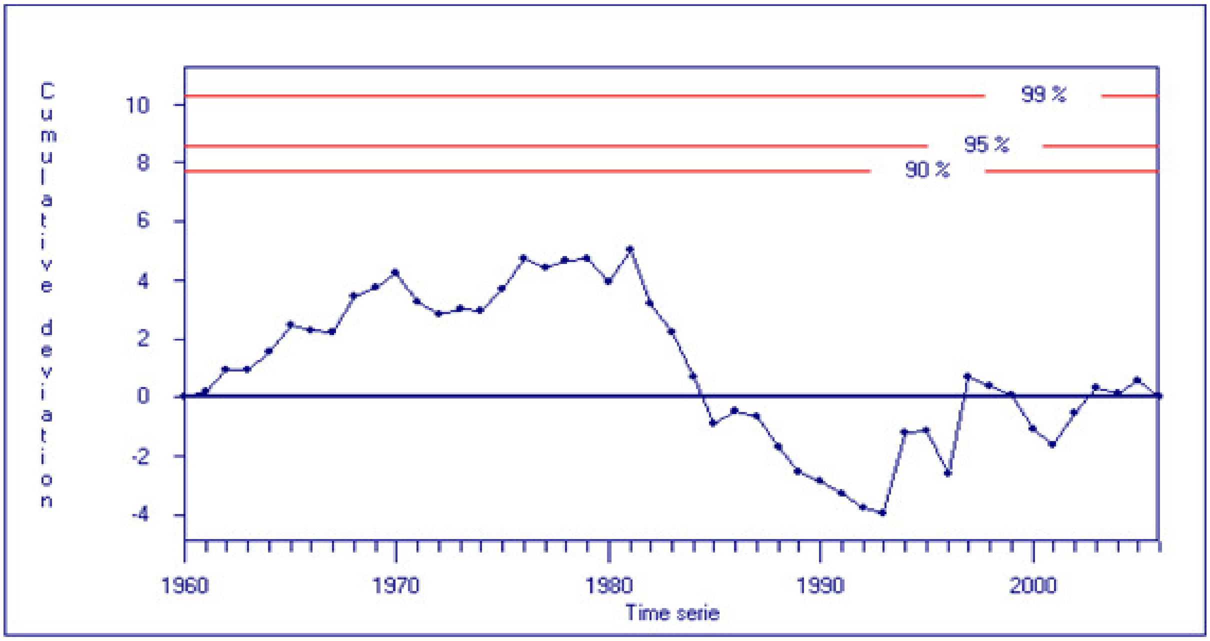


Figure 14: Cumulative deviations from the mean for the total annual rainfall (1960 – 2012) for Bousse.

Table 10: Analysis of frequency of Bousse station

Probability of exceedance (%)	Rainfall (mm)
10	876.0
30	769.9
50	696.5
70	623.2
90	517.1

- **Ouagadougou Station**

At Ouagadougou station over the period 1960–2012, 53 observations were made. The homogeneity of the data is depicted in figure 15. The data homogeneity is rejected from 1975 to 1980 at 90 to 95%. Table 11 shows the frequency analysis of the data. It can be assumed that the probability to record a total rainfall of 999.9mm is 5% while the probability to have a total rainfall amount exceeding 589.9 mm is 90%.

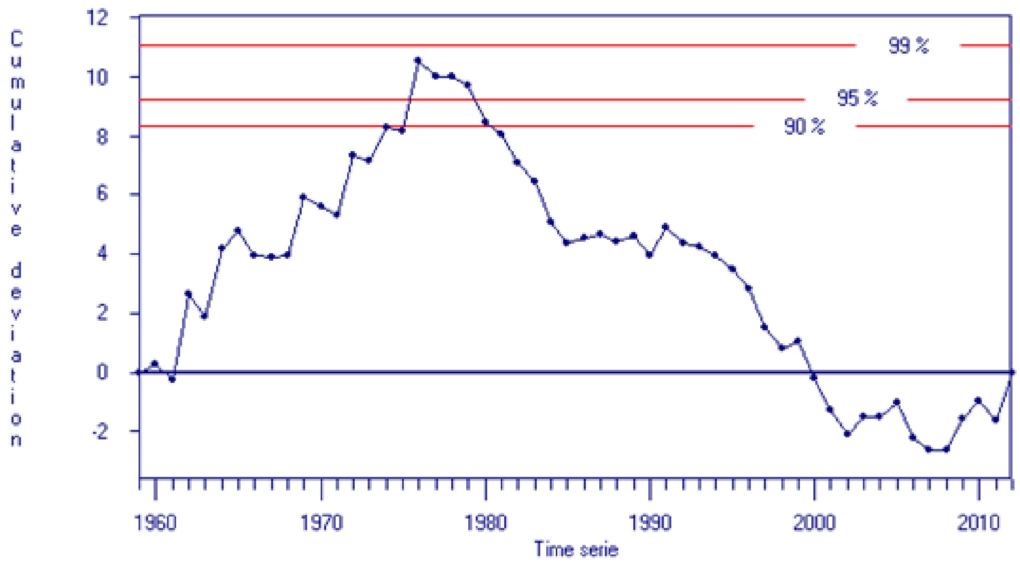


Figure 15: Cumulative deviations from the mean for the total annual rainfall (1960 – 2012) for Ouagadougou.

Table 11: Analysis of frequency of Ouagadougou station.

Probability of exceedance (%)	Rainfall(mm)
10	949.0
30	842.9
50	769.5
70	696.6
90	589.9

- **Homogeneity test of Ouagadougou climatic parameters**

From 1980 to 2005, the sunshine time series homogeneity is rejected at 90 to 99%.

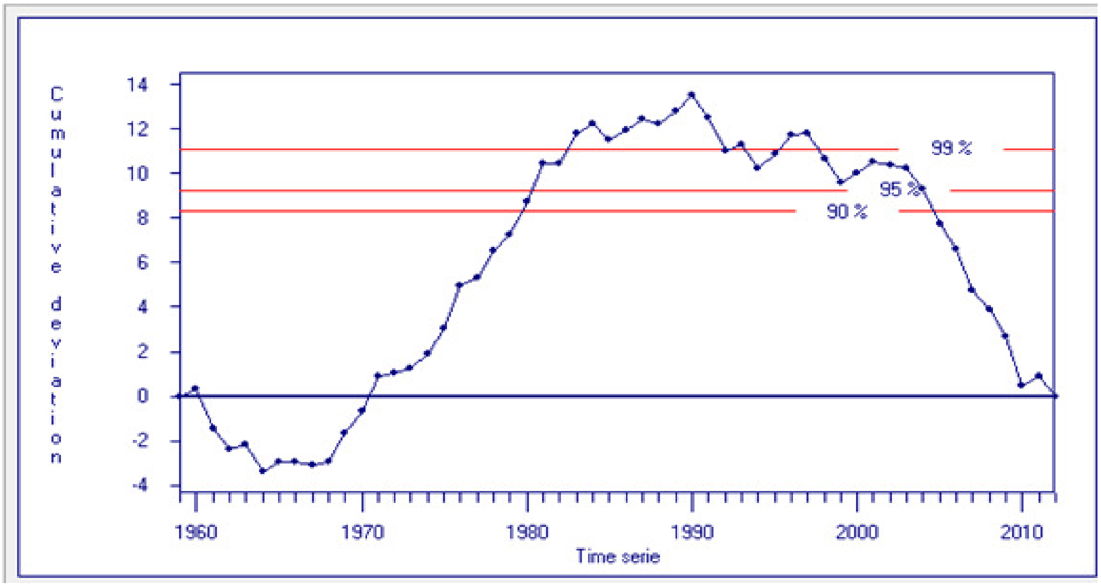


Figure 16: Cumulative deviations from the mean for the total annual sunshine (1960 – 2012) for Ouagadougou.

The evaporation time series homogeneity is accepted from 1960 to 2010.

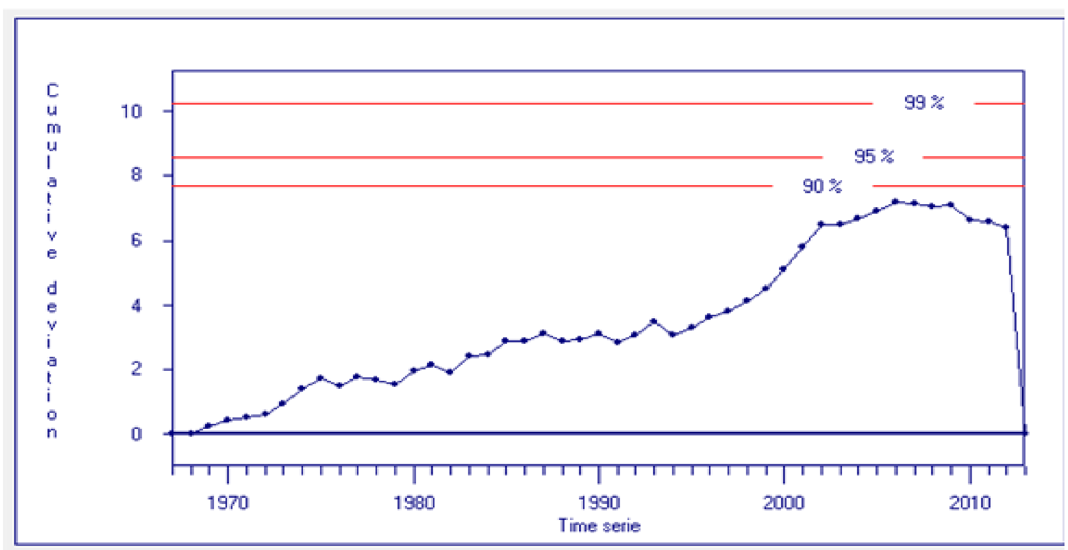


Figure 17: Cumulative deviations from the mean for the total annual evaporation (1960 – 2012) for Ouagadougou.

The air humidity time series homogeneity is rejected in 1972 and from 1975-1983.

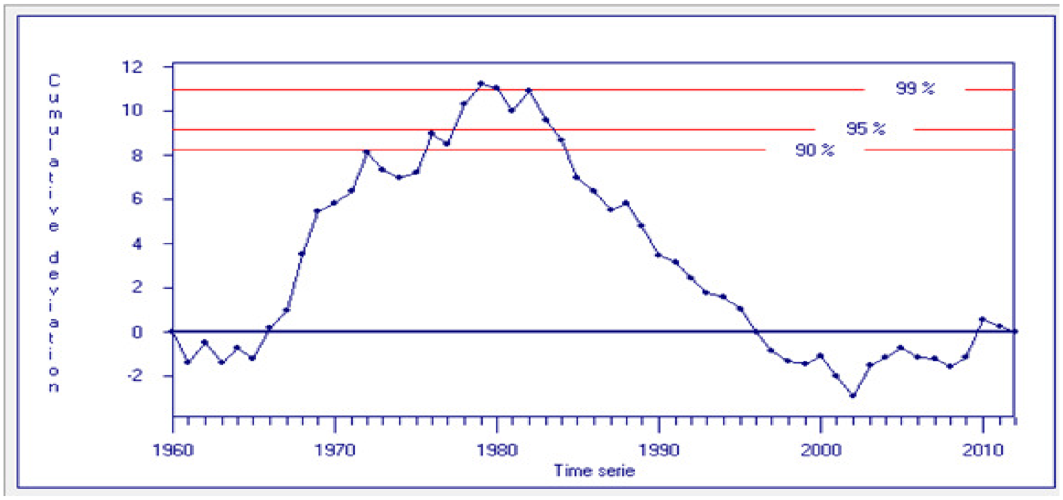


Figure 18: Cumulative deviations from the mean for the total annual air humidity (1960 – 2012) for Ouagadougou.

The wind speed time series homogeneity is rejected from 1972 to 1987.

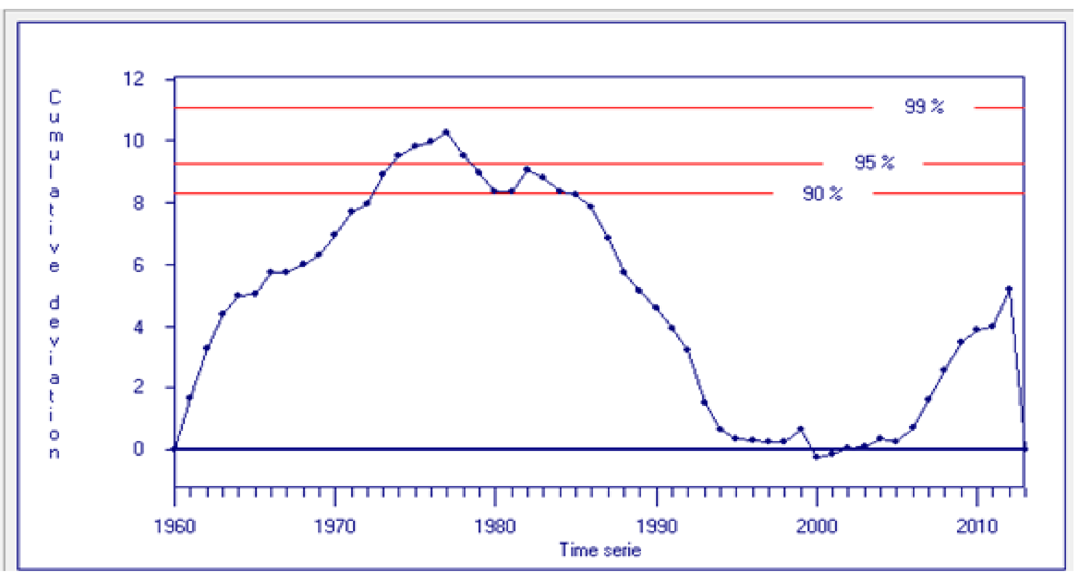


Figure 19: Cumulative deviations from the mean for the total annual wind speed (1960 – 2012) for Ouagadougou.

Ouagadougou temperature time series is accepted fron 1960 to 2012.

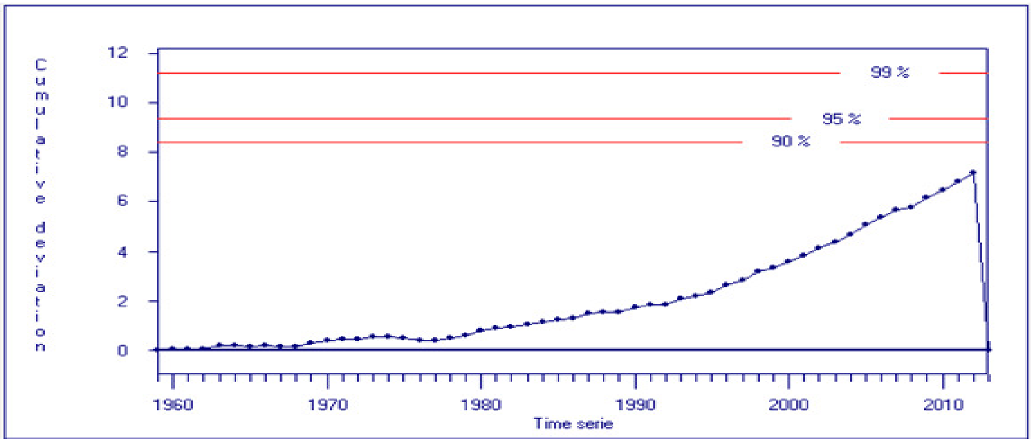


Figure 20: Cumulative deviations from the mean for the total annual temperature (1960 – 2012) for Ouagadougou.

The table below summarizes results of the frequency analysis .The linear tendency to the point was used for the treatment of the missing value.

Table 12: Frequency analysis of Ouagadougou climatic pattern over 1960-2010

	Sunshine(H/day)	Wind speed (m/s)	Temperature(^{0}C)	Humidity	Evaporation (mm)
Minimum	0	0,0	18.5	10	0,3
First quartile	7.5	1,6	26.4	31	6,4
Median	9.4	2,1	28.4	49	8,1
Average	8.463	2,272	28.55	49,62	8.265
Third quartile	10.3	2,9	30.6	69	10,1
Maximum	12.2	6,6	37.7	93	33
Na's	35	45	52	108	149

Homogeneity test of discharge data.

Table 133: Frequency analysis of discharge data

	Bissiga	Rambo	Gonse	Wayen
Minimum	0	0	0	0
First quartile	0	0	0	0.374
Median	0.1	0	0.0022	1.3853
Average	5.961	0.7829	1.4605	12.07
Third quartile	5.325	0.175	1.2966	8.5
Maximum	65.800	11	167.1	352.7
Na’s	0	130	0	0

- **Correction of rainfall data times series**

The data consistency control shows that the data is not homogenous. However, the observation of isohyets trend within the basin (Figure 11) indicated that the annual rainfall within the watershed is homogenous. Thus there was a need to correct the data. The correction of the data was done using the method of the nearest stations and linear regression. After correction and gap filling using linear regression method, the following result was obtained.

Table 14: Kendall and Spearman’s rho coefficient for corrected rainfall time series

		Ouagadougou	Boulbi	Bousse	Guiloungou
Kendall's tau_b	Ouagadougou	1.000	0.885	0.881	0.880
	Boulbi	0.885	1.000	0.884	0.878
	Bousse	0.881	0.884	1.000	0.883
	Guiloungou	0.880	0.878	0.883	1.000
Spearman's rho	Ouagadougou	1.000	0.958	0.957	0.951
	Boulbi	0.958	1.000	0.959	0.947
	Bousse	0.957	0.959	1.000	0.950
	Guiloungou	0.951	0.947	0.950	1.000

3.2.2.3 Survey data processing

The survey data collected was analyzed by applying Statistical Package for Social Sciences (SPSS) tool. The data was analyzed through descriptive statistics by using the mean, percentile and frequencies.

3.2.2.4 Satellites images processing

Scientific comity opinion about satellites images processing is charred. For instance, while Collet (2001) highlighted the importance of images correction before use, Song et al. (2001) esteemed those satellites images processing is not always useful. The former think indeed that one should restitute the specific spectral property to each type of soil use in order to favor it determination through visuals and numerical means and observe it evolution. However satellite data processing is an important step as some errors can occur.

- **Preprocessing**

According to Ries and Friesz (2000), satellite data processing can be fulfilled in three steps: preprocessing, image enhancement, and image classification. Preprocessing which is composed by radiometric and geometric correction. Radiometric correction is a set of image treatment which is carried out in the ground station with the main aim to approximate the differences in pixel value to their original reflectance values. Thus radiometric correction is related to the correction of data due to sensor irregularity, noise due to sensor or atmosphere. Geometric corrections refer to the geometric distortions correction due to the variations of the geometry Land-sensor, and to the transformation of data on the Earth surface coordinates.

- **Image enhancement**

Image enhancement allows improving the image appearance to help for interpretation and visual analysis. They allow the modification of the contrast, linear stretch or histogram equalization, spatial filtering, smoothing (low-pass), sharpening (high-pass) and band transformations. Image transformation combines several spectral band treatments at the same time to one band of data at the same time. Some arithmetic operations (addition, subtraction, multiplication and division) are done to combine and transform the originals band in new images which show clearly some elements of the area. This can be done with GIS software (ERDAS imagine, GRASS, ARC GIS).

- **Image classification**

Classification (supervised and unsupervised) is a process through which the number and location of the spectral classes are determined. Some field data can be used to check the accuracy of the classification in the case of supervised classification.

The realization of this study required satellites data processing to avoid artifact linked to the images. In this study, the processing was carried out through the ERDAS IMAGINE software which is a raster based tool that is specifically designed for information extraction from images a remote sensing application with raster graphics editor abilities designed by ERDAS for geospatial applications. They are designed to provide comprehensive analysis of satellite and aircraft remote sensing data. They are not only innovative but very much user-friendly to display and analyze images. Then the data interpretation was carried out.

Remote sensing interpretation can be characterized as an inverse procedure of remote sensing imaging. It reconstructs a geographic landscape through target recognition and phenomenon identification, which is in turn achieved by analyzing a variety of characteristic information provided by the images acquired through remote sensing. There are many different approaches to interpret remote sensing image, including frequency domain analysis with high resolution image, texture processing, high resolution SSMC (Spatial and Spectral Mixed Classifier), interactive method between researcher and computer, neural network (Zhang, Songling, 1999; Zhou, Tinggang, 2004; Yang, Bin, 2004; Huang, Xin, 2006; Zhang, Su, 2008). For this study, the data used was retrieved from Landsat 8, the remote sensing images taken by China-Brazil earth resource satellite during July 2006. The images studied were taken by IRMSS (Infrared Multi-Spectral Scanner). The spatial resolution of the images is 20 m. Images have 4 bands of spectrum, namely 1, 2, 3, and 4. The study chose 2, 3, and 4 bands of spectrum designated with red, blue and green. Classification was done base on field truth.

4 CHAPITER IV: ASSESSMENT OF CLIMATE VARIABILITY AND PEASANT PERCEPTION OF CLIMATE CHANGE.

4.1 Introduction

Change due to climate variability may affect water supply: droughts and lower precipitation reduce water availability, higher temperatures increase the loss of water and increase water demand, droughts and high temperatures combined have the largest impacts on water supply and demand. In other words, rising temperature, rising potential evapotranspiration rates and declining rainfalls conspire to increase the severity, frequency and duration of droughts (IPCC, 2007).

However, temperature and rainfall projections show that climate change will impact regions in different ways, with spatiotemporal changes in rainfall pattern, but generally increasing temperatures (IPCC, 2001; Meissner et al., 2003; Snyder et al., 2004; Tarhule, 2005; Dang et al., 2007; Barrios et al., 2008). Indeed, impacts of climate change will vary across regions and populations, through space and time, depending on myriad factors including none climate stressors and the extent of mitigation and adaptation (IPCC, 2014). Given the uncertainty of global assessments and model efforts, more detailed information about regional patterns of climate change as emphasized by IPCC (2001) would support the development of adaptation and mitigation strategies. Thus, there is a need to downscale knowledge on temperature and rainfall trends at local scale in order to have relevant and detail information. Indeed, knowledge of climate variability and trend (temperature and rainfall) of a given area is very relevant and challenging to farmers, decision makers and the population in general. Most of the world’s food is produced under rain-fed systems where climate variability and change play an important role in determining the productivity (Slingo et al., 2005). Several authors (Fitter et al., 1995; Le Houérou, 1996; Sparks et al., 2000; Huang et al., 2003; Matsumoto et al., 2003; Gordo and Sanz, 2005; Slingo et al., 2005; Ahas and Aasa, 2006; Lu et al., 2006; Rasul, 2010; Kosa, 2011; Pérez-Sánchez et al., 2011) highlighted the effects of increasing temperatures on crop production systems. In addition, Barbier et al. (2009), Ouedraogo et al. (2010), and Zorom et al. (2013) showed that extreme climatic conditions, especially droughts, have severely affected crop production and motivated pastoralists to move out of their original agro-ecological zones (FAO, 1997). Lodoun et al. (2013) have estimated onset and cessation over the entire Burkina Faso using 39 stations.

This study is focus on climate variability in Massili basin (Central Burkina Faso) and evaluates its perception by local peasants. The analysis allows apprehending the Massili basin population vulnerability. The establishment of the link between climate variability and peasants' perception on climate change helps to better determine the local consequences of climate change and to make suggestion for adaptation strategies.

4.2 Methods

4.2.1 Description of the climate variability from climate data

The main ways to characterize the frequency, intensity and duration of climate extremes is to calculate climates indices based on daily time series of temperature and rainfall (Karl et al., 1999; Peterson et al., 2002). For the purpose of this study, eight climate indicators were calculated. The selection of these indices was done to satisfy the needs of decisions makers and rural population and to support efforts in the implementation of adaptation strategies. For instance, the analysis of the consecutives dry days (CDD) aims to detect the period of dry spell occurrence. Knowledge on the exact period of dry spell occurrence is meaningful as it renders farmers ready for the application of complemented irrigation. In addition, onset and offset information analysis may help to avoid early seeding. Awareness on the trend of total precipitation and extreme rainfall occurrence (R1 day), may help water resources managers to better cope with flood management, but also with consequences related to the spread of water borne diseases. Information about consecutive warm days (WSDI) reveals the trend of temperature and in case where WSDI is increasing mitigation decisions should be made to reduce CO_2 release.

- **Onset and cessation of the rainy season**

The onset of the growing period (OGP) at a given location is the date after May 1st when total rainfall over three consecutive days is at least 20 mm, with no dry spell exceeding 7 days during the following 30 days (Sivakumar, 1991). The cessation date of the growing period (CGP) is defined as the date after September 1st when the soil water content down to 60 cm depth is nil with a daily potential evapotranspiration of 5 mm (Maikano, 2006). Recently, Salack et al. (

2011) proposed a method in order to determine the onset and rainfall cessation in Africa and this method was applied in this study as it involved rainfall times series only. According to this author, the onset is established when 3 days rainfall accumulation is equal or more than 20mm starting from first(1st) May and not followed by 7 consecutive dry days (<1mm). The offset is defined with the appearance of 20 consecutive days after the 1st September without rainfall event higher than 1mm.

$$\text{Onset} = \sum_{i=1}^{3} \text{Ri} \geq 20 \text{ mm} + \text{at least 7 days with rainfall more than 1 mm} \quad (04)$$

$$\text{Cessation} = \sum_{i=1}^{20} \text{Ri} < 1\, mm\ after\ 1stseptember \quad (05)$$

- **Rainfall and temperature indices**

The other climate characteristics and indices of rainfall and temperature were calculated from the application of Rclimdex tool. RClimdex allows computing all the basic indices of climate extremes recommended by the Expert team from the CCl/CLIVAR for Climate Change Detection Monitoring and Indices (ETCCDMI) (Easterling et al., 2003) . The ETCCDMI undertook a set of regional analysis for understanding climate extremes and trends. Among the 27 core indices recommended by ETCCDMI eight (08) indices considered as most relevant for this study area were selected and summarized in table 15 (rainfall) and table 16 (temperature). Several studies have applied Rclimdex without adapting the formula criteria to the context of each study area. In this study, the criteria were changed in order to fit the reality of the zone. For instance Rclimdex computes the CDD for all the year. However, estimation of dry spell is important during the rainy season on Burkina rather during all the year, as farmers are more interested in occurrence of dry spell during the rainy season. In addition, most of the assessment of CSDI and WSDI was computing considering their occurrence during six consecutive days. This explains why in most studies, it occurred zero as the value of CSDI and WSDI during some years. In this study, CSDI and WSDI were computed during 3 consecutive days in order to show at which level those indices are occurring.

Table 15: list of the Rainfall indices

Indices	Names	Formula
PRCPTOT	Amount of annual rainfall	$PRCPTOT_j = \sum_{i=1}^{I} RR_{ij}$ (06) RR_{ij} the daily precipitation amount on day i in period j. I represents the number of days in j
RX1day	The maximum 1-day values for period j	$Rx1day_j = \max(RR_{ij})$ (07) RR_{ij} the daily precipitation amount on day i in period j.
CWD	The largest number of consecutive days where the rainfall is higher than 1mm.	$RR_{ij} \geq 1mm$. RR_{ij} the daily precipitation amount on day i in period j.
CDD	The largest number of consecutive days during the rainy season where the rainfall is lower than 1mm	$RR_{ij} < 1mm$ RR_{ij} the daily precipitation amount on day i in period j

Table 16 : list of Temperature indices

Indices	Names	Formula
TXx	Annual maximum of the daily maximum temperatures	$TNx_{kj} = \max(Tn_{kj})$ (08) Tx_{kj} the daily maximum temperatures in month k in period j.
TNn	The annual minimum of the daily minimum temperature	$TNn_{kj} = \min(Tn_{kj})$ (09) Tn_{kj} the daily minimum temperatures in month k in period j.
CSDI	Cold spell duration indicator (annual maximum duration)	$Tn_{ij} < Tn_{in}10$ Tn_{ij} the daily minimum temperature at day i in period j and $Tx_{in}10$ the 10th percentile of the annual minimum temperature. Annual count of days with 3 consecutive days when TN<10th percentile
WSDI	Warm spell duration indicator (annual maximum duration).	$Tx_{ij} > Tx_{in}90$ Tx_{ij} the daily maximum temperature on day i in period j and $Tx_{in}90$ is the 90th percentile of the annual maximum temperature. Annual count of days with 3 consecutive days when TX>90th percentile.

4.2.2 Climate variability and climate change from peasants'perception.

A survey was conducted within the basin to evaluate the peasant's perception on climate variability and change. An ensemble of 20 villages was randomly selected based on quota sampling method (Figure 21). Battaglia et al. (2012) claim that quota sampling falls under the category of non-probability sampling. In order to get information from local farmers, a questionnaire was developed based on a list of objectives and research goals. This list has served as plan for the survey questionnaire. A pre-survey was done to improve the questionnaires. As, climate change is a very complex pervasive and uncertain phenomenon, generally difficult for people to conceptualize and to relate to their daily activities (Bostrom et al., 1994; Kempton, 1997; Ungar, 2000), the questionnaire was elaborated based on local natural hazards and impacts of climate.The questionnaire was then administrated to two hundred people (table 17) aged between 30 to 75 years of age who are considered being the main actors in the agricultural sector. To support the results, a focus group discussion was also carried out in order to have a general overview of the population's opinion. SPSS tool was applied to analyse the survey data collected. The sampling time step is defined as the ratio of localities and Targeted number of localities. The number of population to interview by locality was estimated in order to reach the quota of 200 persons. This was been fulfilled by multiplying the population of each locality (obtained from the last census of population in 2006) by the sampling rate. The sampling rate was obtained by dividing the quota by the total population. The number of population to be interviewed by locality in order to reach the quota of 200 persons was been obtained by multiplying the population of each village by the sampling rate. Table 17 shows the number of people interviewed by localities.

Table 17: number of peasants interviewed per locality

Village	Respondent		Village	Respondent
Sandogo	42		Tanguen-Manega	5
Zongo	1		Mouni	7
Gampela	11		Boulala	4
Diguila	4		Barogo	8
LOUMBILA	8		Sandogo	2
Penlogo	1		Bilogo	10
Goue	10		Sao	26
Pagatenga	5		Sakoula	4
Taonsgo	4		PABRE	16
Tampoui	16		Basseko	16

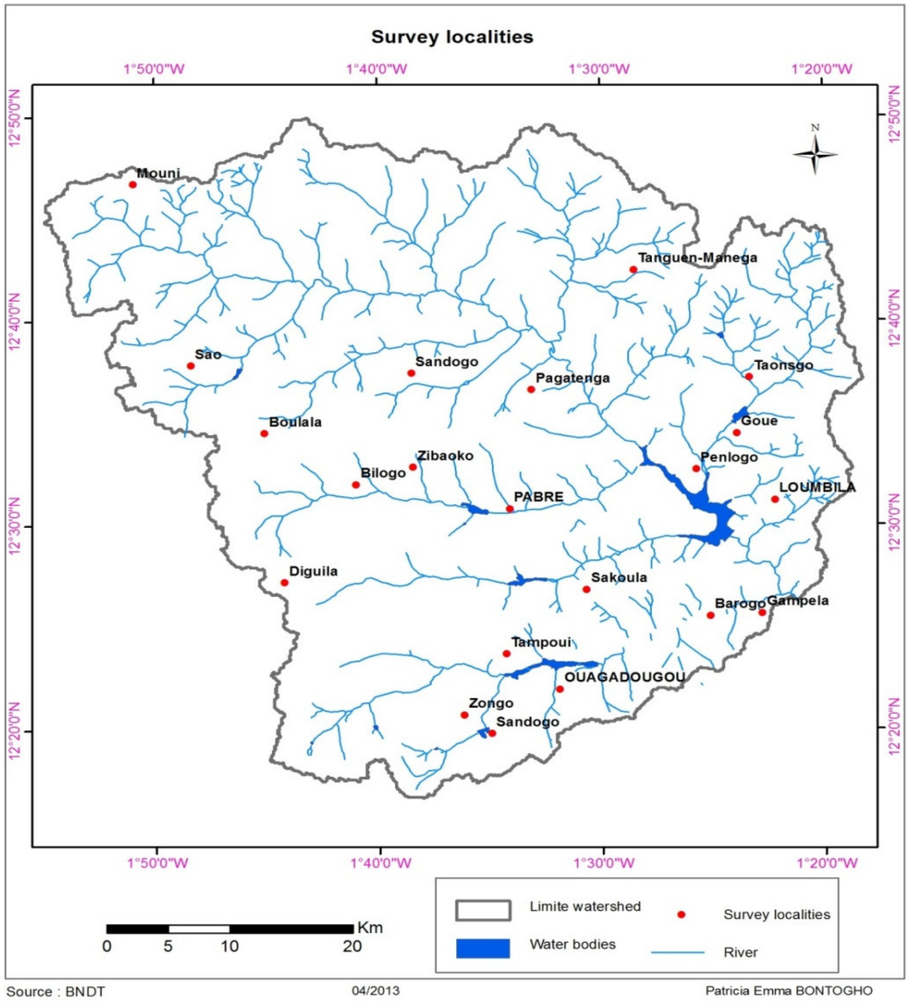


Figure 21: Localization of the localities concerned by the survey

4.3 Results and discussion.

4.3.1Main characteristics of the rainy season

The analysis of past rainfall onset and cessation days as defined by Salack et al. (2011) indicates an upward trend of onset and a downward trend of offset. This indicates that there is a shift in onset and cessation in the past 50 years (figure 22). 1996 is the year where the onset has started earlier at the 144th day of the year while 1986 represents the year where the onset has started later at the 222th day. In addition in 1961 the offset has start earlier (271th day) than the rest of the years while in 1976 the offset has occurred in 305th day.

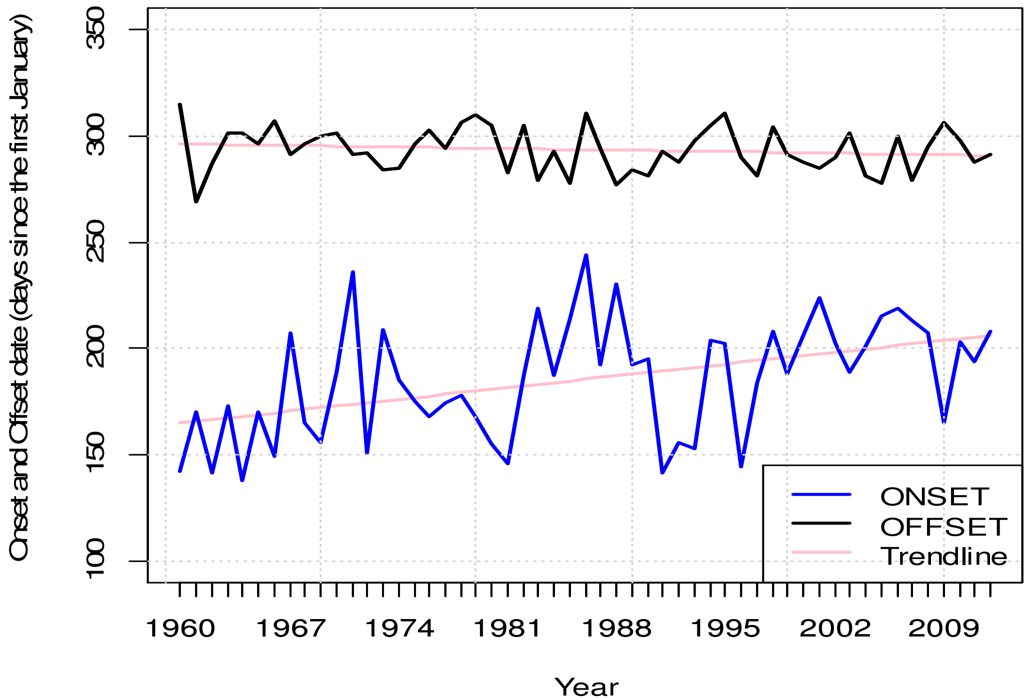


Figure 22: Evolution of the date of the onset and offset (cessation) of the rainy season

4.3.1 Evolution of the climate indices

4.3.1.1 Evolution of rainfall indices

The total annual precipitation amount was computed by using the PRCPTOT indices which wet day criteria is a day where RR>=1mm. In general, the results show a slightly decrease of rainfall (figure 23.a). This result is in agreement with previous findings showing the decrease in precipitation over the entire Burkina Faso. (Hess et al., 1995; Le Barbé and Lebel, 1997; Lebel et al., 2003; Ibrahim et al., 2014). Moreover, the projections reflect a decrease in precipitation from a rate of 3.4% by 2025 to a rate of 7.3% by 2050 in comparison to the past rainfall (NAPA, 2007). However the 5 years moving average shows an increase of the rainfall quantity during the previous seven years (2005 to 2011).

For the period analysed, the recorded maximum one-day precipitation has slightly increased (figure 23b). With 263.1mm, the highest rainfall amount recorded in the basin was measured on the 1st September 2009 (day 245) at Ouagadougou station. An amount of 221.8 mm was also recorded the same day in Boulbi station. In general, extreme events usually occurred between the 141 and the 254 day (21stMay to 11th September) of each year. This result corroborate with the results of Trenberth et al. (2007) showing a clear evidence of changes in the extremes of precipitation. Moreover, IPCC (2013) highlighted that extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century, as global mean surface temperature increases. Heavy precipitation events over many areas have become more frequent and brought more severe consequences such as sudden floods, crop yield decreases, occurrence and increase of diseases (mainly waterborne diseases), food insecurity, livestock and human death.

With a confidence level of 1% (P value= 0.009937), the consecutives dry days (CDD) are increasing (Figure 23c) while the Consecutives Wet Day is decreasing (Figure 23d).

Previous sub-regional studies on rainfall patterns suggest a decreasing trend in annual total rainfall indices (DIOUF et al., 2001; L'hote et al., 2002). According to Sarr (2012) extreme rainfall events became more frequent in the West African Sahel during the last decade, compared to the 1961– 1990 period. This result corroborates the observed upward trend in Massili basin of extremely wet days represented by the RX1Day (Figure 23 b). Table 18 shows that the total precipitation is decreasing at a change rate of -2.05 while the maximum one day precipitation is increasing at a change rate of 0.35. The rate of change in CWD is -0.01 and the rate of change in CDD is about 0.59. Table 18 displays the slope of the trendline.

Table 18: slope of rainfall indices

Indices	Slope
PRCTOT	-2.055
RX1DAY	0.35
CWD	-0.011
CDD	0.591

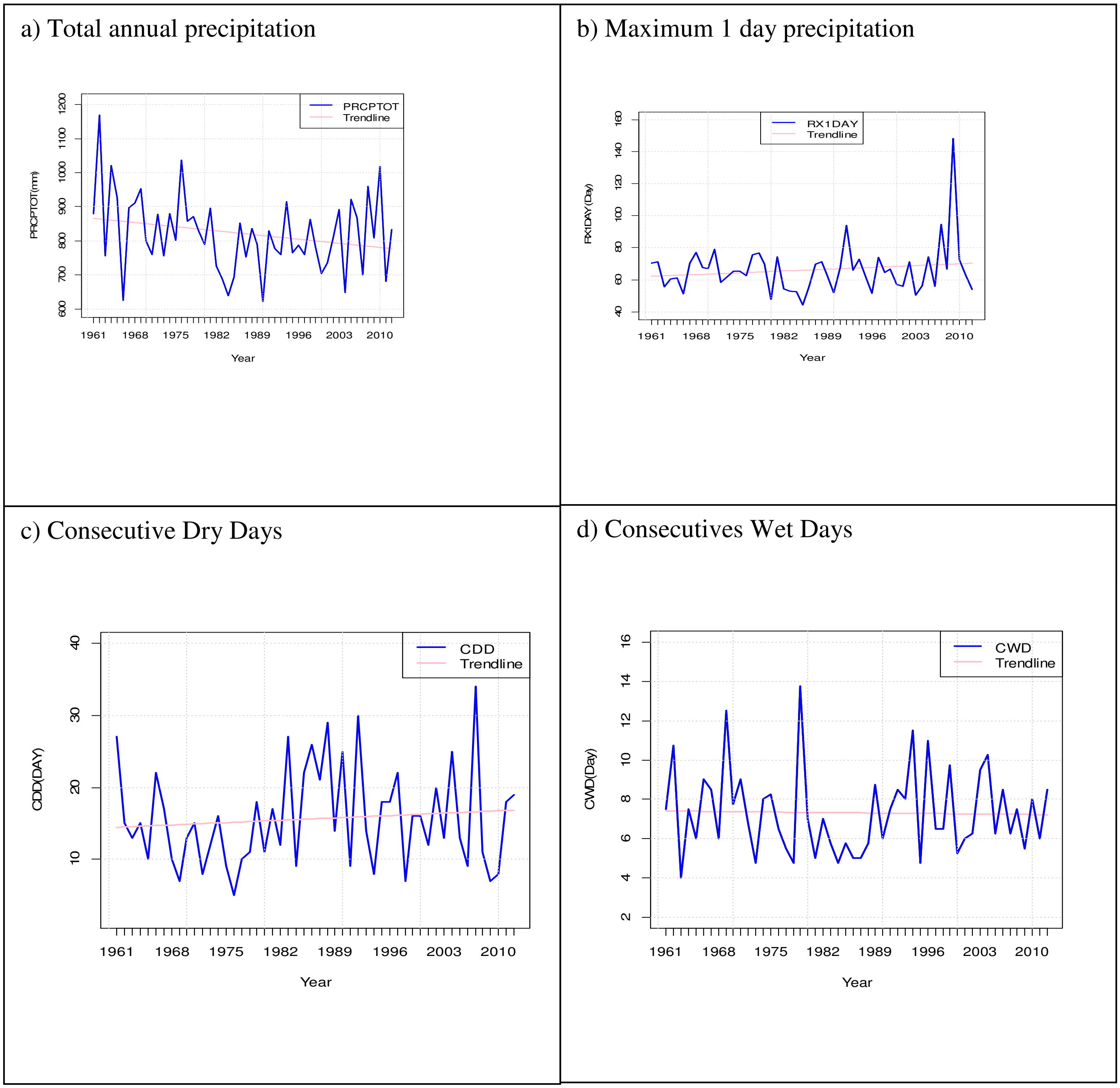


Figure 23: Inter-annual evolution of the rainfall indices from 1961 to 2012. a) Total annual precipitation for the period 1961 to 2012; b) Maximum 1 day precipitation; c) Consecutive Dry Days for the 1961–2012 analysis period) ; d) Consecutives Wet Days for the 1961–2012 analysis period

4.3.1.2 Evolution of temperature indices

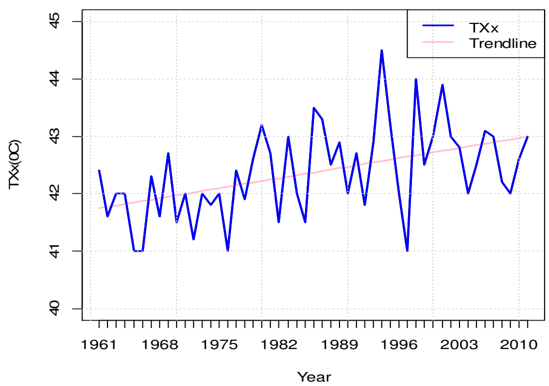
The annual maximum of the daily maximum temperatures (TXx) shows an increasing trend in the Massili basin (Figure 24a). The trend is statistically significant with a p-value of 1%. The highest maximum daily temperature was measured in 1994 (44.5°C) while the lowest maximum daily temperature was measured in 1965, 1966, 1976 and 1997 (41°C). As shown by various studies, this trend of increasing maximum temperatures is supposed to continue in the future projections (IPCC, 2007).

TNn depicting the evolution of annual minimum of daily minimum temperature is also increasing during study period (figure 24b). Cold spell duration indicator (CSDI) which is the annual longest duration of three consecutive days with minimum temperature lower than the 10th percentile of minimum temperature has a decreasing trend (Figure 24 c). The increasing trends were statistically significant for 5% (0.054231). Those results corroborate with the results of IPCC (2012) which state that the phenomenon and direction of trends in weather and climate events has become increasingly deviant from normal, with more warmer and fewer cold days and nights, also warmer and more frequent hot days and nights over most land areas. Warm spell duration indices (WSDI) which reflects the annual number of periods with at least 3 consecutive days when the days temperature (TX>90th percentile) is on the rise (Figure 24d). The increasing trends were statistically significant for 1% (0.000478). Those results are in line with IPCC 2014stating that since 1950, the numbers of cold days/nights have decreased and the numbers of warm days/nights have increased globally. Temperatures indices are increasing with a slope between 0.025 to 0.27 Table 19 displays the slopes of the increases.

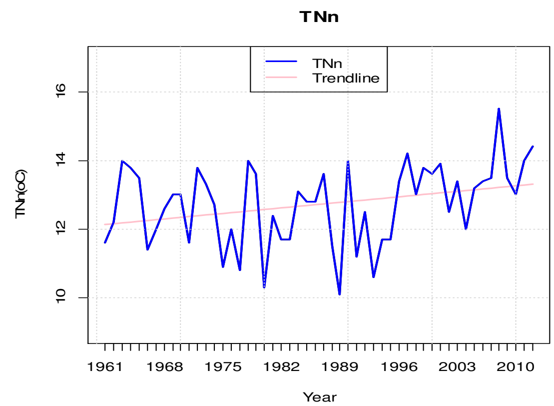
Table 19: slope of temperature indices

Indices	Slope
TXx	0.025
TNn	0.017
WSDI	0.276
CSDI	0.057

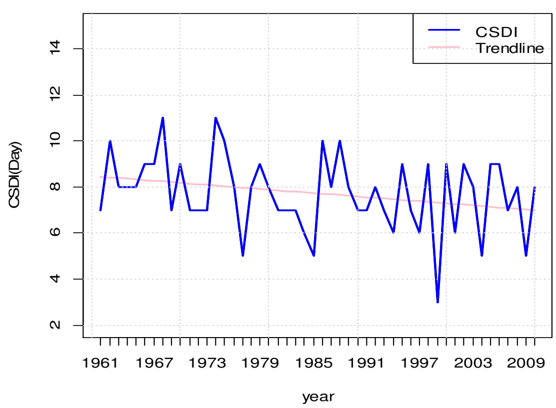
a) Annual maximum of daily maximum temperature



b) Annual minimum of daily minimum temperature



c) Annual CSDI relative to daily minimum temperature



d) Annual WSDI relative to daily maximum temperature

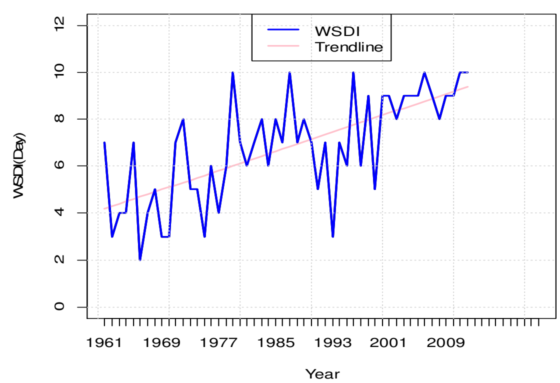


Figure 24: evolution of the temperature indices over the Massili basin

a) Annual maximum of daily maximum temperature TXx for the period 1961 to 2012; b) Annual maximum daily of minimum temperature (TNx); c) Annual CSDI relative to daily minimum temperature (for the 1961–2012 analysis period) ; d) Annual WSDI relative to daily maximum temperature (for the 1960 2011analysis period).

4.3.2 Local population perception on temperature and precipitation trends

Results on local population perception regarding temperature and precipitation trends confirm that impact of climate change on population and their behaviour is evident figure 25. The majority of farmers (80%) in Massili basin are aware about climate change, and almost two third (71.5%) have already heard about climate change. However, those who have never heard about climate change acknowledge nevertheless that climate is changing.

There is an overall awareness that climate change is a threat for human being since it will affect crop production. More than 80% of the basin population perceived climate change as a severe phenomenon. Climate change is understood by the farmers as the occurrence of temperature rise paired with a decrease in rainfall. Those perceptions are similar to those found in West Africa (Ouedraogo et al., 2010; Agossou et al., 2012; Kisauzi et al., 2012; Macharia et al., 2012; Moyo et al., 2012; Tambo and Abdoulaye, 2013; Vissoh et al., 2013).

About 99% of the peasants underline that the onset is becoming delayed and 75% stated that the cessation of the rainy season is becoming earlier. There is a net decrease in rainfall amount (79%) and an increase in dry spell occurrence (95%). The results are in line with those obtained by Ouedraogo et al. (2010), who showed that almost 86% of the population estimate that rainfall decreases in the Sahelian zone of Burkina Faso. In addition, they are in concordance with the analysis of the National Meteorological Agency of over the period 1961-2010. About 95% of farmers noticed that dry spells are more and more frequent and have great influence on crops. This observation is in agreement with the increased trend of consecutives dry days (CDD). Furthermore, 97% of farmers highlight that warm spell is increasing while cold spell duration is decreasing.

According to the peasants, climate change is reducing the crop yield as stated by 79% of the farmers interviewed. This aspect could also be linked to the increase in temperature in this sense that temperature has a great influence on germination. Indeed, according to Huang et al.(2003), historically increased surface temperature affects seeds germination, plant phenology (Fitter et al., 1995; Sparks et al., 2000; Matsumoto et al., 2003; Gordo and Sanz, 2005; Ahas and Aasa, 2006; Lu et al., 2006) and evapotranspiration (Le Houérou, 1996; Rasul, 2010; Kosa, 2011).

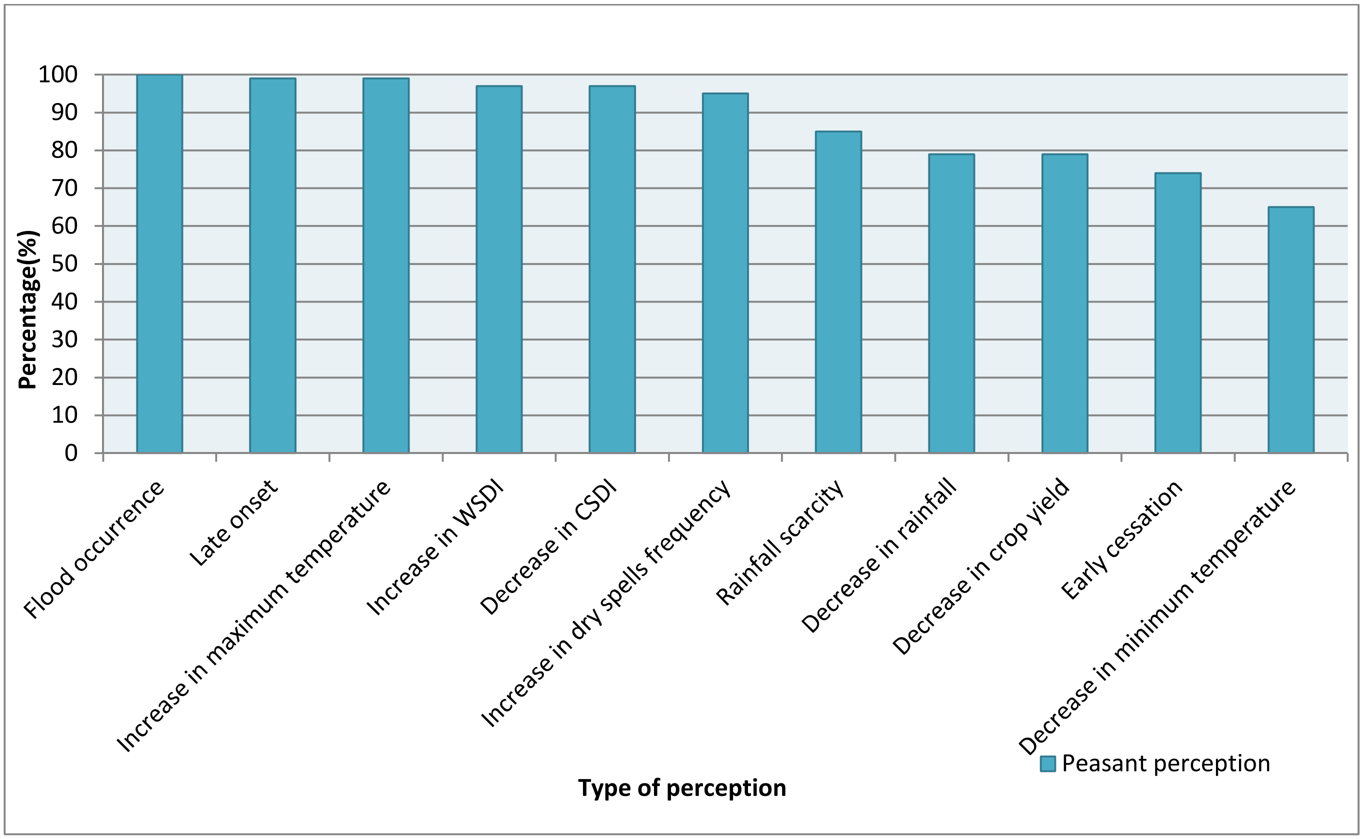


Figure 25: Peasant perception on climate change

4.4 Discussion

Rainfall onset marks the beginning of three major activities - planting, weeding and harvesting (Mortimore and Adams, 1999) which determines the socio-economic life and survival of the farming households. Figure (22) shows a shift from early to late onset in the year. This observation is similar to the results of Lodoun et al. (2013) for Burkina Faso who found a precocious start of the rainy season, between 1947 and 1955 and a late start from 1955 to 2000 and ends earlier. Since Burkina Faso is a rain-fed and developing country, where about 90% of the working population is engaged in agriculture and livestock (Belemviré et al., 2008), the shortening of the rainy season may exacerbate rural population vulnerability as confirmed by UDAID (2007): the consequences of climate variability and change affect more the poor populations in developing countries than those living in more prosperous nation. The knowledge of the rainy season onset is very important in this sense that these parameters allow respectively farmers to avoid early seeding and eventually the waste of seeds.

Farmers believe that the cessation of rainfall is becoming more uncertain. Moreover, occurrence of dry spells during the rainy season illustrated by CDD indices is increasing while CWD is decreasing. Consequently, change in climate variability is exacerbating farmers' vulnerability to food security as they are facing lower yields. To cope with this situation, efforts have been undertaken in the context of seeds adaptability. In fact, research has led to the availability of short duration seeds which are adapted to the current rainy season period. Unfortunately as noticed by farmers, most of the seeds must be bought each year and sometimes those seeds are available on the market only many days after the rainfall onset. Thus, there is a need to allow for a permanent disposition of early seeds to the peasants before the annual rain season starts. In addition, changes in rainfall quantity and frequency would alter the pattern of stream flows and demands for water (particularly agricultural), spatial and temporal distribution of runoff, soil moisture, and ground water resources (Jain et al., 2013) . This may exacerbates consequently the challenge of water management issue in the study area.

The annual rainfall amount shows a slight increasing trend during the last seven years. These results confirm the findings of several authors (Sene and Ozer, 2002; Herrmann et al., 2005; Schulz et al., 2009) which indicated that the Sahel is growing green again. The slight increase in occurrence of extreme rainfall (RX1Day) illustrated in figure 23b is depicting a watershed which may experience floods. Thus, some precocious adaptation measures must be undertaken. Heavy precipitation events over many areas have become more frequent and brought more severe consequences such as abrupt floods, crops yield decrease, occurrence and increase of disease (mainly water borne diseases), food insecurity, livestock and human deaths. For instance, the watershed has experienced an extreme rainfall on 1st of September 2009, with an amount of 261mm of rainfall recorded in one day (Karambiri et al., 2011). During this event; more than 25000 victims were recorded, 11 people died and infrastructure was heavily destroyed. The damage caused by this event showed how the occurrence and the severity of extreme events may impact natural and societal systems. In addition daily minimum and maximum temperature are both increasing. Consequently, this finding is in concordance with the note of IPCC (2007) which reveals a global average temperature increase by 0.6 ± 0.2 °C over the last century and a projected increase of 1.4 to 5.8 °C. Moreover, the projections for temperature trends in Burkina Faso based on A2 and B2 scenarios of SRES reflect a most likely increase of mean temperatures that ranges from 2.4°C to 3.9°C in 2050 and from 5.7°C to 9.7°C in 2100 for the A2 scenario, whereas the B2 scenario indicates increases of between 2.4°C and 3.8°C in 2050 and between 4°C and 7.1°C in 2100 (Strzepek and McCluskey, 2006).

Given future projections, it can be argued that the impact of climate change has already started. The increasing trend may have severe impact on human being and nature. Indeed, increased heat is expected to reduce crop yields and increase levels of food insecurity even in the moist tropics, it is predicted that during the next decade, millions of people, particularly in developing countries, will face major changes in rainfall patterns and temperature variability regimes thereby increasing risks in the agricultural sector (IPCC, 2007). In general, temperature increase and rainfall decrease may lead to high disturbance on agricultural systems (Dyson, 2009).

The decrease of cold spell duration and the increase of warm spell duration combined to the increase of consecutive dry days and to decrease of consecutive wet days, refer to a study realized by Dai (2011) showing that warming accelerates land-surface drying by an increase of evaporation, and this increases the potential incidence and severity of droughts, which were observed in many places worldwide. Therefore, there is a risk for the Massili basin to experience severe droughts in the future if the trend in WSDI is ongoing.

Farmers are aware of climate change and their perceptions are in agreement with the observed trends in precipitation and temperature. However, for this population, the minimum temperature is decreasing which is not reflected by the analysis of daily minimum and maximum temperature displayed on figure 24a and figure 24b which means that peasants are not aware that the climate change is increasing both the maximum and minimum temperature

4.5 Conclusion

Since climate change is unavoidable, it is important to understand the past trend of its patterns at local scale which will serve as precursor for accurate adaptations strategies and options for better land management. The purpose of this paper is thus to present the climate variability and peasants perception of climate change in the Massili basin This work is realized using daily data of rainfall, minimal temperature and maximal temperature from a 52 years record (1961- 2012). Farmer interviews were also used to analyse the peasant's perception of climate change in the context of observed climatic data. This study provides a comprehensive analysis with regards to the temporal patterns of changes in precipitation and temperature. The general finding that emerges from this study is that high variability of rainfall and temperatures have prevailed in the basin. Intensity and frequency of extreme precipitation and temperature events are increasing. Although the annual rainfall remains almost stable, the rainfall season is becoming shorter with more intense events. In addition, the occurrence of dry spell is obvious. In general peasant's perceptions on climate change corroborate the observed trends. For instance, their affirmation of never experiencing the flood like those of 1st September is true in this sense that over the fifty years of observation, no precipitation amount recorded has ever reached this quantity. Climate change in the Massili basin is univocal and the effectiveness of adaptation strategies will depend on the availability of relevant knowledge on the area and the climate pattern. Climate variability analysis will constitute the base for the development of adaptation strategies through the implementation of early warning system. For instance, the increase in the dry spell length found in this study need to be considered in adaptation plans as it may impose challenges for agricultural systems (Sivakumar, 1991; Laux et al., 2008). Some adaptations strategies such as supplemental irrigation need to be taken into consideration and if considered well implemented.

5 CHAPTER V: ESTIMATION OF LOUMBILA DAM WATER BALANCE

The accurate assessment of water balance is an indispensable prerequisite for water resources modeling. The Loumbila dam is mainly used for Ouagadougou water supply, irrigation and public work. The estimation of a dam´s water balance requires the computation of many components such as the dam inflows, the water needed for irrigation, the withdrawals for water supply systems, the water needed for the public work and the infiltration on the dam site. For this study, data on water supply withdrawal, public work and infiltration was available and provided by the national agency of water and sanitation (ONEA). However the Loumbila dam is located in an ungauged basin where the main inflow to the reservoir is not monitored. Moreover, there is no data on the market gardening water requirement. Thus, the reconstitution of the dam inflows and the estimation of the irrigation water requirements will be an important step in the estimation of the water balance. This chapter presents both an attempt to reconstitute reservoir inflows in an ungauged basin and estimate the irrigation area.

5.1 Derivation of water balance component

The Loumbila dam water budget was estimated by computing the dam storage which is the difference between all inflow and outflow water volumes. The input components of the Loumbila dam are inflow at the dam upstream and precipitation on the reservoir. The output components are water withdrawal for irrigation, water supply, municipal purpose, evaporation and release volume. The remaining parameter constitutes the change due to the difference between inputs and outputs. For the Loumbila dam, groundwater recharge and infiltration are neglected as the dam is characterized with low seepage capacity. Therefore, the components of the Loumbila reservoir water balance are rainfall over the reservoir, surface runoff from the catchment area, outflow from the dam, evaporation from the reservoir, change in reservoir storage and withdrawals for gardening, water supply and municipalities. The water balance of the reservoir is expressed by the following hydrological equation:

$\Delta Vs = (Vqi + Vp) - (Vmg + Vws + Ve + Vm + Vqr)$ (14) Where:

ΔVs = Storage volume of the reservoir.

Vqi = Discharge that inflow to the reservoir.

Vp= The monthly precipitation that fall to the reservoir.

Vmg = Volume of water extracted for market gardening.

Vws = Volume of water extracted for Water supply.

Ve = The monthly evaporation from the reservoir.

Vm= Volume of water extracted for Municipalities.

Vqr= discharge that out from the reservoir.

The unknown components in the water balance equations are the inflow discharges into the reservoir and the Volume of water extracted for market gardening which will be estimated in the following sections. The estimation of the inflow volume will involve regression analysis while the estimation of water extracted for market gardening will involve estimation of the market gardening area through digitalization of aerial photo and CROPWAT modeling.

5.1.1 Reconstitution of Loumbila dam inflow.

The lack of inflows data contributes to the characterization of the Loumbila basin as ungauged. Owing to the key role of this hydrological data in dams' water balance estimation, the reconstitution of the inflows is mandatory. However accurate estimation of hydrologic variables at ungauged sites is still a significant challenge that the hydrologic community is facing nowadays.

5.1.1.1 Methodology on Prediction in unguaged basin

An ungauged basin is defined as a basin without past hydrological observations. Catchments that are poorly gauged are also broadly considered as ungauged basins. Hydrological data is required for sustainable water resources planning and management to enable quantification of water quantity and quality (Oyebande, 2001). Indeed, without data, no model or study can be verified and hypotheses will remain unproven. Management of water resources described above shows the importance of observed hydrological time series. Many basins worldwide are ungauged . Indeed, predicting water runoff in ungauged watersheds is vital for sustainable water resources assessment and allocation at basin scale. However availability of accurate hydrological time series still constitutes a challenge, mainly in developing countries where socio-economic or political reasons result in data scarcity (both spatial and temporal data lack and gaps). The main method for predicting streamflow in ungauged basins could be summarized into five groups: spatial proximity, similarity, model averaging, parameter regression and regional calibration.

- **Low-cost solution or spatial proximity** consists in transferring gauged basin data to a neighboring ungauged basin assuming that climate and catchment characteristics vary only smoothly in space. Proximity is usually defined on the basis of distances between the catchments outlets or catchments centroids. It is also possible to use the geostatistical distances, which account for the nestedness of the catchments. Young (2000) demonstrates that the approach often produces unreliable result.
- **Similarity:** this approach is almost similar to the previous one as it consists in transferring also gauged basin´s parameters to an ungauged analogue basin. Two basins are considered similar when the climate and the watersheds ´characteristics for both catchments are the same. The notion of similarity may differ from studies. Indeed, Kokkonen and Jakeman (2002) transferred the entire parameters set from a catchment with the most similar elevation to the catchment´s outlet. Mc Intyre et al. (2005) defined the most similar catchment in terms of catchment´s area, standardized annual average precipitation, and baseflow index. Other studies used a larger number of characteristics, such as Parajka et al. (2013) who defined the similarity by mean catchment elevation, areal proportion of porous aquifers, lake index, stream network density, soils, geology and land use, and Zhang and Lu (2009)who identified the most similar catchments in terms of catchment´s area, mean elevation, slope, stream length, aridity, woody vegetation fraction and plant-available water-holding capacity. Furthermore, Goswami et al. in the region, and the degree of similarity of the gauged and the ungauged sites (Littlewood, 2003). All these studies were generally ‘‘limited in terms of statistical accuracy’’ (Sefton and Howarth, 1998), producing rather poor results particularly if the analogue catchment is not nested with the target catchment.
- **Model averaging**: sometimes a weighted combination of the parameter sets from more than one donor catchment is used, where the catchments are selected either based on proximity, catchments´ characteristics or both (Goswami et al., 2007; Kim and Kaluarachchi, 2008; Seibert and Beven, 2009). One can either assume a fixed subdivision

of the region into groups of catchments or, alternatively, allow each catchment to have its own group of donor catchments (Burn and Boorman, 1993).

- **Regression**: The technique of multiple regressions has been applied extensively, primarily to estimate event and unit hydrograph characteristics, a good description of which can be found in Sefton and Howarth (1998). The first step of this approach is to establish empirical relationship between calibrated model parameters to catchment characteristics in order to estimate the ungauged catchments model parameters. Then the parameters obtained are used to simulate the ungauged basin´s time series. Several authors have used this method to predict streamflow (Fennessey and Vogel, 1990; Smakhtin, 1997; Sugiyama et al., 2003). One requirement of regression method is that the relationship between the model parameters and the catchment characteristics should be hydrologically justifiable to give confidence for extrapolation to ungauged basins. However, due to unrepresentative catchment characteristics and identifiability issues of the model parameters (Blöschl et al., 2013) this is not always the case (Sefton and Howarth, 1998; Fernandez et al., 2000; Peel et al., 2000).
- **Regionalization:** based on spatial proximity (Hundecha and Bárdossy, 2004; Merz and Blöschl, 2004), the method consists in calibrating the coefficients of relation between gauged basin´s model parameters and catchment characteristics. Indeed, a linear transfer function is applied to relate parameters values to land use, soil types, size, slope and shape of catchments. Thus regionalization involves correlating the conceptual parameters to catchment characteristics from several gauged catchments (Nathan et al., 1990; Shaw, 1996; Funke et al., 1999). Uncertainties in regionalization method may occur as geographical proximity between catchments does not necessarily mean close functional behavior. One of the regionalization approach challenge is therefore the requirement of data from many catchments in the same region (Kokkonen, 2002) as this may be accompanied by loss of accuracy due to optimization error, adjustment of boundary conditions and use of transfer functions.

In this study, the fundamental approach adopted to reconstitute the Loumbila dam inflows is the regression method defended by many authors (Fennessey and Vogel, 1990; Smakhtin, 1997; Sugiyama et al., 2003). This method is based on estimating model parameters for gauged basin which are then used in relationships with catchments´(both gauged and ungauged) characteristics to estimate parameters for ungauged catchments. Finally the estimated ungauged basin parameters are used for modeling the ungauged basin´s streamflow. This involved hydrologic models whose selection criteria is based on the knowledge of the hydrologic system and data availability. GR2M and Yates which have been widely used in the Nakanbe basin were selected (Paturel et al., 2003; Diello et al., 2005; Karambiri et al., 2011).

- **Characterization of the models**

- **GR2M model**

GR2M (Génie Rural à deux paramètres au pas de temps Mensuel) is a rainfall-discharge model originated from Cemagref (France) at the end of the year 1980. The performance of the model was frequently improved through the successive review of the different versions done by Kabouya (1990), Kabouya and Michel (1991), Makhlouf (1994), Mouelhi (2003) and Mouelhi et al. (2006). It is a model with two parameters (GR2M) built from the variants of models inspired from the GR4J model. This simple conceptual specialized, model at monthly time step runs with two parameters X1 which regulate respectively the precipitation (P) and the Potential Evapotranspiration (PET) and X2 which controls the discharge flowing from S reservoir. The model input variables are P, ETP and the WHC (Water Holding Capacity) or A. As intermediary and output variables it can be enumerated the levels of reservoirs H and S, the ETo (Reference Evapotranspiration) and the Discharge Q. Its structure associates a production reservoir and a routing reservoir with also an opening to the outside other than the atmosphere environment. Those tree functions allow the simulation of the watershed (Perrin et al., 2003). P and PET are modulate by the first parameter X1 which can be optimized (0 < X1 < 1). Two new inputs (P' and PET') are thus obtained of which it could be subtracted a same quantity U with U described as followed:

$$U = \frac{P'.PET'}{(\sqrt{P'}+\sqrt{PET'})^2} \qquad (15)$$

Thus P_n= P'-U and E_n = PET'-U (16)

At the beginning of the modeling it is assumed that the reservoir level is H and one part of the rainfall P_n increases this levelat H_1 (Malkouf, 1994).

$$H1 = \frac{H+AV}{1+\frac{H1}{A}} \quad \text{Where } V = \text{TANH}\frac{Pn}{A} \quad (17)$$

E_n allows increasing the level of the reservoir from H1 to H2 for the next time step.

$$H2 = \frac{H1(1-W)}{1+W(1-\frac{H1}{A})} \quad \text{Where: } W = \text{TANH}\frac{En}{A} \quad (18)$$

The reservoir of gravitational water received $\frac{4}{5}$Pe and its level pass from S to S1=S+$\frac{4}{5}$Pe. The remaining $\frac{1}{5}$Pe flows directly. The reservoir of gravitational water provides a runoff under the shape of Q_g=X_2.$S_1$with S1 the second parameter. The total runoff is thus:

$$Q = Q_g + \frac{1}{5}Pe \quad (19)$$

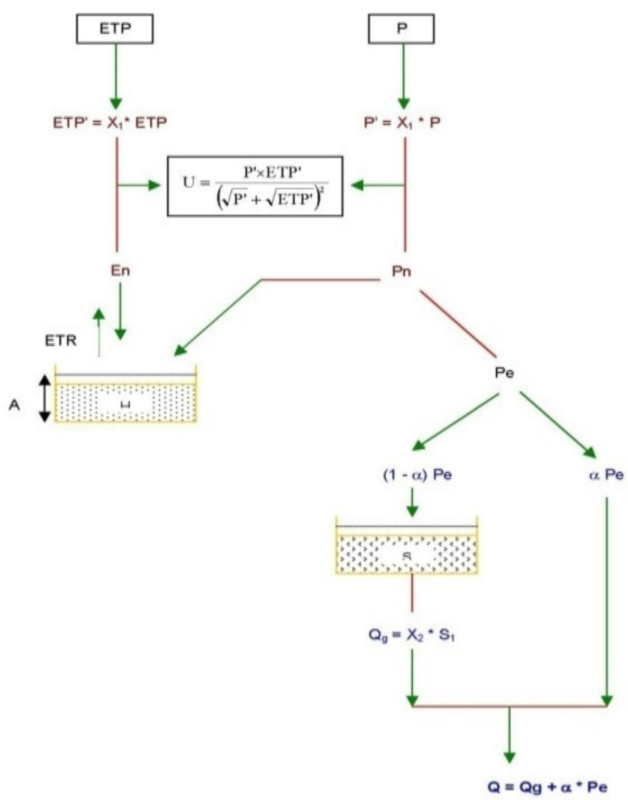


Figure 26: GR2M model structure

This model does not take into account the dynamic of the environment. The simulation is done by considering that hydrological characteristics are stables in the time but in reality it cannot be said that hydrological processes are stable while regarding the environmental modifications in the sahelian context, especially with respect to the surface characteristics. Some others such as Diello (2007) have integrated the environment dynamic aspect in the GR2M model.

GR2M is a simple model with a little number of parameters. The Nash coefficient which testifies the performance of calibration and validation could be increased by adjusting the reservoir capacity. Application of GR2M has shown some goods results on the West and Central Africa basins (Ouedraogo et al., 2006; Servat et al., 1997). GR2M was applied by Diello (2007) in a Sahelian context with the aim to evaluate its performance. The keys findings are that the climatic break happened in the sahelian regions around 1970 have modified hydrological regimes of streams. Most of rainfall and discharge data series have seen their average changed after this period. The response of watershed to the pluviometric impulse has also changed so that at same rainfall, the runoff is higher after 1970 than before. Diello (2007) concluded that it is so primordial to be sure that simulation models of rainfall-runoff fluently used in the Sahelian context will reproduce those new hydroclimatic conditions. The evaluation of GR2M performances on five watercheds (Alcongui, Diongoré, Koriziena, Tera and Wayen) was carried out. As result the author found that except to the station of Diongoré, the fourth stations have known an increase in the runoff coefficient after 1970 and the rainfall has decreased globally in the Sahel zone. Applied to the sahelian context GR2M shown: a calibration relatively correct in general with a decrease of performance for the periods including the climatic break happened in 1970; a non satisfactory validation characterized by NASH criterion generally less than 50% with some time negative NASH and finally some important gap between the observes modules and the simulated modules whatever the source of rainfall used (Diello, 2007). The Nash coefficient which testifies the performance of calibration and validation could be increased by adjusting the height of the reservoir.

- **Yates model**

The model created by Yates in 1996 is an empirical model based on a water balance developed to quantify discharge. This hydrological model water balance component is composed by five parameters which are: direct runoff, surface runoff, sub-surface runoff, maximum catchment water-holding capacity and base flow (Yates, 1996). Yates is a conceptual model that operates on a monthly time step at a basin scale. The objective of this model is to predict discharge. Requiring rainfall (P) and potential evapotranspiration (ETP) data as inputs, the model provides simulated discharges as output. The Yates model has three parameters: S_{max} or maximal soil water content capacity of the watershed (between 500 and 2400 mm); α which is a coefficient related to the soil water storage (between 0.2 and 8mm/j) and ε a coefficient that determines the influence of the soil water content on runoff (between 1 and 5). The three parameters are derived from Holdridge (1947) climate-vegetation classification scheme. It is based on the continuity equation and the relative variation of soil water content to represent the surface and sub-surface runoff and the evaporation. Performances of the Yates model have been experimented through a study realized by Ouédraogo (2001). Indeed the author has analyzed the results of different hydrological model simulating runoff at monthly time step and at 0.5*0.5 degree grid scale. According to Ouédraogo (2001), Yates model seems to be effective for watersheds in West and Central Africa.

The water balance of the model is based on equation 20:

$$S_{max}\frac{\Delta z}{\Delta t} = P(1-\beta) - R_s(z,t) - R_{ss}(z,t) - E_r(ETP,z,t) - R_b \qquad (20)$$

P: Precipitation (length/time)

R_s : Surface runoff (length/time)

R_{ss} : sub-surface runoff (length/time)

R_b: delayed runoff (length/time)

$R_d = \beta P$: Direct runoff (length/time)

S_{max} : maximal soil water content capacity(length)

Z: relative water content in regard to S_{max} ($0 \leq z \leq 1$)

Δz : relative variation of water content

Δt : time step of the computation (monthly in our case)

β : Fraction of the rainfall for direct runoff

Total runoff is estimated as follow: $R_t = R_s(z,t) + R_{ss}(z,t) + R_b + R_d = Q$ (24)

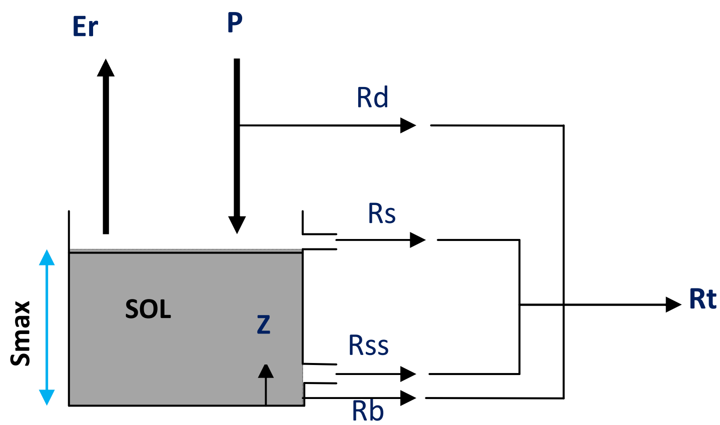


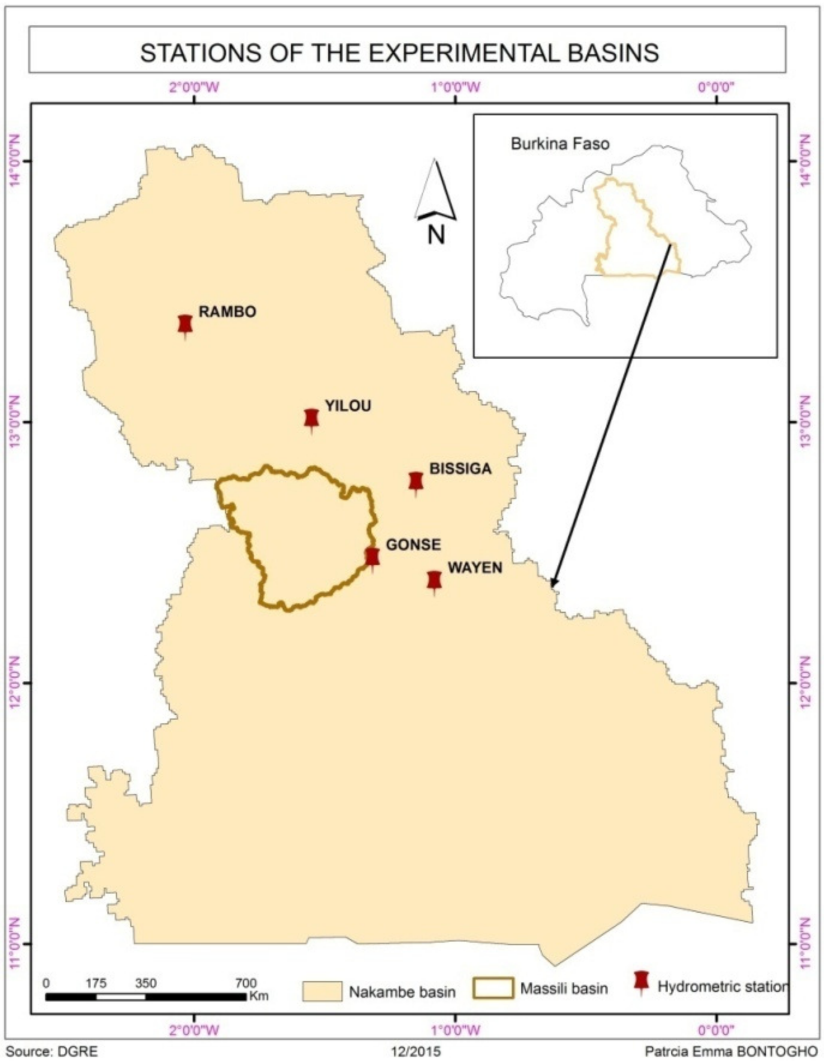
Figure 27: Schema of Yates functioning

Table 20: Summary of GR2M and Yates characteristics

	GR2M	**Yates**
Author and dates	Makhlouf 1994	Yates 1997
Model type	Conceptual specialized	Empirical model
Parameters	**X_1**: control input P and ETP **X_2**: control discharge at reservoir S outlet	**Smax**: maximum storage capacity **α:** coefficient related to the soil water storage (between 0.2 and 8mm/j) **ε:** coefficient that determines the influence of the soil water content on runoff (between 1 and 5).
Soil water reservoir characterized by WHC	**Soil reservoir (H)**: production function characterized by WHC or A. **Gravities water reservoir**: transfer function	Surface and subsurface runoff are represented by a continue function of soil humidity
Input variables	P, ETP, WHC or A	P, ETP
Output variables	Discharge	Discharge

- **Calibration and validation of the referential watershed**

In the framework of this study, five (05) gauged watersheds called referential watersheds; Gonse, Rambo, Bissiga, Wayen and Yilou; have been chosen based on their proximity to the target watershed (Loumbila dam) and the availability of discharge data. Most of the referential watershed is located on the Northern part of the basin. The figure 28 shows the location of the experimental watersheds compared to Massili basin. Table 20 displayed the coordinates and characteristics of the gauged watershed.



Figures 28: location of the referential watersheds stations.

It is relevant to underscore that the experimental watershed is a sub-basin of Massili basin. In order to determine the parameters of the five referential watersheds GR2M and Yates models will be used. The choice of those models is guided by the fact that they are simple models with two inputs data (rainfall, Potential Evaporation). GR2M and Yates models are calibrated and validated for each gauged basin. The calibration was performed manually by changing model input parameter values to produce simulated values that are within a certain range of the measured data as highlighted by Balascio et al. (1998). The calibration process was performed by comparing observed and simulated values to determine the best result. The model performance was evaluated using Nash goodness-of-fit statistics. The Nash-Sutcliffe efficiency index Ef is a reliable statistic widely used for assessing the goodness-of-fit of hydrologic models. Ef ranges from 1 to -∞, where Ef =1 indicates a perfect match of simulated to measured data; Ef = 0 corresponds to the model predictions matching the mean of the measured data; a negative Ef shows that the measured mean is a better predictor than the model predictions. The Nash index increases to 100% for perfect simulation. The success of the use of this index in many reports shows how useful this tool is in assessing the efficiency of a model, e.g., Erpul et al. (2003) used the index to assess nonlinear regression models of sediment transport. Merz and Blöschl (2004) used the index in the calibration and verification of catchment model parameters, while Kalin and Hantush, (2003) used the index as a goodness-of-fit indicator for a storm event model. Ef has also been used in a wide range of continuous moisture accounting models as reflected in Birikundavyi et al. (2002), (Johnson and Hamilton, 1988), and (Downer and Ogden, 2004). The ASCE Task Committee on Definition of Criteria for Evaluation of Watershed Models of the Watershed Management (ASCE 1993) recommends the Nash Sutcliffe index for the evaluation of continuous moisture accounting models. The use of this index for a wide variety of model types indicates its flexibility as a goodness-of-fit statistic and it is the reason for its use in this study. Ef is calculated as:

$$NASHindex(\%) = 100[1 - \frac{\sum_i^n (Q_{obs}^i - Q_{cal}^i)^2}{\sum_i^n (Q_{obs}^i - Q_m^i)^2}] \quad (25)$$

Table 21: Characteristics of the referential watersheds

Refrential Watershed	Period of data	Time-step	Upstream area (km^2)	Perimeter (km)	Mean WHC (mm)	Latitude	Longitude
Wayen	1975-2005	Monthly	20159	776.57	110	12.38	-1.05
Yilou	1973-1982	Monthly	10631.57	485.92	93	13.02	-1.55
Gonse	1975-2006	Monthly	2612	218.52	92.81	12.47	-1.32
Bissiga	1976-2006	Monthly	3741.18	311.12	121.03	12.75	-1.15
Rambo	1983-2006	Monthly	2375.63	220.63	132.59	13.59	-2

- **Estimation of the experimental watersheds parameters**

The following step has employed regression method to establish relationship between watershed model parameters and watershed climate characteristics. Using the R software, multiple regression analysis was applied to derive from gauged and ungauged sites, equations relating physical basin parameters to climatic basin characteristics. Thus, multiple linear regression analysis was performed according to standard statistical texts (Haan, 1977) to relate the physiographic and climatological characteristics (P, and aridity index) to the referential catchments model parameter (X_1, X_2, Smax). This enables estimation of watershed model parameters at the ungauged sites (experimental watershed). A set of parameters combination was made to determine the combinations resulting in the best R-square. Multiple R^2 and adjusted R^2 were applied to estimate the model accuracy. The correlation coefficient R^2 reveals the accuracy with which the experimental watershed parameters (X_1, X_2 and S_{max}) could be predicted from the referential watershed variables. Multiple R^2 is widely employed for detecting the degree of fitting between values.

Table 22: Characteristics of the experimental watershed

Experimental Watershed	Period	Time-step	Upstream area (km^2)	Perimeter (km)	Mean WHC (mm)	Latitude	Longitude
Loumbila	1976-2006	Monthly	2120	188	92.81	12.47	-1.32

5.1.1.2 Results

- **Calibration and validation of the referential watersheds**

The tables 23 and 24 depict respectively the results of the experimental watershed parameters obtained from the modelling with GR2M and Yates model. During the calibration and validation period, the Nash-Sutcliffe coefficient (Ens) was greater than 60 and these results suggest that the calibrated model can accurately simulate the streamflow in the five gauged basins. Figure 29 and 39 show the simulations curves for the five referential watersheds.

Table 23: GR2M model parameters and Nash performance criteria for calibration and validation for referential watershed

Watersheds	Discharge record	Calibration period	Calibration Nash (%)	Validation period	Validation Nash(%)	X_1	X_2
Wayen	1975-2005	1976-1982	68.8	1983-1991	68.1	448.65	0.52
Yilou	1973-1982	1974-1978	65.0	1979-1981	73.1	61.48	0.14
Gonse	1975-2006	1979-1985	80.9	1986-1998	62.6	334.09	0.33
Rambo	1983-2006	1984-1986	88.1	1986-1991	60.4	90.13	0.35
Bissiga	1976-2006	1977-1982	60.9	1987-1993	74	638.17	0.63

Table 24: Yates model parameters and Nash performance criteria for calibration and validation for referential watershed

Watersheds	Discharge record	Calibration period	Calibration Nash (%)	Validation period	Validation Nash (%)	Smax (mm)
Wayen	1975-2005	1977-1982	72.1	1983-1988	66.1	527.04
Yilou	1973-1982	1973-1974	70.5	1977-1981	73.1	2400
Gonse	1975-2006	1987-1990	62.9	1998-2003	61.1	997.28
Rambo	1983-2006	1984-1988	64.1	1989-1992	62.4	844.38
Bissiga	1976-2006	1980-1985	66.2	1986-1992	81.6	956.61

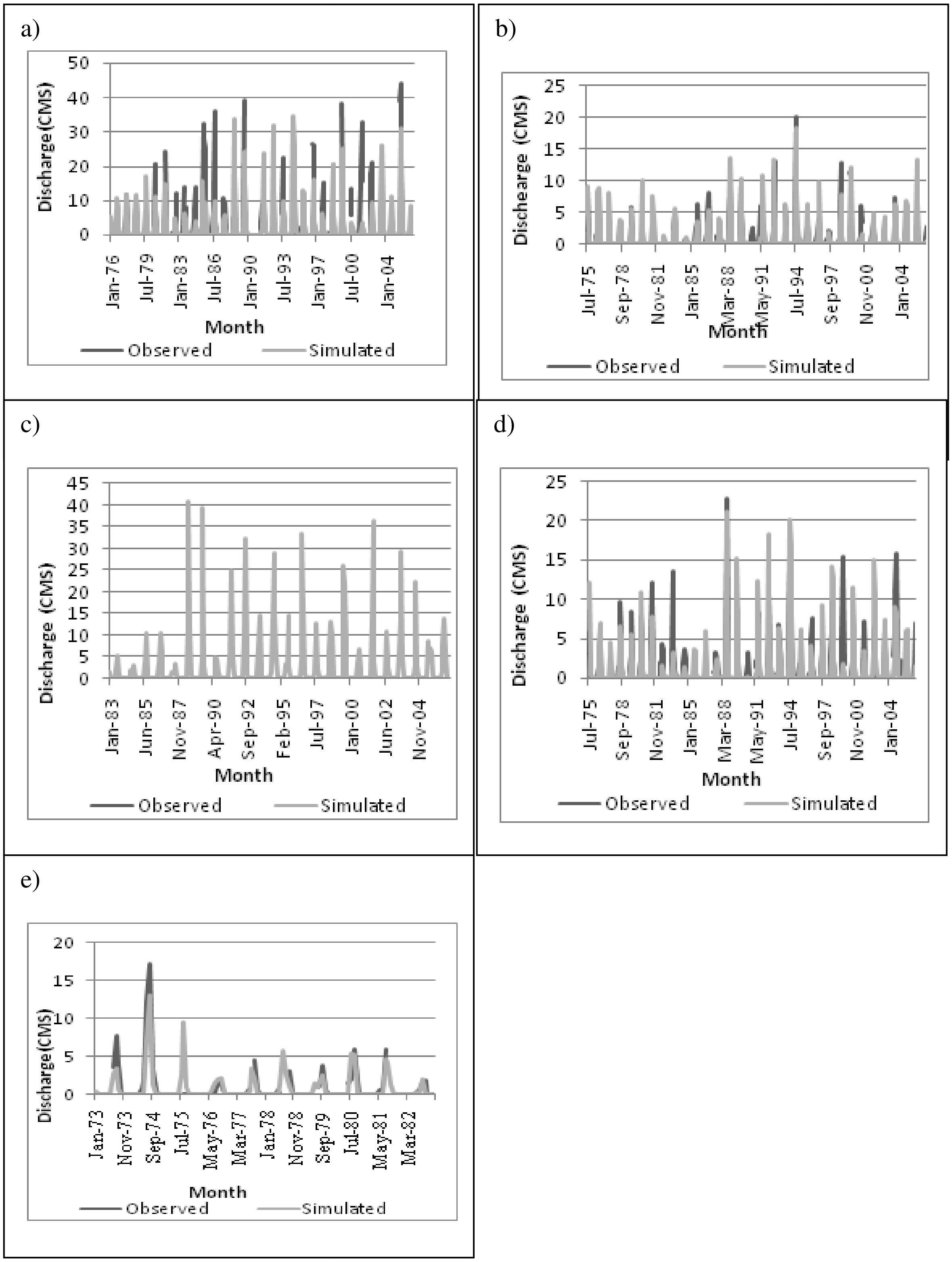


Figure 29a) Monthly simulation by GR2M of Bissiga station discharge; b) Monthly simulation by GR2M of Gonse discharge; c) Monthly simulation by GR2M of Rambo discharge; d)Monthly simulation by GR2M of Wayen discharge; e) Monthly simulation by GR2M of Yilou station discharge.

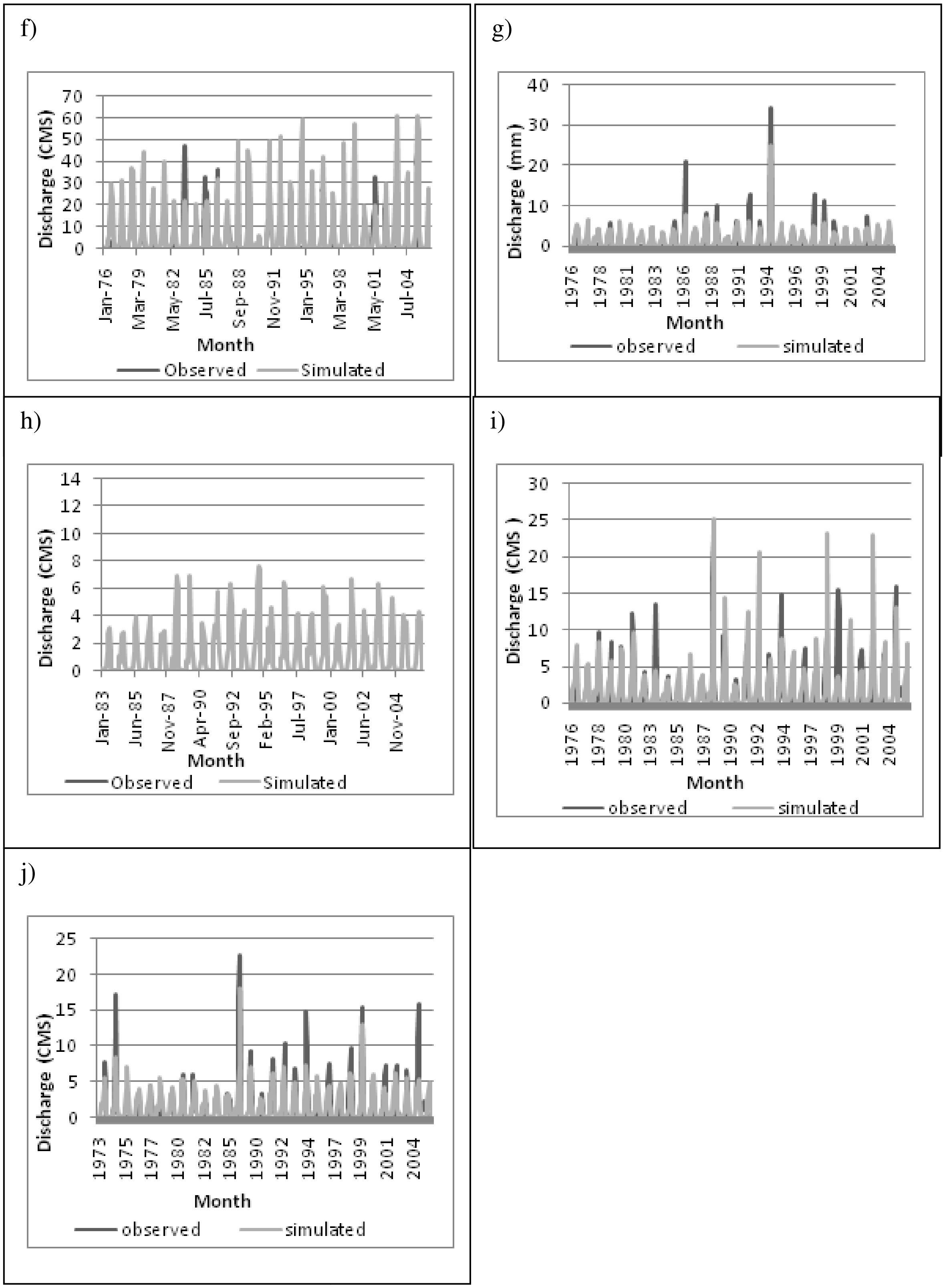


Figure 30f) Monthly simulation by GR2M of Bissiga discharge; g) Monthly simulation by Yates of Gonse station discharge; h) Monthly simulation by Yates of Rambo discharge; h) Monthly simulation by Yates of Wayen discharge; i) Monthly simulation by Yates of Yilou discharge.

The table 25 recapitulates the results of parameters obtained through GR2M and Yates modeling (X_1, X_2, Smax) and the parameters obtained through the multiple linear regression model between referential watersheds and experimental watershed (X_1', X_2', S_{max}). A critical analysis of the error margin shows that the margin error between real and estimated values of X_1 is high. However, the margin error between estimated and real values of X_2 and S_{max} is less than 1 (< 1mm) for former and less than 30 (< 30mm) for the later. It can be concluded that linear regression model allows a satisfactory representation of X_2 parameters while the representation of Smax' and X_1'are respectively slightly and highly different from the original values.

Table 25: Experimental watershed parameters estimation

	X_1	X_1'	Error margin	X_2	X_2'	Error margin	S_{max} (mm)	S_{max}'(mm)	Error margin
Wayen	448.65	443.66	4.99	0.52	0.51	-0.008	527.04	543.07	-16.08
Yilou	61.48	57.02	4.46	0.14	0.15	-0.986	2400	2382.85	-17.15
Gonse	334.09	302.74	31.35	0.33	0.37	0.045	997.28	1004.80	-7.52
Bissiga	638.17	632.61	5.56	0.63	0.61	-0.016	956.62	972.26	-15.65
Rambo	90	76.99	13.01	0.35	0.41	-0.008	844.39	877.74	-33.35
Loumbila		266.58			0.34			1332.12	

Table 26: Value of R^2 from Linear multiple regression

Variables	X1	X2	Smax
Multiple-R^2	0.96	0.93	0.89
Adjusted R^2	0.92	0.59	0.67

- **Reconstitution of the experimental watershed inflow**

The figure below shows the results of the inflow obtained from the modelling with GR2M model.

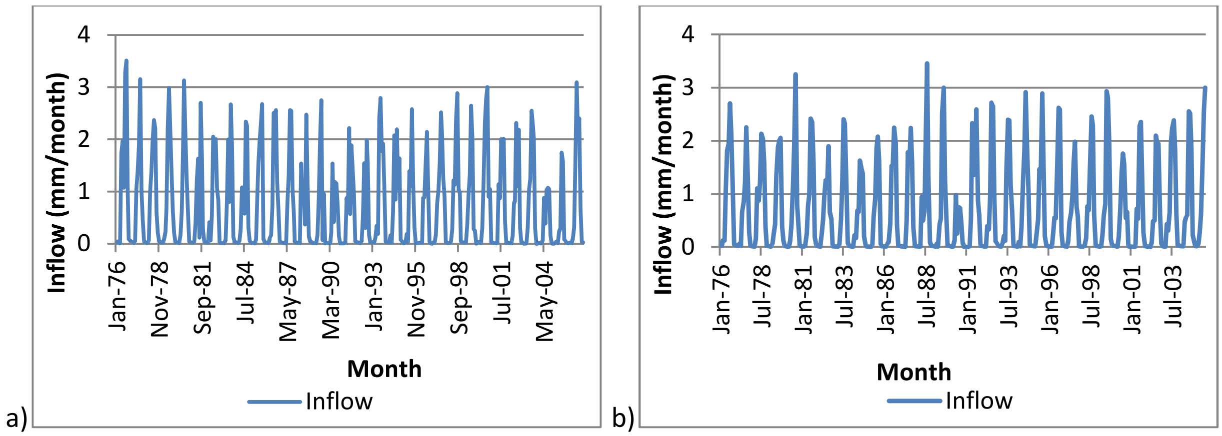


Figure 31: a)Loumbila dam inflow from GR2M over the period 1976-2007; b) Loumbila dam inflow from Yates over the period 1976-2005

For the estimation of the water balance components, the values of discharges obtained by Yates modeling will be used. This research points the possibility of combining gauged basins and unguaged basins characteristics to derive unknown flows for ungauged basins. Therefore, this part contributes for the Predictions in Ungauged Basins. The results presented demonstrate how regression method can be achieved and applied for the reconstitution of flows in an ungauged basin.

5.1.2 Estimation of irrigation water needs

The world over, the irrigation sector is the largest user of water as almost 80 percent of the water in the world is withdrawn for this activity. Thus irrigation plays a key role in society as it offers opportunities for greater livelihoods security and poverty reduction. Nonetheless, scarce water resources and growing competition for water will reduce its availability for irrigation. The aim of irrigation is to compensate crop water insufficiencies to maintain crop evapotranspiration (ETc). Aforementioned, the Loumbila dam is surrounded by water gardening practice which is informal and not monitored. The aim of this part is to estimate crops water requirements around Loumbila. Irrigation being part of a reservoir balance system, estimating irrigation water requirements accurately is important for a dam´s water management. The first step will involve the identification of the crops around the dam and the estimation of the irrigated area spatial extent. Then applying CROPWAT model, the crop water requirement will be estimated.

5.1.2.1 Methodology

- **Assessment of Loumbila dam market gardening area and identification of crops.**

The objective of this part is to develop a methodology for estimating the spatial extent of Loumbila dam market gardening area. Several methods were developed worldwide to estimate area. For instance the joint use of satellites images and GPS allows KABRE (2000) to track a portion of the Bagre dam water area during the dry season. Calera et al. (2004) used remote sensing data and GIS to evaluate surfaces of the spatial crop distribution in each growing season and to follow up the development of the area.

Irrigated areas are defined as surfaces developed for irrigated crops. Potential total irrigated area in Burkina Faso is estimated to about 233 500 ha and more than 200000 persons are involved in the water gardening. Most of Burkina Faso irrigated perimeters are settled near water bodies. Based on the size of the perimeters, the following classification was derived:

- The big perimeters (12 000 ha): it includes generally perimeters of size greater than 400 ha. The main crop is rice but maize, wheat sorghum and soja are also cultivated. The management cost is almost 10 million F CFA.
- Mean perimeters (3000 ha): They include small irrigated area at dam downstream (50 ha in average). The irrigation is the gravity system and the exploitation are household (0.10 to 0.25 ha).
- The small irrigation (4500 ha): They include the small village irrigation for rice, maize and beans and the individual irrigation (less than 1 ha) for the water gardening and arboriculture. From this type of irrigation, the village irrigation is 500 ha on the 4500ha (APPIA).

The method adopted in this study to estimate the irrigation area extents involves remote sensing and field work. Indeed, aerial photographs were used to delimit the market gardening area extents around the Loumbila dam. After classification, images processing was done with the ERDAS Imagine software. Classification Methodology and Results Temporal monitoring of the Normalized Differences Vegetation Index (NDVI) provides a good indicator of the phonological evolution (Moran et al., 1997). Later on, the area and coordinates of eight (08) targeted zones was selected for the field visit in order to check if the area estimated through the field work corresponds to the area retrieved from the aerial photographs. GPS records through field work were also employed to track the irrigated area and the type of crops around the dam. Indeed a GPS team was deployed on the field to identify the type of culture and track their area in each zone. The Fieldwork allowed also checking the accuracy of the classified image. This method being very expensive it was impossible to extend the study over the entire market gardening area. Subsequently, eight zones were selected as sampling area. This sampling area was sufficient to allow a significant estimation of the market gardening area by extrapolation and the identification of the type of culture. Data collected by GPS were directly transferred on a computer and proceed with Excel. Then the resulting table was integrated in ARCGIS 10 in order to view on a map (source plan of lot Loumbila dam) the coordinate census on the field. These points gave an idea about the distribution of crop around the dam. The additional data used to establish the market gardening map are the BNDT/IGB and Google earth images. Crops and natural vegetation have been discriminated by means of the temporal evolution of NDVI based on differences in phonological development (Gopal et al., 1999).

- **Estimation of crop water requirement**

- **Description of CROPWAT model.**

CROPWAT is a computer program for irrigation planning and management, developed by the Land and Water Development Division of FAO (FAO, 1992). CROPWAT 8.0 allows calculation of crop water requirements and irrigation requirements based on soil, climate and crop data. In addition, the program allows the development of irrigation schedules under different conditions and the calculation of scheme water supply for varying crop patterns. CROPWAT 8.0 can also be used to evaluate farmers' irrigation practices and to estimate crop performance under both rainfed and irrigated conditions. The computation of irrigation water requirements requires inputs of climatic, crop and soil data.

The climatic input data required are reference evapotranspiration (monthly/decade) and rainfall (monthly/decade/daily). Reference evapotranspiration can be calculated from actual temperature, humidity, and sunshine/radiation and wind-speed data, according to the FAO Penman-Monteith method (FAO, 1998). Climatic data such as mean daily maximum temperature (°C), mean daily minimum temperature (°C), mean relative humidity in (%), mean wind speed in km/day and mean sunshine hour/day can be downloaded from CLIMWAT-database (http://www.fao.org/landandwater/aglw/climwat.stm). This database provides long-term monthly mean climatic data for CROPWAT on 144 countries (FAO, 1993). Crop files provide information about the crop area, crop coefficient at different growth stages, sowing and harvesting data, season length and irrigation duration days. The soil files provided also information about the soils type. However, this tool presents many gaps such as the limit on the type of crop file. Indeed, many crops are not included in the crops file and therefore there is a need to create crops files base on Burkina Faso crop coefficient. In addition, CROPWAT does not possess a system which allows integration of many campaigns for the same culture within the same year. However, most of the crops censuses around Loumbila dam are subjected to two (02) campaigns in the same year. So, this was taken into account for the CROPWAT modeling.

- **Crop water requirement estimation**

The term crop water requirement is defined as the "amount of water required to compensate the evapotranspiration loss from the cropped field". "Although the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration (Allen et al., 1998). CROPWAT was run to estimate the crop water requirements based on the following equation:

$$CWR = ET0 * Kc - Pe \quad (26)$$

Where, CWR is the Crop Water Requirement; Kc is the crop coefficient; Pe is the effective rainfall calculated by USDA soil conservation service method (Obreza and Pitts, 2002).

5.1.2.2 Results and discussion

- **Market gardening area extend and type of crops**

The findings indicate that the total area occupied by the market gardening around the Loumbila dam is estimated to about 177 hectares in 2013. Figure 32 shows the market gardening extents while figure 33 shows the various crops around the dam. Table 27 shows the area occupied by each crop.

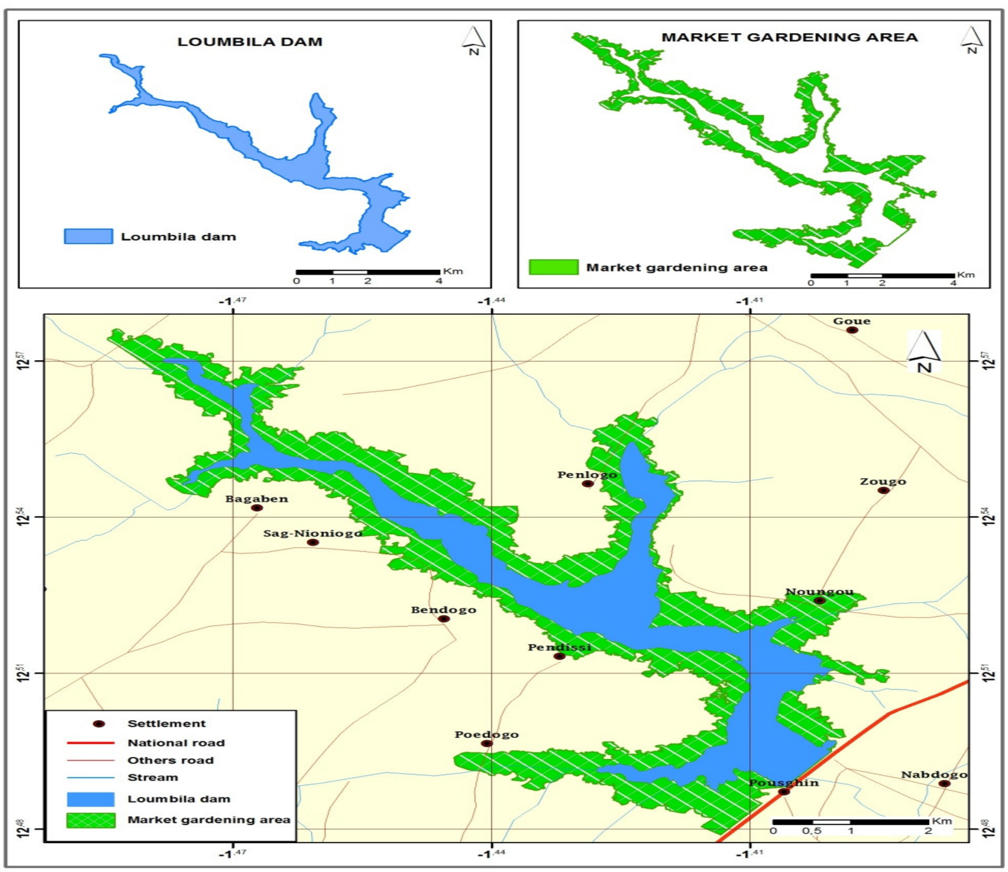


Figure 9: Loumbila dam and water gardening area

Table 27: area occupied by each type of culture and the number of campaign

Type of culture	Tomato	Carrot	Aubergine	Sweet pepper	Bean	Concomber	Sorrel	Onion	Courgette	Okra	Cabbage
Area (ha)	52	26	14	8	11	12	13	19	9	4	2
Number of campaign	2	2	2	2	2	2	2	2	2	2	2
Total					170 (ha)						

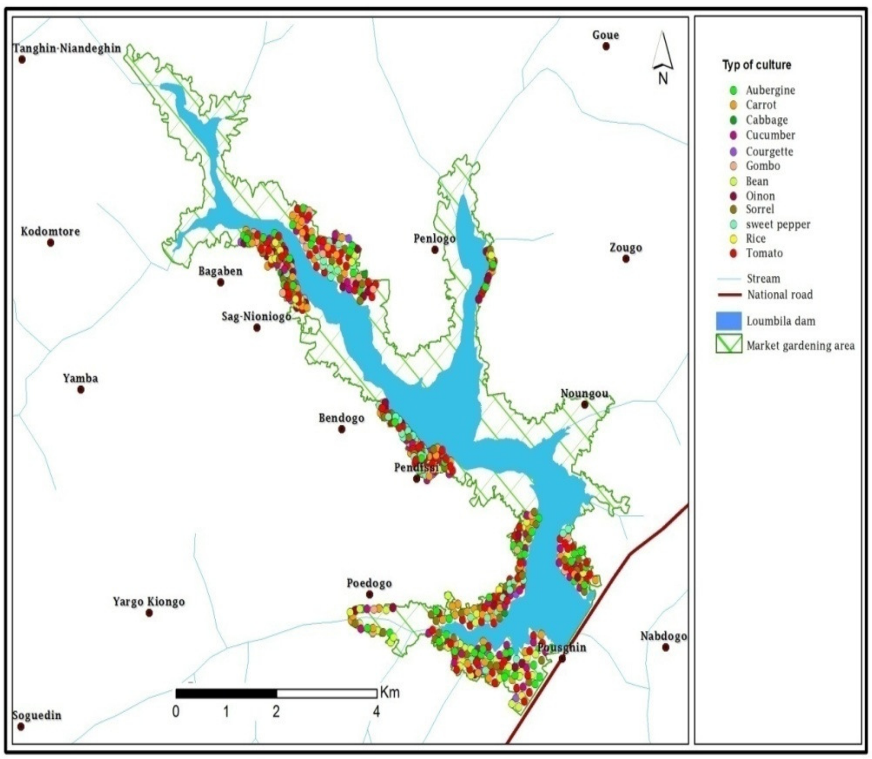


Figure 10:Market gardening areas showing the type of culture in the eight sites.

➢ Market gardening water requirement

The results of the computations of tomato for instance are as obtained in tables 28. This table shows the crop coefficient according to the development stage, the effective rainfall and the crop water needs.

Table 28: Tomato water needs during the campaign

Month	Decade	Kc	ETc	ETc	Effective rain	Irrigation. Requirement
		coefficient	mm/day	mm/decade	mm/decade	mm/decade
May	1	1.15	8.81	79.2	7.5	70.9
May	2	1.15	8.65	86.5	8.4	78.1
May	3	1.15	8.23	90.5	15.4	75.2
June	1	1.13	7.71	77.1	23	54
June	2	1.04	6.68	66.8	29.2	37.6
June	3	0.93	5.54	55.4	35.4	19.9
July	1	0.83	4.44	44.4	43.9	0.5
July	2	0.72	3.49	34.9	51.2	0
July	3	0.67	3.26	35.9	48.4	0
August	1	0.67	3.28	32.8	45.7	0
August	2	0.67	3.26	32.6	44.6	0
August	3	0.67	3.24	35.7	38.1	0
September	1	0.67	3.18	31.8	31.3	0.5
September	2	0.67	3.13	31.3	25.5	5.8
September	3	0.72	3.66	36.6	18.7	17.9
October	1	0.9	5.07	50.7	10.4	40.2
October	2	0.9	5.46	54.6	3	51.6
October	3	0.9	5.38	43.1	1.5	41.1
Total (mm/decade)				919.9	481.4	493.4

Fifure 34 shows the irrigation requierement per decade and Figure 35 shows the graph of the ETo which can be divided into three groups: increase from January to March (from 7.36 to 8.92), decrease from April to September (from 7.95 to 4.75mm/day), increase from September to December (from 4.75 to 6.15 mm/day). The highest value is recorded in March (8.92mm/day); the lowest value is recorded in September (4.75mm/day).

It could be observed that the ETo values increased steadily from 7.11 mmday-1 in January to a highest value of 6.59 mmday -1 in May and declined to 6.38 mmday-1 in June. The decline progressively continued to a lowest value of 3.65 mmday -1 in December. Tomato crop water requirementaround the Loumbila dam increases from the beginning of the season to the end of the cultivation period (October to March).

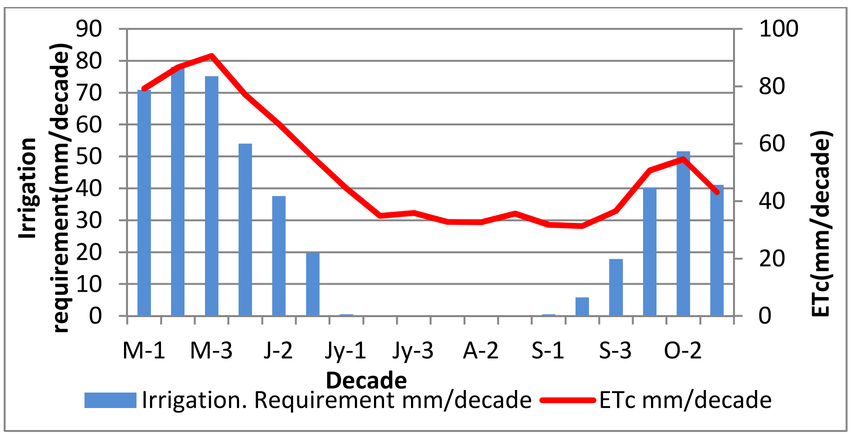


Figure 11: Irrigation requirement and Etc for tomato crop

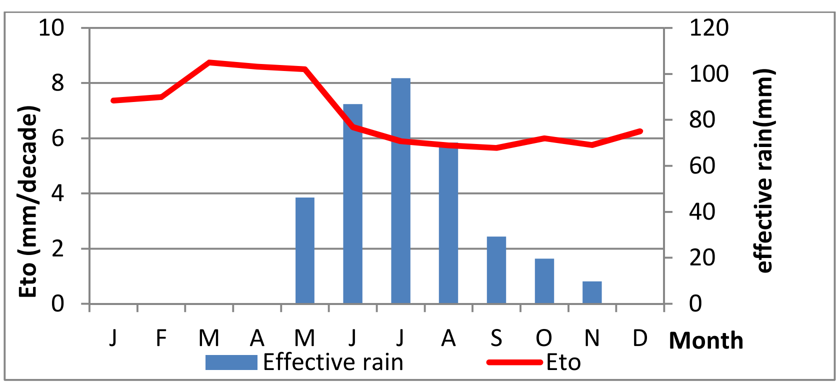


Figure 12: ETo and effective rain for crops

The CROPWAT model allowed estimating the crops water needs. A total amount of 10,462,015.3m ^{3} of water needs was found. Owing to the fact that the water gardening is not controlled by the government (anarchic exploitation), we can assume that the irrigated area does not increase or decrease over the years. Thus, the water needs for the market gardening is supposed to remain stable over the years.

- **Water withdrawal for market gardening**

CROPWAT allows assessing the quantity of water required by the crops around the dam. However in the framework of this study, it is needed to estimate the water withdrawn from the reservoir for the irrigation. In order to estimate the irrigation supply, it is important to take into account the water use efficiency which is illustrated here by the transport efficiency as water withdrawal is greater than crop consumption. The water use efficiency is an indicator often used to express the level of performance of irrigation systems between the source and the crop: it is the ratio between the crop water requirement and the water extracted from reservoirs. In general, values used to calibrate discharge at the source of irrigation techniques, are around: 30 < EI < 70 in surface irrigation and 70 < EI < 90 in irrigation under pressure (van Halsema et al. 2012).

$$\mathrm{WUE} = \frac{\text{Crop Water needs}}{\text{Water extracted}} \qquad (27)$$

The results of the computations are as obtained in tables 24 and figure 33. Table 1 shows the crop coefficient according to the development stage, the effective rainfall and the crop water needs. Figure 33 shows the graph of the ETo which can be divided into three groups: increase from January to March (from 7.36 to 8.92), decrease from April to September (from 7.95 to 4.75mm/day), increase from September to December (from 4.75 to 6.15 mm/day). The highest value is recorded in March (8.92mm/day); the lowest value is recorded in September (4.75mm/day). A total amount of 1.869.141 m^3 was found for the irrigation water needs around the Loumbila dam. Some studies were carried out in Banfora, Sourou and Bagre sites on the estimation of irrigation water needs based on the use of climatic parameters such as potential evapotranspiration, formula of Penmann energy balance, crop coefficient and effective rainfall. Another study realized by SOGREAH (December 1978) was carried out on the Bagre dam. It can be summarized from those studies that for the estimation of water needs, the values notice on the following table could be considered. From those studies, water needs for water gardening located in improved perimeters is estimated to 8000 m^3/ha/year (source: DGRE 2001). The Loumbila dam market gardening extent is estimated to around 177 ha. Thus based on those norms the irrigation water needs around this dam must be around (8000*177 ~ 1.416.000m^3). However through the use of CROPWAT model, it was found a value of1.869.141 m^3. Thus, the difference is about 453 141 m^3. But this could be explained by the fact that the methods used by DGRE do not take into account the different type of culture and their own crop coefficient. In addition that estimation was done on improved dregs while the market gardening around Loumbila dam is informal. This could affect the estimation of the water needs nonetheless Cropwat allows having a precised estimation of the water needs. This study was realized for the year 2013 only. Knowing the size of the irrigated area for the years 1980, 1996 and 2011, estimation of water needs for those years was done by extrapolation. The table below summarized the crop water needs for the previous years.

Table 29: Crop water needs according to the years

YEARS	AREA (ha)	Water needs (m^3)
1980	26	274.563
1996	66	696.968
2011	159	1.679.059

The quantity of water extracted in 2013 was estimated at 2.670.201m^3.

Table 30: Water extracted according to the years.

YEARS	AREA (ha)	Water extracted (m^3)
1980	26	392.233
1996	66	995.668
2011	159	2.398.655
2013	177	2.670.201

5.1.3 Estimation of the dam evaporation

Evaporation has a great impact on open water surface mainly in Sahelian countries where sunshine duration can vary between 2,700 hours (about 61% of the daylight hours) to 3,500 hours (more than 79% of the daylight hours). Neglecting the contribution of evaporation in water balance estimation may impede the results. Evaporation of water is a process whose scientific exploration can be traced back to the late Seventeenth century (MONTEITH 1981, pp. 1-2). It describes the "emission of water vapor by a free surface [, or in other words, the transformation from the liquid to the gaseous state of aggregation] at a temperature above the boiling point" (WMO 1974, p. 75). The increase of evaporation contributes greatly to the decrease of dam water availability for irrigation mainly. Indeed the topography of Burkina Faso renders the water storage sensible to evaporation. Owing to the flat state of the country, water bodies are less profound and for a given volume they are exposed to a high evaporation than the small dams of Côte d'Ivoire, Ghana, or Northeastern Brazil (Gourdin et al, 2007). The loss from evaporation is today estimated at about 40% of the volumes for big dams and up to 70% for small reservoirs (Programme GIRE, 2001). However the GIEC forecast an increase of the mean temperature of 0, 8°C by 2025 and 1, 7°C by 2050 for the A2 scenarios (the less favorable). The fewer reservoirs must thus dry early during the dry season than today. For the estimation of potential evaporation from free-water surfaces, various different approaches are available. For the purpose of this exercise the estimation of the evaporation bac will be used. The data of evaporation bac over the period 2000 to 2012 was retrieved from the National Agency of Metereology. This was used to estimate the rate of the evaporation over the water body through the use of the formula proposed by Pauyaud (1986).

$$\boxed{E_{lac} = 1.664 E_{bac\,A}^{0.602}}$$

1.4.4 Estimation of Loumbila dam water balance

Dam water balance knowledge is important as it allows guiding the choice of development projects around resources. The Loumbila dam provided currently 36% of Ouagadougou water supply but the probability that this dam will be more solicited in the future is higher with regards to population growth and water stress forecasted. Therefore there will be a conflict between the water supply and irrigation. Therefore estimating the dam´s water balance is very relevant. Water balance principle is based on the estimation and confrontation of dam input and output (inflow and withdrawal). The surplus constitutes the runoff. A negative balance means that the inflow is greater than the losses. A negative balance means that the level of the dam has decreased.

5.2 Assessment of Loumbila dam water balance

A water budget encompasses all inflows into and outflows from an investigated area that takes part in the “hydrologic” or “water” cycle. Outflows must equal inflows plus or minus storage. The water budget for a catchment (with no inflows other than from precipitation) therefore reads in a basic form. The estimation above allows computing the main components of the water balance. The estimation of the water balance is then feasible. The water balance reveals the part of inflow, precipitation, withdrawal due to water supply, evaporation, infiltration and market gardening. The table above shows the evolution of the water balance over the period 2000-2005 taking into account the inflow simulated by GR2M and YATES model. In 1998, the inflows were slightly higher compared to the outflows, resulting in a surplus of around 4.8 million of cubic meter in the reservoir between the beginning and the end of the year (water level in the reservoir rose by 2 cm. The comparison of water balance computed using GR2M or Yates models shows a positive balance over the period of the study (2000-2005). 2001, 2003 and 2004 constitute the years with a low level of dam storage. A great part of the water is used for the market gardening. The quantity of water withdrawn is greater than the water supply quantity over the period 2000-2005. Moreover the quantity of water losses through evaporation is not negligible. This balance shows that from 2000 to 2002, the dam is exploited until the minimum level of storage. In addition the market gardening constitutes a huge consumer of water. Thus it should be conceivable another source for water gardening. The Loumbila dam water balance reveals the part of rainfall, inflow and the contribution of withdrawal through public work, water supply, irrigation and evaporation. From 2000 to 2005 the input was greater than the withdrawal. However 2005 is the year with most input while 2000 and 2001 remain the year with less storage. Those results corroborate with the result of ONEA (2008) which reveals the dam water balance using Map basin.

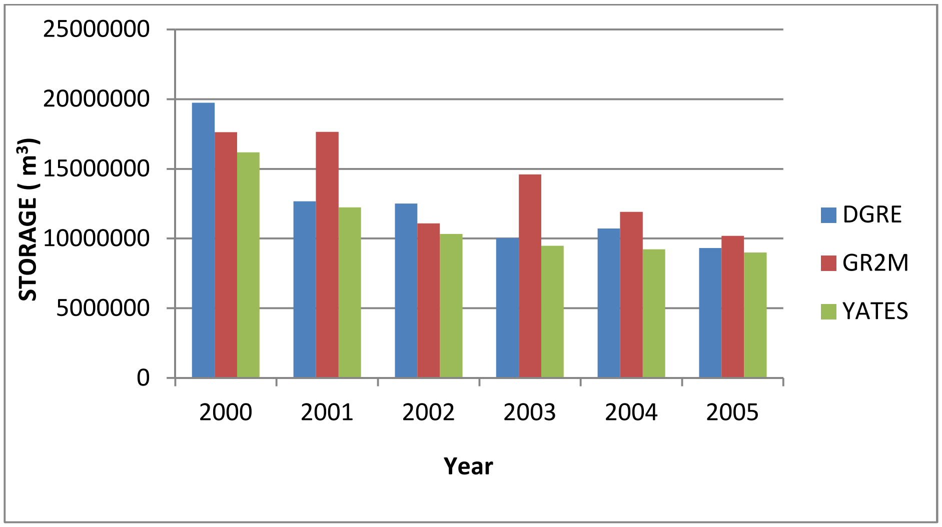


Figure 36: Loumbila dam water balance over the period 2000-2005

6 CHAPTER VI: MODELING OF LOUMBILA DAM WATER RESOURCES ALLOCATION UNDER CLIMATE CHANGE SCENARIOS.

Sustainable water availability is a worldwide issue nowadays as water shortages affect more than 2 billion people in more than 40 countries among which 1.1 billion have limited access to safe water. The situation is particularly challenging for developing countries as mentioned by the UNWWAP (2003).The major reasons are high water demand from population growth, degraded water quality, pollution of surface and groundwater sources and the loss of potential sources of fresh water supply because of old and unsustainable water management practices (UNCSD, 1994). In sahelian countries for instance, integrated water resource management challenges are higher owing both to the scare character of the water resources and to the worst effect of climate change.

As seen in chapter 4 about climate variability, water resources are scarce and highly variable in the Massili basin and this has led to reservoirs construction throughout the basin. However, water demand for agricultural, urban, and environmental needs has intensified with population growth and increasing environmental allocations. The aim of this chapter is to determine the Loumbila dam water allocation under the increasing problems of population growth and climate change pressure. This chapter is organized as follows. Section 1 consists of recall on hydrological modeling under climate change and section 2 is related to the model description. The model for water allocation (WEAP model) is calibrated and validated in section 3. The climate and human pressure scenarios are introduce in section 4 to assess the future demand and unmet demand. The results of the modeling are presented in section 5. Hydrological models are able to simulate the natural processes involved in translating precipitation to runoff with a reasonable degree of success.Albeit hydrological models do not reflect perfectly field reality, they allow to apprehend in a simply way the water inflow, withdrawal and charring between conflicting users. The integration of Regional climatic models downscale output in hydrological model gives an overview on the future trend of water state both at watershed and reservoir scale.

- **Recall on hydrological modeling under a changing climate.**

Hydrological modeling is a process that used model designed to simulate river flow and to understand hydrologic processes. The first models that predicted runoff from rainfall were developed as early as halfway the nineteenth century (Mulvaney, 1851) and in 1932, Sherman introduced the concept of the unit hydrograph on the basis of the principle of superposition. Then many hydrological models have been developed applying various scientific methods and modeling approaches. The main principle in hydrological modeling is to generate discharge based on observed or simulated meteorological data. Hydrological models have become increasingly important tools for the management of the water resources at basin scale. They are designed for flow forecasting to support reservoir operation, for flood control, and management purposes. Hydrological models investigating climate change impacts on water resources are well documented Gleick, 1987; Lettenmaier and Gan, 1990; Nash and Gleick, 1991; Sælthun et al., 1998).

Hydrological modeling is a valuable approach for studying the processes governing impacts of climate change and urban development on water resources and for projecting potential ranges of impacts from scenarios of future change. According to Thompson et al. (2013), evaluating the hydrological impacts of climate change is most commonly based on the use of hydrological models with climate change scenarios derived from the general circulation model (GCM) forced with emission scenarios. However different aspects of uncertainty occurred in hydrological impact studies throughout the modeling process and can be summarized in two groups. The first one is related to the parameters and structures of hydrological models used for impact assessment. Indeed, models developed in a certain climatic or geologic region often have difficulties when used in a different setting. Thus models need to be calibrated based on the local conditions. The second source of uncertainties is related to the choice of general circulation models (GCMs) for climatic time series extraction as they remain relatively coarse in resolution and are unable to resolve significant sub grid scale features such as topography, clouds and land use (Grotch and MacCracken, 1991) and need to be downscaled. A number of papers have previously reviewed downscaling concepts, including (Wilby and Wigley, 1997; Xu, 1999; Wilby et al., 2004; Hewitson and Crane, 2006) and regionally for Scandinavia (Hanssen-Bauer et al., 2005).

Modeling hydrological processes under climate change impacts have gained the attention of Burkina Faso scientists. Indeed, Karambiri et al.(2011) used the RACMO KNMI and REMO MPI models (both driven by ECHAM5 GCM) and the RCA SMHI RCM (driven by HadCM3 GCM) to assess the climate change impacts on Nakanbe water resources. In addition, Ibrahim et al. (2014) applied five model (CCLM, HadRM3P, RACMO, REMO and RCA) to simulate the future climate impact on water resources. The principle involves the use of hydrological models calibrated and then forced with RCM or GCM output data. From their findings, it can be retained that although some models are indicating an apparent decrease of rainfall, the Nakambe basin is experiencing a paradoxically increased in runoff, this results in increased discharges (Mahe et al., 2005) and consequently a greater vulnerability to flooding has been observed in 2009 and 2010. This could be argued as the consequences of land use/ land management practices, mainly the deforestation.

Despite the effort in improving hydrological modeling, there are still several knowledge gaps challenging the hydrological scientific community. Indeed, there is a need to improve GCMs downscaling methods, bias corrections methods and a need to integrate land use/ land cover dynamics in models.

6.1 Description and example of WEAP model application

Yates et al. (2005) defined WEAP (Water and Evaluating Planning) as a demand-priority and preference-driven water planning model. This hydrological model constitutes a good tool for water planning. The aim of the model is to close the gap between water management and watershed hydrology by addressing both systems influencing the river basin (Yates et al., 2005). This hydrological system is influenced by biophysical (climatic, topography, land cover surface and groundwater hydrology) and socio economics factors (population growth, water supply and irrigation needs). The WEAP model has two primary functions (Sieber and Purkey, 2007) which are the simulation of natural hydrological processes (evapotranspiration, runoff and infiltration) to enable the assessment of water availability within a catchment and the simulation of anthropogenic activities, superimposed on the natural system influencing water resources and their allocation (consumptive and non-consumptive water demands) to evaluate the impact of human water use.

At monthly time step, WEAP is based on a water mass balance calculation throughout every node and link in the system. Thus the water balance is calculated at each node and link. Nodes represent demand or supply points while links form the linkages between them. According to targeted aim, four types of methods can be chosen for the modeling (Wigley, 2007):

- **Irrigation Demands Only Method**

This method is based on the FAO Crop Requirement approach. It calculates the potential evapotranspiration in the catchment using crop coefficients and determines irrigation requirements in the event that potential evapotranspiration cannot be satisfied by rainfall. This method cannot simulate infiltration, changes of moisture in the soil or runoff.

- **Rainfall Runoff Method (based on the FAO Crop Requirement)**

This method is similar to the first one since it calculates evapotranspiration using FAO crop coefficients. Nonetheless, the remainder of precipitation that cannot evaporate and transpire by soils and crops is simulated to be runoff to the river.

- **Rainfall Runoff Method (based on Soil Moisture Method)**

The Soil Moisture Method simulates the catchment with two soil layers along with potential for accumulating snow. Runoff and shallow interflow, moisture change in soils and evapotranspiration can be simulated as well as the routing of base flow to the river and changes of soil moisture. This method allows characterizing land use and/or soil types to explore effects on land use /land cover. This method requires thus a lot of data for running.

- **MABIA Method**

The MABIA method calculates evaporation, transpiration, amount of water for irrigation and time of irrigation, interval of crop growth along with amount of yields for each crop. This method runs at daily time step.

The existence of a user defined scenarios rubric allows forecasting demand and supply under different climatic, socio economic scenarios. Even though the ‘Water Evaluation and Planning’ system supports decision makers, the outcome of WEAP does not substitute detailed water operation models for e.g. hydropower (Yates et al., 2005). Moreover, scenarios can be built for wet, very wet, dry normal and very dry periods. Hence, the yearly and monthly inflows depends on the characteristics of each simulated water year (SEI, 2008).

Groundwater aquifers, rivers, and reservoirs are other possible water suppliers which can be accounted for in WEAP. Furthermore, integrated groundwater surface water modeling and a link to MODFLOW - an external modular three-dimensional finite-difference groundwater model are available to better reflect the hydrological processes. Inflows to the system can be prescribed with time series derived from other models or can be modeled within WEAP with the Water Year Method. In addition to the above mentioned options, WEAP also offers water quality modeling. The water quality model includes the simulation of water sanitation systems, e.g. the effects of water treatment plants (Yates et al., 2005; Aamodt et al., 2008). Furthermore, a financial planning tool models the cost and revenues of the current and future water supply, testing the economic side of distinct water demand management strategies. As can be seen from this description, WEAP offers a wide range of options and analysis tools required by IWRM and the water balancing approach to adequately support decision and policy makers. WEAP was developed in 1988 and had its first major application in the Aral Sea Region (Raskin et al., 1992). Since then the system has been applied in many projects and regions such as in United States, Central Asia, China and Africa with continuous improvements (SEI, 2008). WEAP was applied to the Volta River Basin in Ghana and the Limpopo River Basin in South Africa within the Small Reservoirs Project (SRP). This project aims at improving livelihoods and food security by planning and evaluating small reservoirs. As data for each node has to be entered separately, the project also aims at developing a cluster input option to improve usage for scenarios with large numbers of reservoirs (SRP, 2008). Many authors have applied WEAP such as Roberto and (Hoff et al., 2007; Purkey et al., 2008; Al-Omari et al., 2009). WEAP was also used for another application in the Volta Basin, however, the focus of the 'Adaptation to Changing Environments' (ADAPT) study was in assessing the impact of climate change on the availability of water resources. The Volta Basin extends over 400,000 km², but, the area was divided into only seven sub-catchments with three demand sites each (domestic demand, large and small scale irrigation). The project started with a more detailed node-link network but then used a higher level of aggregation to simulate water supply and demand as this made determining in- and outflows of each link easier .

Water demand management under scenarios was investigated in the Steelport Basin (7,130 km²) of the Olifant Basin in South Africa (Lévite et al., 2003). They assessed the model as a useful tool for rapid assessment of water allocation decisions in a river basin, however, the water year method has been judged insufficient in adequately describing the hydrological phenomena. A follow-up tested the integrated rainfall-runoff component of WEAP for the whole Olifant Basin.

The study especially aimed at testing the potential of WEAP to sufficiently represent the basin´s hydrology with limited input data instead of describing the hydrological processes exactly. The main limit of WEAP functionalities is the lack of automated calibration of the rainfall-runoff parameter for the calibration of input parameters. Nevertheless the model was evaluated as a useful tool for rapid assessment of natural catchments conditions (Roy, 2005). Indeed, most of the disadvantages and uncertainties experienced in most of studies come from limited or uncertain input data rather than from the model structure. Thus WEAP is a reliable and useful tool for integrated water resources planning because of its strength on balancing water supply and demand. The aim of this chapter is to apply WEAP model to assess future water demands and resources in the Loumbila basin.

6.2 Methodology and Approach of WEAP modeling for the Massili basin

In the need of modeling the Loumbila dam´s water allocation under socio economic and climatic scenarios on the basis of the rainfall-runoff method, WEAP has been applied in Massili basin. The water resources and demands in the basin are modeled as a network of supply and demand nodes connected by links.

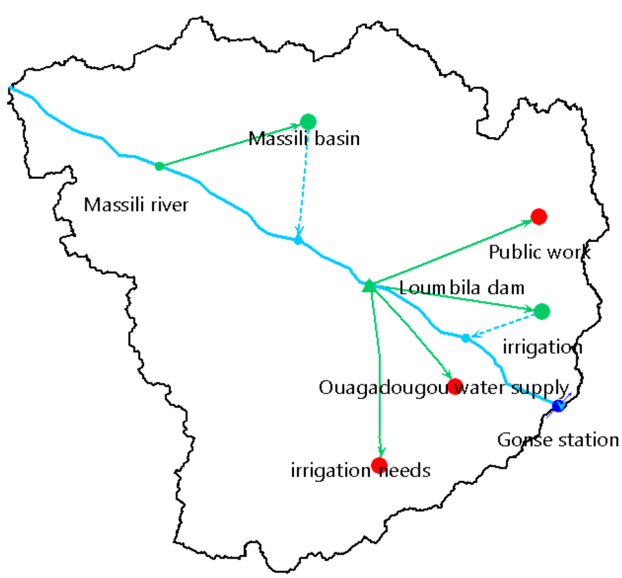


Figure 37: Schematic view of Weap model in the Massili basin

WEAP is used to run scenarios based on climate change projections. The relevant parameters used as a baseline scenario are: population growth, domestic water use efficiency, and agricultural water use efficiency. In order to build these time series, step functions are created for the period of projection 2005-2050. The relevant parameters to simulate climate change are: catchment precipitation, groundwater recharge, and irrigation water use rate. These time series are created in form of linear interpolation for the same period of projection.

- **Temporal Scale**

The "current account" year chosen for the model to serve as base year is 2000. Current account year contains all relevant system information and forms the dataset from which scenarios will be built. The period of time for which scenarios are generated is 2001 - 2050. Due to the level of precision of available data, the model is run on monthly time steps and will make assertions on climate change trends.

- **Relevant System Components and Configuration**

The WEAP model is organized within a watershed where Loumbila dam is used for water supply, irrigation and public work. Ouagadougou water supply site and public work (municipality demand) are equipped with an annual activity level (population), an annual water use rate (per capita) and information on consumption (water that does not return to the system). Water gardening demand node represents the size of the irrigated area and annual water gardening water requirements (per hectare). The demand nodes are connected to the resources with a transmission link for the supply, and with a return flow link for water that flows back from demand sites and infiltrates to local groundwater or returns to rivers either through a treatment plant or directly.

- **Baseline and scenarios**

2000 was defined as the current year account which constitute the base year for the model. Data about the catchment, the demands and supply are integrated in the base year. In this baseline is integrated observed data of nodes and links. Scenarios were built over the period 2001-2050. Two types of scenarios from one RCM were integrated in the model to assess the impact of climate change on water resource availability and demand patterns. Urban water demand is influenced by changes in population. Water supply demand data was retrieved from the National Agency of water and sanitation (ONEA). In addition, in order to build the 2050 water demand scenarios, population data from the National Institute for statistics and population (INSD, 2006b) were used. Irrigation needs were retrieved from the previous estimation using the CROPWAT software.

6.2.1 WEAP Model Calibration

Calibration is a set of procedures which seek to determine a model's parameters, resulting in a rough simulation of a given time series observations. WEAP calibration is a challenging process and must be done before the scenarios analysis (Fariborz, 2012). Calibration and validation of streamflow and reservoir are necessary to make sure the WEAP model is correctly representing the current situation in the study area. Four main instance of calibration could be done in WEAP: the settlement, the catchment, the Groundwater and the runoff coefficient. For the purpose of this study, variables relative to the settlement, catchment and reservoir will be applied for the calibration process. Annual activity level and consumption of the demands sites were incremented to have a good representation of the demand by the model. The dam storage, the discharge and the inflow were also calibrated. The model parameters were estimated over 2000 (current year) and the validation was run over 2001 to 2006. The dam was calibrated using the historical data of reservoir storage from 2000 to 2006 provided by the National Agency of water and sanitation (ONEA).

Table 31: Calibration parameters / variables and plausible ranges

Instance	Variable / Parameter	Range [Unit]
Settlement	Annual activity level	40 – 120 [m³/cap*a]
	Consumption	0 – 30 [%]
Watershed	Precipitation	0.7 – 1.3 mm
	ETo	0.7 – 1.3 mm
	Effective Precipitation	0.5 – 1 mm
Groundwater	Storage Capacity	Catchment area * 5 – 15 m [10^6 m³]
	Initial Storage	0 – Storage Capacity [10^6m³]
	Hydraulic Conductivity	1 – 20 [m/d]
	Horizontal Distance	1000 – 10000 [m]
	Wetted Depth	1 – 10 [m]
	Storage at River Level	0 – Storage Capacity [10^6m³]
Runoff Coefficient	Runoff fraction to GW	10 - 90

6.2.2 Methodology of scenario building

WEAP was used to model actual water requirement and forecast future trends through the establishment of scenarios. As WEAP allows users to build and integrate scenarios in the modeling approach, a first set of scenarios was build based on population growth and increase in water gardening use, a second set of scenarios was based on main climate parameters (rainfall and temperature) projections derived from two (02) Regional Climate Models (RCMs). The approach chosen in this study is to assess unmet irrigation and water supply demands through modeling future water resource availability. Two climatic scenarios and two socio-economic scenarios are developed to assess the impact of climate change on Loumbila dam water allocation. The set of scenarios developed for Massili basin limited at Gonse station was built based on CORDEX data.

- **Business as Usual**

The business as usual scenario is the base scenario that extrapolates historical trends, to provide a baseline for the studied period. This involves mainly increase in population growth by 10% (INSD, 2006a).

- **Climate change scenarios**

. A scenario is a storyline or image that describes a potential future, developed to inform decision making under uncertainty (Parson et al., 2007). Climate change scenarios developed by the IPCC constitute a base for future climate change assessment. The first categories of SRESS scenarios were developed in 2000 and differs from the scenarios developed in 2011 (RCPs) and are based on the estimation of Green House Gas emissions. Four family type of Representative Concentration Pathway (RCP) were developed and each one defines a specific emissions trajectory and subsequent radioactive forcing.

Some models are more ‘skilled’ at predicting specific parameters in certain regions, without a comprehensive exploration of multiple model outputs choosing a single model for a specific region is not advisable (IPCC, 2007). According to Paeth et al. (2011) the RCMs differ in how they reproduce the seasonal cycle due mainly to their cycle, their different dynamical schemes and physical parameterizations of the parameterizations of the West African monsoon. Indeed, each RCM has it ability to reproduce the historical and future trends of climate patterns. The previsions reflect a worrying increase of mean temperatures to 0,8°C by 2025 and up to 1,7°C by 2050 (NAPA, 2007) and a decrease of rainfall up to 3.4% by 2025 and up to 7.3% by 2050 (NAPA, 2007). In addition , the analysis of this first decade shows in figure2 that the two RCM were not able to reproduce very well the flood occurred in Burkina Faso in 2009. The next decades show an occurrence of exceptional rainfall in 2018, 2021 and 2024 respectively at the level of 307.33mm, 272.58mm and 272.48mm.

Burkina Faso is facing tremendous challenges for its water and agricultural sector considering extreme droughts and floods which increased during the previous decades and given IPCC climate projections for West Africa. Addressing the lack of knowledge on past, present and future climate trends at local and regional scale in central Burkina Faso, this part assesses trends in rainfall as well as in mean temperature (Tmean) from 1971 to 2050 in the Massili basin. Hence, a 50 years record (1961-2011) from Gonse station as well as data from Regional Climate Models (MPI-M-MPI-ESM-LR, CCCma-CanESM2, AFR44-HIRHAM5 and AFri-MPIrf HIRHAM5) was analyzed. The model data was extracted from the Coordinated Regional Climate Downscaling Experiment (CORDEX) data archive and included historical runs (1971-2005) and two representative concentration pathways scenarios (RCP_4.5 and RCP_8.5) for the period 2006-2050, all at 50*50 km² spatial resolution.

RCP_8.5 was developed using the MESSAGE model and the IIASA Integrated Assessment Framework by the International Institute for Applied Systems Analysis (IIASA), Austria. This RCP is characterized by increasing greenhouse gas emissions overtime, representative of scenarios in the literature that lead to high greenhouse gas concentration levels (Riahi et al., 2007) and the radioactive forcing level reaches 8.5 W/m^2. Yet, RCP_4.5 was developed by the GCAM (General Circulation Atmospheric Model) modeling team at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI) in the United States. It is a stabilization scenario in which total radioactive forcing is stabilized shortly after 2100, without overshooting the long-run radioactive forcing target level (Smith and Wigley, 2006; Clarke et al., 2007; Wise et al., 2009). In other words the RCP_4.5 scenario is a stabilization scenario, which means the radioactive forcing level stabilizes at 4.5 W/m^2 before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions.

- **Choice of RCMs models for projected rainfall and temperature data extraction**

Current hydrological impact studies involve application of RCMs outputs. This requires a selection of appropriate RCM models. Indeed, as mentioned by Paeth et al. (2011), RCMs differs in how they reproduce the seasonal cycle due mainly to their different dynamical schemes and physical parametrizations of the West African monsoon. However, random choice of RCMs data is a huge task and should be avoided. In order to select the RCM model which will present a better ability to reproduce the past observed rainfall and temperature the method of Taylor diagram was adopted. This method offers a set of RCM data and their performance according to the study area location. This study makes use of the RCM simulations from the CORDEX database CORDEX-Africa Matrix RCP_4.5 and RCP_8.5, 2006-2050, about 50km resolution. Projections for the period 2006-2050 in mean temperature and precipitation at monthly time step for Massili basin are used. Therefore the most extreme scenarios RCP_8.5 and the steady RCP_4.5 from AFR44-HIRHAM5 RCP_8.5 was developed using the MESSAGE model and the IIASA. Grads were applied to extract Cordex temperature and rainfall dataset at the basin scale.

- **Projected evapotranspiration dataset estimation**

Evapotranspiration is defined as the combination of soil evaporation and vegetation transpiration and is affected by meteorological variables, crop characteristics and management, as well as environmental aspects. According to Prudhommeetal.(2013)future changes in evapotranspiration will be equally important as changes in precipitation patterns for determining changes in river flows. Therefore, long-term changes in evapotranspiration are to be considered while assessing the potential impacts of climate change on water availability in reservoirs. For Singh et al. (2005) ETP estimation formula are based on the type of climatic parameters involved: global radiation, masses transfer, and temperature. Penman–Monteith formula is the referential formula for ETP estimation as this formula involved three of the above parameters mentioned. However, the requirement of various climatic parameters renders this formula the most complicated(Trajkovic, 2005). The future evapotranspiration must be integrated in WEAP modeling under climate change scenarios. However, RCM does not simulate the future evapotranspiration. In this study, possible future changes of evapotranspiration are investigated using Thornwaite´s (Thornwaite, 1944) formula described as follows:

$$\mathrm{ETP(m)} = 16 * \frac{[10*T(m)]^a}{[I]} * F(m,\phi) \qquad (28)$$

- ETP (m):l'ETP mean of month m (m = 1 to 12) in mm.
- T (m) =interannual mean of monthly temperature, °C.
- Approximative formula of a : a = 0.016 * I + 0.5.
- F(m,ϕ) : correctif factor depending on month m and latitude ϕ.
- I, annual thermic index:

$$\mathrm{I} = \sum_{m=1}^{12} \mathrm{i(m)} \qquad (29)$$

$$\mathrm{i(m)} = \frac{[T(m)]^{1.514}}{[5]} \qquad (30)$$

The correction coefficient F (m,ϕ) which is related to the month and latitude of the study area was deducted from the table of Thornwaith formula coefficient.

- **Bias correction of RCM output data: delta change method**

Hydrological climate change impact studies at local scale involve application of regional climate model (RCM) simulations which provides more detailed regional information (Grotch and MacCracken, 1991; Salathé, 2003; Fowler et al., 2007). However, in many of these climate impact studies, the RCMs output data is applied without a quality control of the RCM data. Thus application of RCMs is still challenging for the hydrological community as RCM raw data contains some biases mainly due to model high performance to simulate past and future climate pattern trend. Model bias is defined as a systematic distortion of statistical findings from the expected value. Indeed, climate variables simulated by individual RCMs often do not agree with observed time series.

Many authors have highlighted the frequent bias met in RCMs simulations. RCMs may misestimate climate variables in general and may simulate incorrect seasonal variations of precipitation (Christensen et al., 2007; Terink et al., 2009; Teutschbein and Seibert, 2010). In addition, Ines and Hansen (2006) noticed that RCM simulate low rain intensity. Consequently, RCMs raw data need to be corrected before application to impact studies. Correction approaches can be classified according to their degree of complexity or simplicity and have low or great ability to reduce errors in climate model output. Whatever the method used for bias correction, the correction simulations cannot reproduce exactly the observed time series as the choice of a correction technique is an additional source of uncertainty (Teutschbein et al., 2011; Teutschbein and Seibert, 2012; Chen et al., 2013).

Three methods are used for bias correction of RCMs data output: Precipitation threshold, Delta change conversion and Distribution Mapping or quantile-quantile mapping. The Precipitation threshold simulates the precipitation only while the Delta change and the quantile quantile methods simulate both temperature and precipitation. Precipitation threshold is calibrated such that the number of RCM-simulated days exceeding this threshold matches the number of observed days with precipitation (Schmidi et al., 2006). In Delta change method, simulated future change signals (anomalies) are superimposed upon observational time series Johnson and Sharma (2011). Distribution Mapping matches the distribution functions of Observations and RCM-simulated climate values a precipitation threshold can be introduced to avoid substantial distortion of the distribution Johnson and Sharma (2011). Table 32 gives a brief review of methods needed in this study for transforming regional climate model output for use with hydrological models.

Table 32: Overview of methods used to correct RCM-simulated precipitation and/or temperature data.

Method	Variable	Short descriptions	References
Precipitation threshold	Precipitation	A RCM-specific threshold is calibrated such that the number of RCM-simulated days exceeding this threshold matches the number of observed days with precipitation. • rarely used as a “stand-alone” method but often combined with other correction procedure.	Schmidi et al (2006)
Delta change conversion	Precipitation Temperatures	RCM-simulated future change signals (anomalies) are superimposed upon observational time series • usually done with a multiplicative correction for precipitation and an additive correction for temperature	Gellens and Roulin (1998) Graham et al. (2007a, b) Johnson and Sharma (2011) Lettenmaier et al. (1999)
Distribution Mapping or quantile-quantile mapping or statistical downscaling	Precipitation Temperature	matches the distribution functions of Observations and RCM-simulated climate values a precipitation threshold can be introduced to avoid substantial distortion of the distribution caused by too many drizzle days.	Block et al. (2009) Boe et al. (2007) Déqué et al. (2007) Ines and Hansen (2006) Johnson and Sharma (2011) Piani et al. (2010)

Prior to bias correction of the RCMs output data, it is important to detect the biases through comparison of past, current and projected data. In this study, methods of annual average and standard deviation were applied to check the existence of eventual bias on the data. Then the delta change approach is employed to make the output of RCMs respecting the trend of the past climate pattern. The delta-change approach is a transfer method and has been widely used (Lettenmaier and Gan, 1990; Gellens and Roulin, 1998; Middelkoop et al., 2001; Graham et al., 2007; Moore et al., 2008) because it is straightforward and easy to implement due to its simplicity. The method is based on application of a change factor which is the ratio between mean value in the future and historical run. This factor is then applied to the observed time series to transform this time series into a time series which is representative of the future climate.

The monthly temperature deltas and precipitation ratios from the scenarios were applied to the corresponding monthly climate data of the validation period as shown by the following equations:

$$T^{i}_{fut,m\text{-}y} = T_{obs,m\text{-}y} + DeltaT^{i},_{m\text{-}y} \qquad (31)$$

$$P^{i}_{fut,m\text{-}y} = P_{obs,m\text{-}y} * RatioP^{i}_{m} \qquad (32)$$

$$ETP^{i}_{fut,m\text{-}y} = ETP_{obs,m\text{-}y} * RatioETP^{i}_{m} \qquad (33)$$

Where i is the scenario index (i=4.5 ,8.5) ;T^{i}fut, m-y is the projected (T^{o}C) for scenario i and month m(m=1,...,12) in year y ; Tobs,m-y is the observed temperature (T^{o}C) for month m in year y under recent past climate; Delta T is the temperature delta (T^{o}C) for scenario i, computed for month m of future year ; P^{i}fut,m-y is the projected precipitation (mm) for scenario i and month m in year y; Pobs, m–y is the observed precipitation (mm) for day d of month m in year y under recent past. climate; and Ratio P^{i}_{m} is the precipitation ratio (%) for scenario i, computed for month m of future year; ETP^{i}fut,m-y is the projected evapotranspiration (mm) for scenario iand month m in year y; ETP obs, m–y is the observed Evapotranspiration (mm) for day d of month m in year y under recent past. climate; and Ratio ETP^{i}_{m} is the evapotranspiration ratio (%) for scenario i, computed for month m of future year.

6.3 Results

6.3.1 Result of WEAP calibration (Model performance assessment)

WEAP performance was assessed by statistical measures for calibration and validation; Nash–Sutcliffe Efficiency Coefficient (NSE) (Nash and Sutcliffe, 1970), the Percent Bias (PBIAS) (Gupta et al., 1999) and the Root Mean Square Error (RMSE)-Observations Standard Deviation Ratio (RSR) (Singh et al., 2005) recommended by Moriasi et al. (2007) were computed based on the runoff observed and simulated data. The Root Mean Squared Error (RMSE) incorporates both the variance of the estimator and its bias (Lehmann and Casella, 1998).

$$\boldsymbol{NSE} = 1 - \left[\frac{\sum_i^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_i^n (Y_i^{obs} - Y_i^{mean})^2} \right] \qquad (34)$$

$$\boldsymbol{PBIAS} = \left[\frac{\sum_i^n (Y_i^{obs} - Y_i^{sim})}{\sum_i^n (Y_i^{obs})} * 100 \right] \qquad (35)$$

$$\boldsymbol{RMSE} = \sqrt{\frac{\sum_i^n (Q_i^{obs} - Q_i^{sim})^2}{\mathrm{N}}} \qquad (36)$$

$$\mathbf{RSE}=\left[\frac{\sqrt{\sum_i^n (Y_i^{obs}-Y_i^{sim})^2}}{\sqrt{\sum_i^n (Y_i^{obs}-Y_i^{mean})^2}}\right] \qquad (37)$$

The following table summarizes the value of the calibration and validation performance.

- **Outflow performance**

Table 33: Statistics of the WEAP model performance for Massili basin limited at Gonse station (Outflow)

	Period	NSE	RMSE	RSE	PBIAS
Calibration	2000	78%	0.89	0.47	-12.82%
Validation	2001-2006	81%	0.89	0.48	7.58%

The analysis showed in table (33) a Root Square Mean Error (RSME) value of 0.89 both for the calibration and validation. The Standard Deviation Ratio (RSE) was estimated to 0.47 for calibration and 0.48 for the validation; the PBIAS was estimated at -12.82% for the calibration and 7.58% for the validation. Based on the calibration performance conditions established by Santhi et al. (2001a); Moriasi et al. (2007), calibration is successful for NSE >0.50 PBIAS is +/- 25%. Thus the calibration and validation of WEAP over Massili basin can be confirmed good as the trend of simulated flow is reasonably close to the trend of observed streamflow and both the calibration and validation periods show a similar fit to the data despite the existence of some differences in the observed and simulated values. The reason for these deviations might be errors in the amount and distribution of precipitation over the watershed, errors in evapotranspiration estimates, or errors due to other factors that the model did not account for. In addition, table (33) allowed concluding that the model is well calibrated and validated.

- **Inflow performance**

Table 34: Statistics of the WEAP model performance for Massili basin (Inflow).

	Period	NSE	RMSE	RSE	PBIAS
Calibration	2000	0.88	0.34	0.34	10.4%
Validation	2001-2006	0.87	0.53	0.64	4.5%

The analysis showed in table (34) a Root Square Mean Error (RSME) value of 0.34 and 0.53 respectively for calibration and validation. The Standard Deviation Ratio (RSE) was estimated at (0.34 for calibration and 0.64 for the validation); the PBIAS was estimated at 10.4% for the calibration and 4.5% for the validation. Based on the calibration performance conditions established by (Moriasi et al., 2007; Santhi et al., 2001b), calibration is successful for NSE > 0.50 PBIAS is +/- 25%. Thus the calibration and validation of WEAP inflow over Massili basin can be confirmed good as the trend of simulated value is reasonably close to the trend of observed streamflow and both the calibration and validation periods show a similar fit to the data despite the existence of some differences in the observed and simulated values.

Table 35: General performance ratings for recommended statistics at monthly time step

Performance Rating	RSR	NSE	PBIAS (%)
Very good	0.00 <RSR <0.50	0.75 < NSE <1.00	PBIAS < ±10
Good	0.50 < RSR <0.60	0.65 < NSE <0.75 ±10	±10 <PBIAS < ±15
Satisfactory	0.60 < RSR <0.70	0.50 < NSE <0.65	±15 <PBIAS < ±25
Unsatisfactory	RSR > 0.70	NSE <0.50	PBIAS > ±25

- **Calibration of the reservoir storage volume**

Figure (38) presents the result of calibration and validation of inflow over 2000-2006. The evaluation of the graphs indicates that the model is reproducing the storage reasonably well. Indeed the observed and simulated volume is following the same trend. The goal of calibrating the watershed rainfall runoff model in WEAP was not to exactly represent the exact runoff properties of the existing watershed but rather to develop a good representation of the existing streamflow that could serve as a base condition for climate change analysis. Calibration and validation were done through adjustment of parameters such as the crop coefficient (Kc) and the water use rate.

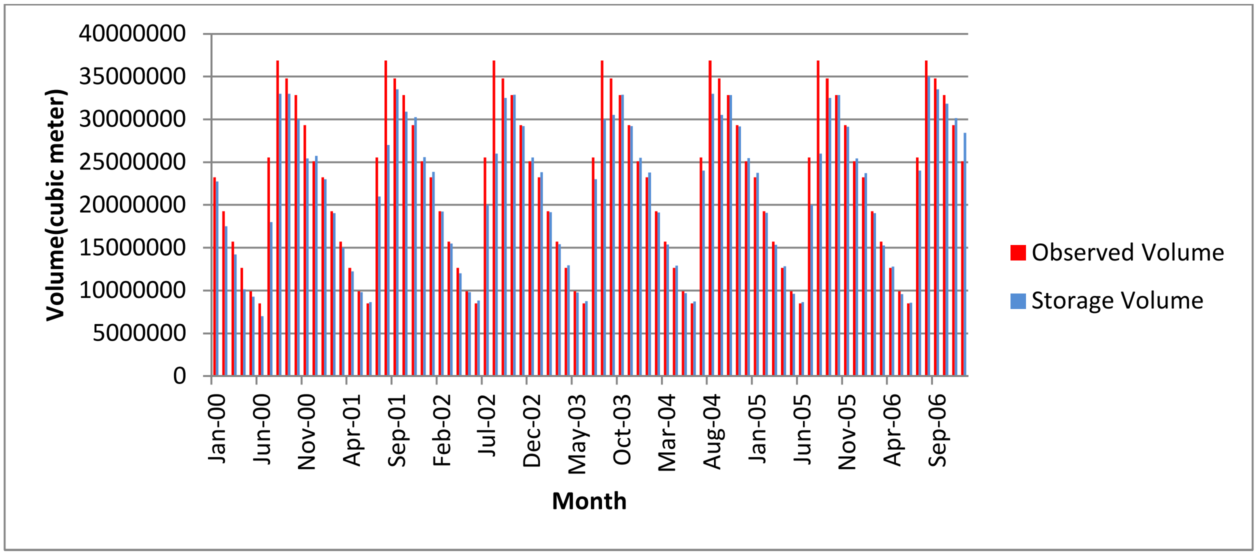


Figure 38: calibration of reservoir storage volume

6.3.2 Result of Scenario building

➢ **Ability of the detected RCMs to reproduce the past temperature**

Figure 39 shows that the monthly mean temperature is underestimated by the RCMs output. MPI-M-MPI-ESM-LR, CCCma-CanESM2 and AFri-MPIrf-HIRHAM5 have a lower ability to reproduce the past temperature in Massili basin compared to AFR-4-HIRHAM5 which offers a better reproduction of the past temperature as shown in figure 40 (a). Indeed, while MPI-M-MPI-ESM-LR gives underestimation of the past Tmean from October to May, and an overestimation of Tmean from May to September, CCCma-CanESM2 shows an underestimation of temperature over months. AFri-MPIrf-HIRHAM5 shows also an underestimation of temperature except in J-J-O. Despite the inability of AFR-44-HIRHAM5 to reproduce well the past Tmean in A-M and O-N-D, this RCM seems to perform better in assessing the trend of the past temperatures in the basin. Thus, this model will be selected for the hydrological impact study.

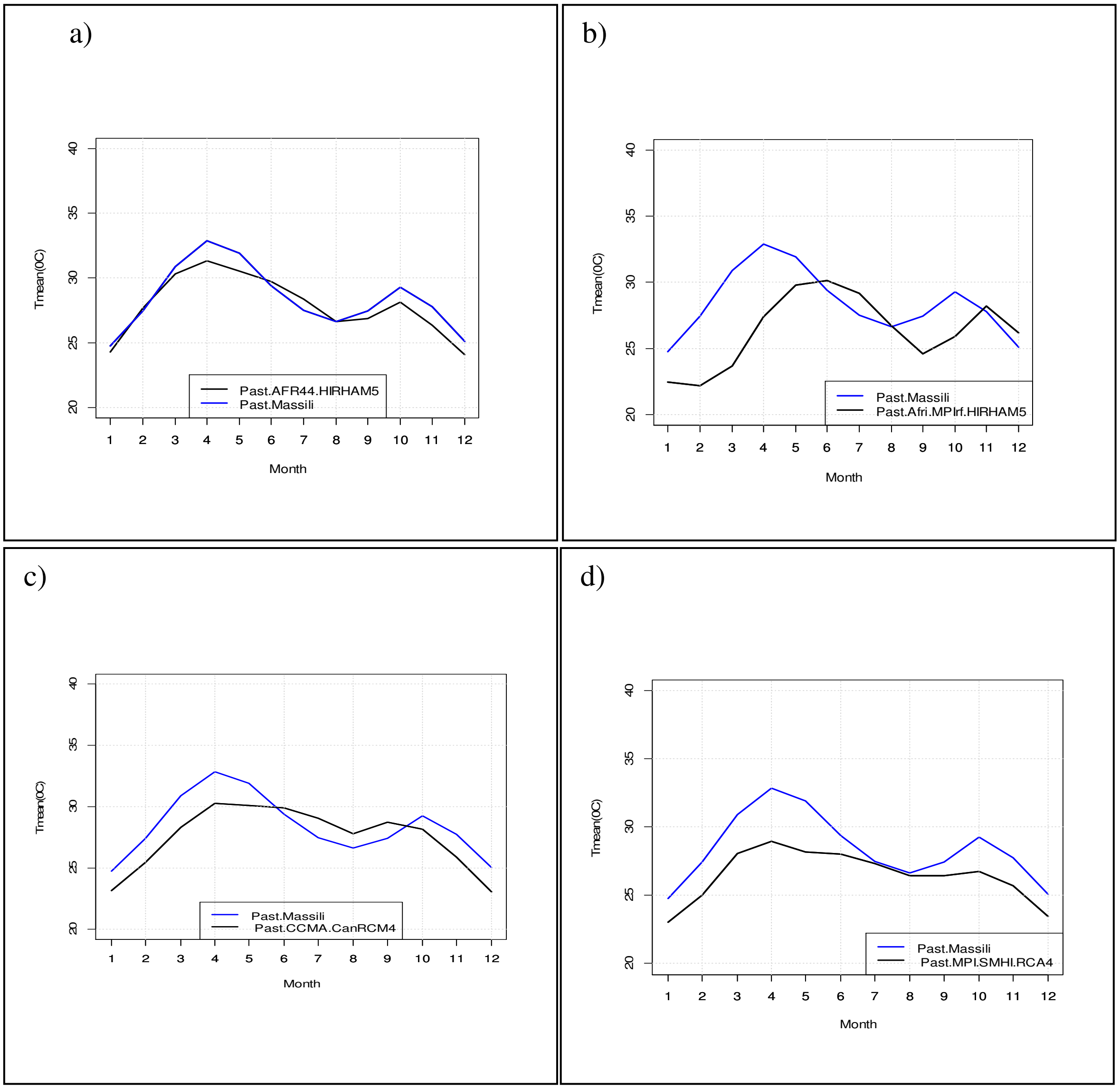


Figure 39a) Monthly mean temperature (Tmean) for the period 1971–2000 as observed and simulated by AFR 44 HIRHAM5 for the Massili catchment; b) Monthly mean temperature (Tmean) for the period 1971–2000 as observed and simulated by AFriMPIrf HIRHAM5 for the Massili catchment; c) Monthly mean temperature (Tmean) for 1971-2000 as observed andsimulayed by CCCma-CanESM2 ; d) Monthly mean temperature (Tmean) for the period 1971-2000 as observed and simulated by MPI-M-MPI-ESM-LR .

MPI-M-MPI-ESM-LR, CCCma-CanESM2 and AFri-MPIrf-HIRHAM5 have a lower ability to reproduce the past rainfall in Massili basin compared to AFR-44-HIRHAM5 which offers a better reproduction of the past rainfall as shown in figure 40. Indeed, both MPI and CCMA gives two peaks during the rainy season while in Massili basin the rainy season occurred only between June-September with high rainfall amount recorded in August. In addition, Afri-MPIrf-HIRHAM5 reproduces slightly the rainfall cycle in the basin but with September as the month of high rainfall occurrence. AFR-44-HIRHAM5 however has a satisfactory reproduction of the rainfall trend. In summary, compared to MPI-M-MPI-ESM-LR ,CCCma-CanESM2 and Afri-MPIrf-HIRHAM5, AFR-44-HIRHAM5 tends to perform better the past rainfall cycle in the Massili basin. Thus, output data of this model will be selected to force the hydrological model for the climate change impact study.

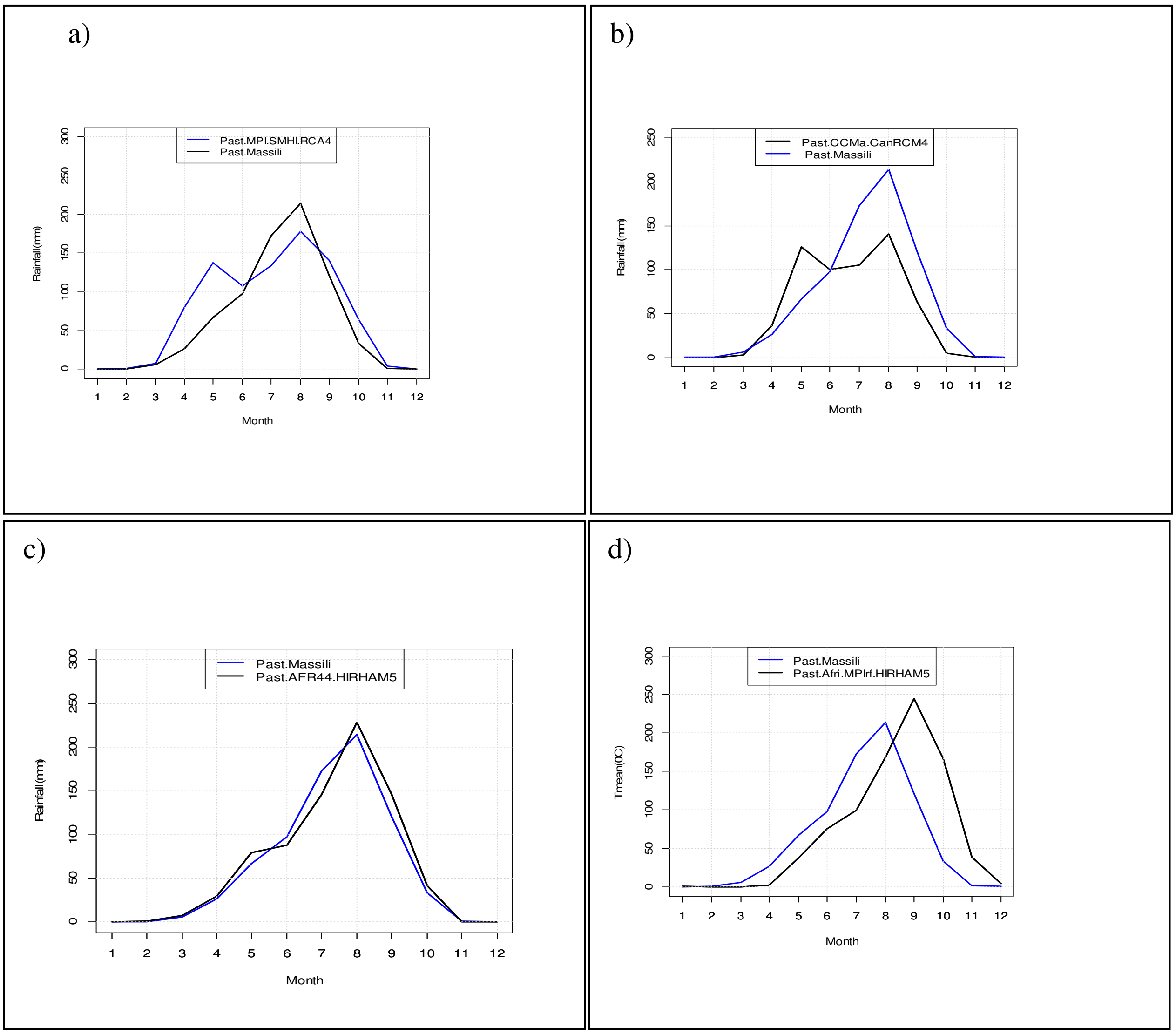


Figure 40a) Monthly rainfall for the period 1971–2000 as observed and simulated by MPI-M-MPI-ESM-LR and for the Massili catchment; b) Monthly rainfall for the period 1971–2000 as observed and simulated by CCCma-CanESM2 for the Massili catchment; c) Monthly rainfall for the period 1971–2000 as observed and simulated by Afri 44 HIRHAM5 for the Massili catchment;d) Monthly rainfall for the period 1971–2000 as observed and simulated by Afri MPIrf HIRHAM5for the Massili catchment.

monthly past (corrected and not corrected) and future (corrected and not corrected) temperature over the past period by 2050. AFR-44-HIRHAM5 under RCP_4.5 and RCP_8.5 scenarios is showing an increase in future rainfall patterns.

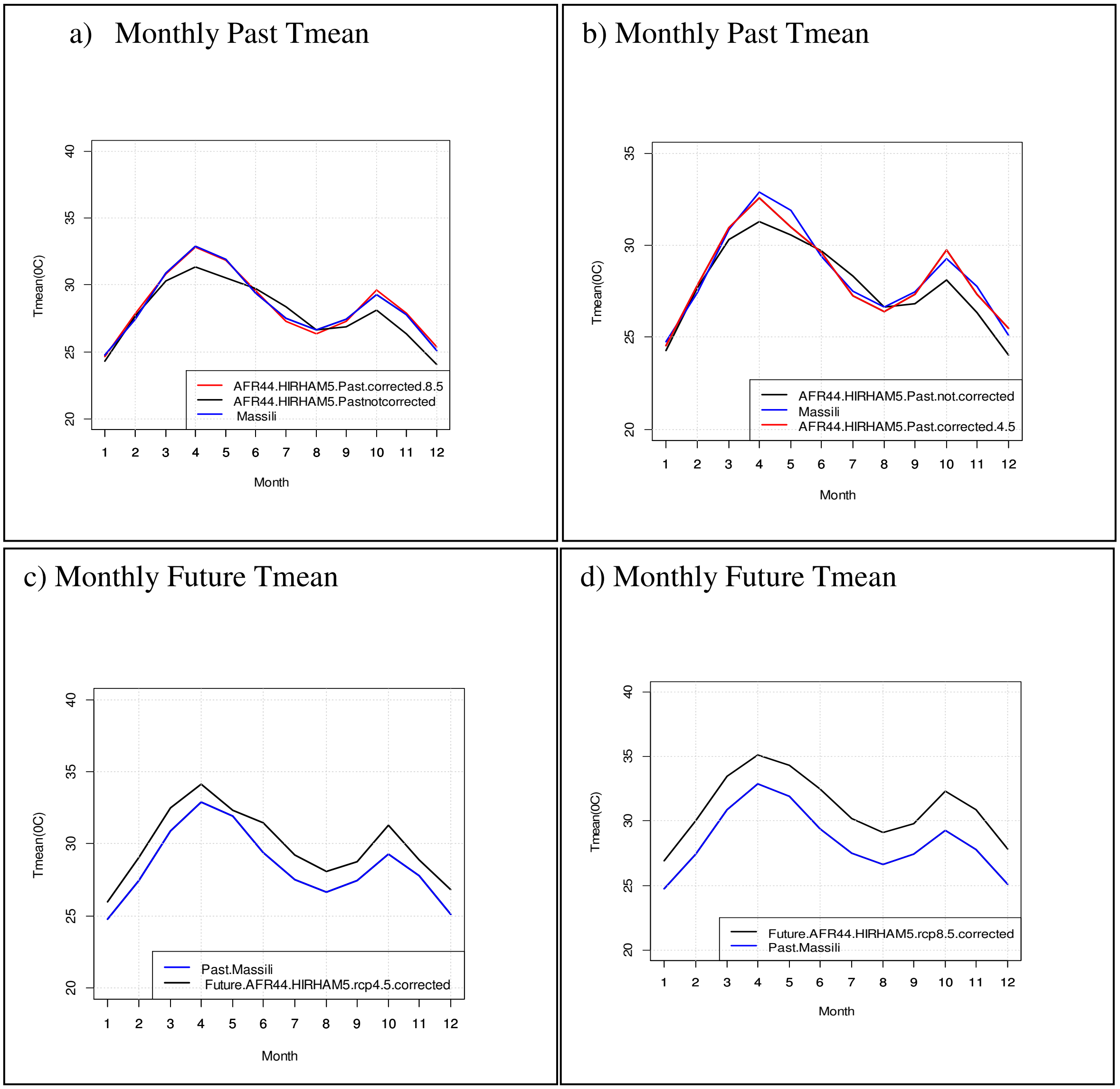
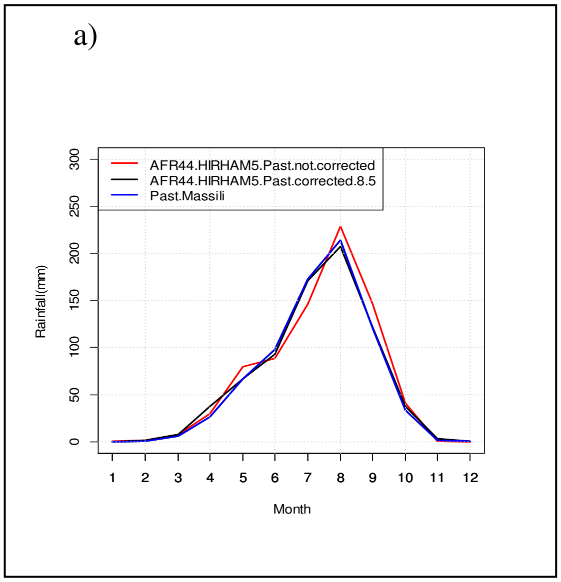


Figure41a) Past monthly mean temperature as simulated by AFR 44 HIRHAM58.5; b)Past and monthly mean temperature as simulated by AFR 44 HIRHAM5 4.5; c) Future monthly mean temperature as simulated by AFR 44 HIRHAM5 4.5; d)Future monthly mean temperature as simulated by AFR 44 HIRHAM5 8.5.

The figure below shows the monthly past (corrected and not corrected) rainfall over the past period up to the year 2050. Both AFR-44-HIRHAM5 4.5 and 8.5 are showing an increase in rainfall patterns. The increasing trend of rainfall indicated corroborates and may attest the finding of Salack et al. (2011) on the Sahel growing green again.



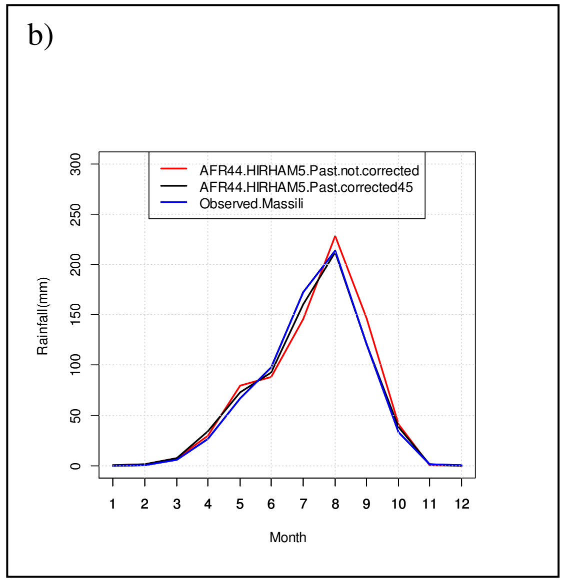


Figure 42: a) Past corrected and not corrected monthly rainfall as simulated by AFR 44 HIRHAM5 rcp 8.5 over 1975-2000 in Massili catchment ; b) Past corrected and not corrected monthly rainfall as simulated by AFR 44 HIRHAM5 rcp 4.5 over 1975-2000 in Massili catchment.

The AFR-44-HIRHAM5 data predicts an increase of Tmean by 1.8 ° C (RCP4.5) and 3.0 °C (RCP8.5) from 1971 to 2050. With an increase of 7.5 mm (RCP8.5) and an increase of 14.8 mm (RCP4.5) in rainfall until 2050 both rainfall scenarios from AFR-44-HIRHAM5 provide increasing estimates

6.4 Discussion on RCM simulations

The findings of this study show that RCMs simulations raw datasets are a source of huge uncertainty which may hamper subsequent impact simulations. Consequently, bias correction seems to be primordial for climate-change impact studies despite the problematic aspects related to bias correction methods (Ehret et al., 2012). To obtain realistic rainfall and temperature in the past and future climate, the delta change method was used. The application of this method showed a satisfactory performance and transferability to potentially changed climate conditions, as it was able to correct the past and future climate conditions. However the limits of delta change method should not be neglected. Indeed, according to Teutschbein and Seibert (2012), physical causes of model errors are not taken into account and, thus, a proper physical foundation is missing .In addition, spatiotemporal field consistency and relations between climate variables are modified. They also highlighted that conservation principles are not met, variability ranges might be reduced without physical justification and feedback mechanisms are neglected (Ehret et al., 2012). The added value of bias correction methods is questionable in a complex modeling chain with other major sources of uncertainty (Muerth et al., 2013). From the analyses carried out, it can be concluded that in general it will appear an increase of climatic patterns both in rainfall and temperature values. Thus the worst impact of climate change on Massili basin is unavoidable.

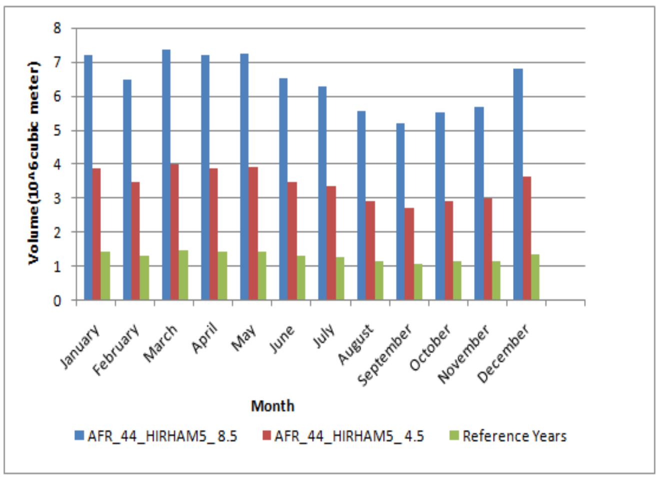
The increasing trends of temperature and rainfall are in line with the IPCC (2014) findings which state that global surface temperature change for the end of the 21st century is likely to exceed 1.5°C relative to 1850 to 1900 for all RCP scenarios except RCP_2.6. It is likely to exceed 2°C for RCP_6.0 and RCP_8.5, and more likely not to exceed 2°C for RCP_4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP_2.6. Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform. The study showed that linking historic climate data with RCM projections are suitable assessing long-term climatic trends and, therewith, providing the required knowledge to develop climate adaptation strategies in Burkina Faso.

Result on water allocation under climate change and human pressure

- **Water supply requirement for all scenarios**

The water demand for Ouagadougou water supply changes according to the scenarios. The demand will increase more under RCP_8.5 scenarios. Analysis of the average monthly unmet demands from water supply shows an increase of water need up to 6.5 million of cubic meter in April-May with RCP_8.5 scenarios while scenarios 4.5 simulate a future unmet water supply demand less than 3.5 million of cubic meter in April-May period. Thus both scenarios show increasing unmet water supply demand. The increase of water supply demand is linked to the increase of population and climate change. Moreover, market gardening around the dam with use of pesticides and fertilizers is leading to the dam silting and water quality depletion. Therefore the combined pressure (anthropogenic and climate) on water resources will increase the water supply demand by 2050. This is in agreement with the fact that water demand is anticipated to increase while water supply is anticipated to decrease (Peterson and Keller, 1990).

b)



b)

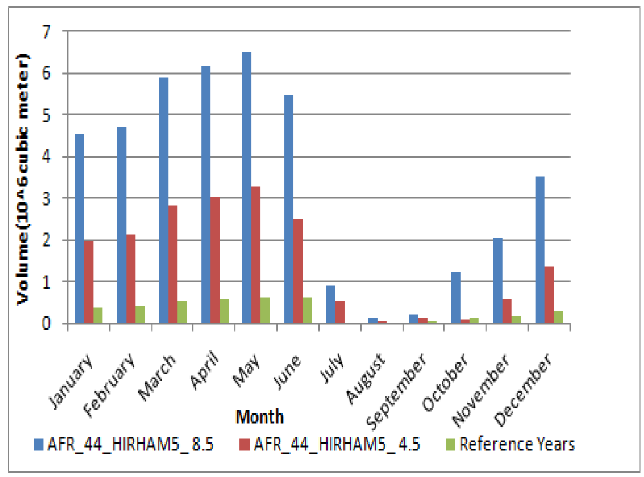
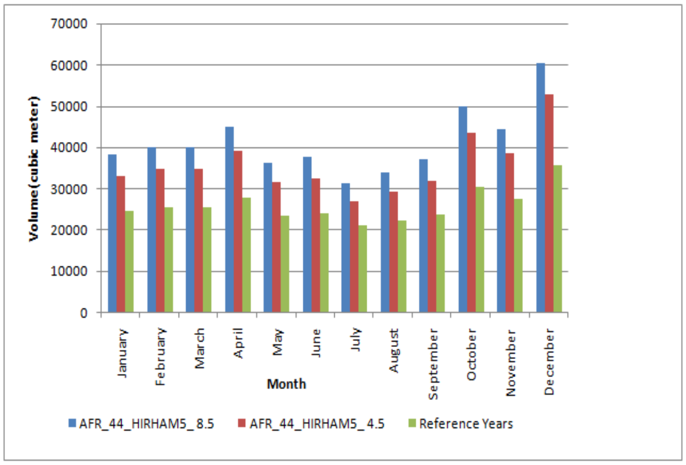


Figure 43: a) Annual average of Water demand for water supply sector; b) Loumbila dam water supply unmet demand for all scenarios

- **Public work water requirement for all scenarios**

The water demand for public work is increasing over the time with a slight increase in scenarios 8.5.Those increase may reach 65000 CM /month (mainly in December). Analysis of the average monthly unmet demands from the public work shows an increase of water need up to 69000 cubic meter in December under RCP_8.5 scenarios a)



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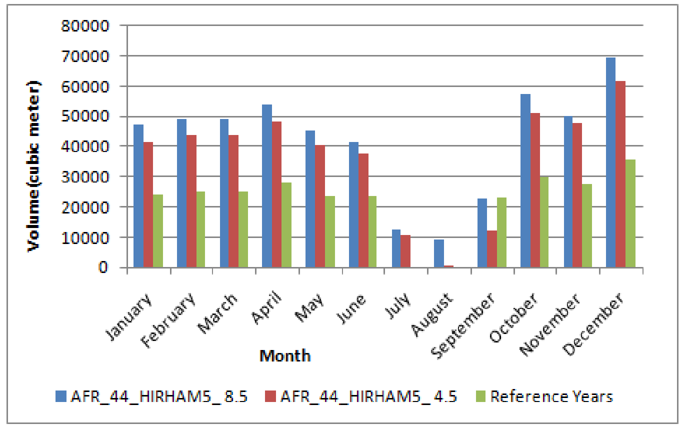
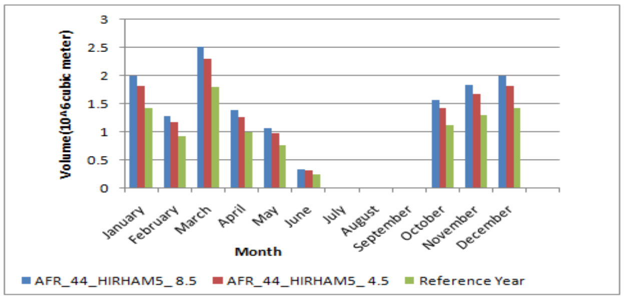


Figure 44: a) Water demand for public work; b) unmet water demand for public work.

- **Irrigation water demand for all scenarios**

Figure 45 (a) shows the monthly average of water gardening need over the period of simulation. The water need varies according to the scenarios . It can be noticed that the simulation is in correlation with the market gardening irrigation schemes (October to June). Under RCP_8.5 scenarios, the water demand for irrigation will increase more than under RCP_4.5 scenarios. The chapter on climate variability in the basin shows how the temperature will increase in the watershed. Thus, agriculture water consumption will increase due to water scarcity, cultivated area expansion and increasing evapotranspiration. Figure 45b) shows the unmet irrigation demands of Loumbila dam. The analysis shows an increase of water need up to 750,000 cubic meter for the baseline year and RCP_8.5 scenarios. The increase in unmet irrigation demands by 2050 can be explained by the effect of population growth which will lead to high demand in vegetable. Thus despite the increase in precipitation the unmet irrigation demand will increase by 2050.

a)



b)

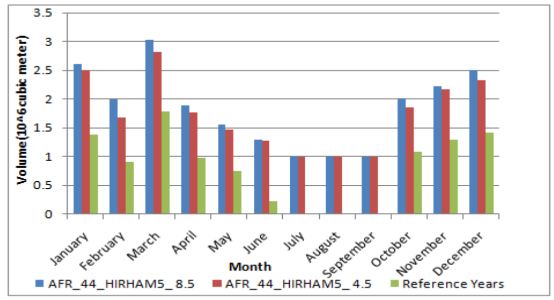


Figure 45: a) Water demand for irrigation ; b) unmet water demand for irrigation.

6.5 DISCUSSION AND CONCLUSION

The Loumbila dam´s water allocation under climatic and human pressure based on WEAP modeling shows an overall increase of the water need over the period of the projection. It can be noticed that from all the analysis the scenarios RCP_8.5 shows a high increase of the water demand for the different users. In recall RCP scenario was set in the WEAP modeling as an increase of rainfall up to 1.7 % and an increase of the mean temperature up to1.06%.

With respect to the result, it could be concluded that the WEAP model reproduces well the water balance for the RCP_4.5 and RCP_8.5 scenarios. The upward trends of the climate variability and population growth will have a huge impact on Loumbila dam´s water availability. Studies have shown that with the increasing population growth, industrial development and expansion of irrigated agriculture activities, water demand will continue to rise to a point where the task of providing water will be very difficult. The key finding of this chapter can be summarized in two points: the necessity to apply delta change method to correct RCM raw data, the assessment of correction factor to correct Thornthwaite´s formula application in the Massili basin. In addition, it can be concluded that in general it will appear an increase of climatic patterns both in rainfall and temperature values. Thus the worst impact of climate change on the Massili basin is unavoidable.

This study has investigated d the possible changes in water availability and demand within the Massili basin. Two scenarios of demand were used and were run for a period of 50 years. The results show that the Massili basin will face water scarcity. The WEAP model for the Massili catchment along with the input data used to perform this study have some limitations which must be considered. The headflow data came from reconstitution using regression analysis. In addition, the irrigated area and crop water requirement were estimated in the framework of this study as no previous estimations were available. Thus those datasets need to be compared with future studies. All these estimations and limitations must be taken into consideration. Nevertheless, the findings of the study provide useful insights into water resources allocation in the catchment.

7 ChapterVII: CONCLUSIONS AND RECOMMENDATIONS

Conflicts over water resources in semi arid and arid regions of the world areas arose from disagreements about water access, control, and use, and frequently involved the marginalization of certain groups. Reservoirs are thus precious assets and tools for ensuring supply of water and integrated management is required to ensure equitable and sustainable water allocation. This thesis was developed around three objectives:

- To assess the Massili basin climatic variability, peasant perception on climate change and their link to climate variability;
- To estimate the Loumbila dam´s water balance
- To model the Loumbila dam water resource allocation under some climate change scenarios

Conclusion

Hydrological impact studies at local scale are particularly critical for an arid country such as Burkina Faso since climate change is expected to exacerbate the situations in Sahelian country. The thesis developed around the Loumbila dam aims at modeling water allocation under climate change and human pressure. Indeed, the Loumbila dam has been selected to address the challenges of water allocation under human pressure and climate changes in order to provide essential information to policy makers (ONEA and Nakambe water resources agency) in their decisions on allocation of the dam´s water resources. To reach these objectives, multidimensional methods were adopted taking into account the past and future climate trends, the hydrological processes, the prediction of streamflow in ungauged basins and population growth.

The first results depicted the Masilli basin as a watershed which is undergoing the worst impacts of climate change since the basin is experiencing the shortening of rainy seasons, occurrence of dry spells during the rainy seasons, increase in maximum and minimum temperatures. In addition, farmers are aware about climate change and this may constitute a strong base for the implementation of sustainable adaptation strategies. The second result related to the dam´s water balance estimation shows that from 2000 to 2005 the input was greater than the withdrawal. However 2005 is the year with most input while 2000 and 2001 remain the years with less storage. The assessment of water allocation under climate change shows that

AFRI44_HIRHAM5 output is suitable for the Massili basin hydrological impact studies. The application of corrected AFRI44_HIRHAM5 data to WEAP model shows an increasing water demand for all demand sites with an increase more highlighted under RCP_8.5 scenarios. Thus water allocation will face great challenges in the future as highlighted by Snover et al. (2003) who confirmed that both an increasing future demand from competing sectors and a decreasing natural availability of freshwater might strongly influence the relation between urban and rural areas. Indeed, climate change is projected to have negative impacts on the Loumbila dam´s water resources within the next decades including water availability reduction and potential competition among water users. Indeed, due to the decrease in rainfall and increase in temperature, the dam is projected to become increasingly unable to meet all requirements. There is a need to implement new water allocation schemes. Water from Ouagadougou series of three dams should be used for municipal sector withdrawal. Additional research should explore possible water pollution in the area.

Perspectives

Four new perspectives can be drawn based on the results of this thesis:

- **Modeling data acquisition and incertitude**

This study was realized in an ungauged basin where the inflow and the market gardening data have been reconstituted. However, the application of the regression method for inflow estimation may be a source of uncertainties as shown by the value of error margin. This may be explained by the fact that some of the referential watersheds were not juxtaposed to the study area. Thus for further study it would be important to select basins near the targeted watershed. This may reduce the uncertainties at this level. In addition, the different steps which led to the hydrological impact studies (RCMs data generation and scenarios simulations), could be a source of uncertainty. Since all the uncertainties were not considered in this study, it would be interesting for further studies to explore those uncertainties.

- **RCMs output and climate change scenarios**

Climate models have become an important tool in conducting hydrological impact studies. A huge quantity of climate models is available and their selection depends on the study area location. The output generated by climate models is complex and subject to a number of uncertainties from different sources. For the assessment of water allocation under climate change, projections are considered using AFRI-44-HIRHAM5 output under RCP_4.5 and RCP_ 8.5 scenarios. It would be interesting to use additional RCPs such as RCP_2.6 and RCP_6.0. Moreover, there would be much interest, for example in combining model output in order to obtain improved projections of climate change.

- **Water quality**

None of the scenarios considered in this study has involved the potential changes in the dam´s water quality. Indeed, the scenarios considered were related to the climate changes and population growth. However, one threat to the multipurpose nature of small dams is siltation which leads to loss of storage capacity (Mugabe et al. 2003; Lawrence and Hasnip, 2004). Frequent siltation evaluation and awareness of ways to reduce soil erosion should be carried out and measures taken to curb soil erosion in the catchments. Water quality issue is important since the allocation rely on the quality. Indeed, the level of the water pollution may involve additional cost for water treatment and this may be challenging. Thus further studies may incorporate concerns about water quality into water allocation under climate change studies.

- **Water allocation**

The main purpose of the Loumbila dam (water supply) has failed nowadays with the occurrence of activities around the dam such as irrigation. However, this activity involved more than 2000 persons which rely on their incomes to feed their families. Moving those populations to this place is thus challenging when it is known that market gardening contributes to alleviating poverty and improve livelihood conditions of the populations. Therefore integrated management of Loumbila dam is required and this approach should recognize that the market gardening could not be canceled around the Loumbila dam. Efforts must be made to re-introduce irrigation to the farmers in a user-friendly manner by avoiding pesticides and fertilizer and doing smart irrigation which take into account the quality of water.

- **Adaptation measures**

IPCC defines adaptation as adjustment in natural or human systems to a new or changing environment. In other words, adaptation is defined as the ways and techniques used to tackle climate change. Three terms are related to adaptation: coping range, resilience range, and failure range. A system with adaptation measures will be more resilient to damage in case of occurrence of severe events. This system will suffer lesser damage in an event with same level of severity, compared to another system without adaptation measures. Based on the importance of adaptation to climate change, future works shall include the development of adaptation measures as improvements in irrigation efficiency in market gardening and the purchase of water rights from fishing, municipalities and nautical sector during the modeling procedures. With regards to the climate pattern trends, it is recommended to settle relevant adaptation and mitigation strategies in order to cope with climate change by embedding climate-change information into existing planning processes.

ANNEX

ANNEX : QUESTIONARY

<table>
<tr><td colspan="6" align="center">QUESTIONARY</td></tr>
<tr><td colspan="6" align="center">« Massili basin farmers perceptions on climate change » 2013</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="2">Date /__/__/-/__/__/-2013</td><td colspan="2">N° fiche /__/__/</td><td>Activity</td><td></td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="6" align="center">I. Identification of the farmer</td></tr>
<tr><td>Village</td><td></td><td>Name of the owner</td><td colspan="2"></td><td>Age :</td></tr>
<tr><td>Status :</td><td>Native /__/</td><td colspan="4">Migrant /__/ (ethnic group) :</td></tr>
</table>

Literacy tongue :	No one /__/	Moore /__/	French /__/	Other /__/ (specify)

II. Organization of the farmer

Individual /__/	Consortium /__/	Cooperative /__/	Professional /__/	Occasional /__/

III. Structural data

Use of Fertilizer :	Yes /__/ No /__/			
Name of the Fertilizer :				
Fertilizer founding	Capital cover /__/	BRS /__/	Savings bank /__/	Others /__/ : …………....
Source of Fertilizer supply	Market /__/	Shop /__/	Displaced sellers /__/	Others /__/ : …………....

VI. CLIMATE CHANGE PERCEPTION
Have you already heard about climate change? **Yes /__/ No/__/**

If yes through which canal? (Radio, television, other?) If no do you think that climate is changing?
What is your perception about climate change? (How do you feel those changes?) Are there some comities for water resources management in the localities? (Dam, borehole , etc.)
Cites climate change impact on your society or activities? (How have you been affected by the climate change impact?) ➢ Irregularity rainfall ➢ Desease ➢ Drought ➢ Hunger ➢ Decrease soil quality ➢ rainfall scarcity ➢ decrease in rainfall ➢ increase in temperature ➢ increase in temperature ➢ increase maximum temperature ➢ meningitides ➢ malaria ➢ tension ➢ decrease in soil quality ➢ violent winds ➢ Loss of land ➢ crops decrease ➢ crops destruction ➢ Flooding ➢ Materials destructions ➢ Dam collapse

- Change in water resource
- Impossibility to cultivate some seed due to lack of water
- Late onset?
- Early cessation?

What important changes can you notice about your water resources?

- Rainfall decrease?
- water decrease
- Retreat of the water table (well level)
- Disappearance of temporaries water resources?
- Baffonds disappearance?

Face to those changes which strategies have you developed to cope with the changing climate?

- Social network, credit
- Forest production
- Artisanal mining extraction
- Exodus
- Activities diversification (trad, breeding ect…)
- Soil and water conservation techniques
- Increase of farming area
- Short cycle Seeds adoption
- Decrease of the number of meal per day
- Increase of man power

Do you know some old technics of water conservation which are not used nowadays but

may be useful?
If no, what adaptation strategies are you planning to implement to face with the changing climate?

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