UNIVERSITE D'ABOMEY - CALAVI (UAC)

INSTITUT NATIONAL DE L'EAU

Registered under N°: 5585-19/UAC/VR-AA/SA

West African Science Service Center on Climate Change and Adapted Land Use

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the degree of
DOCTOR of Philosophy (PhD) of the University of Abomey-Calavi (Benin Republic)
In the framework of the
Graduate Research Program on Climate Change and Water Resources (GRP-CCWR)
By

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Public defense on: 10/23/2019

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MODELLING THE IMPACT OF SMALL DAMS ON THE HYDROLOGICAL RESPONSES OF RIVER BASINS UNDER CHANGING CLIMATE CONDITIONS: CASE STUDY OF THE FAGA BASIN IN BURKINA-FASO

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DEDICATION

For supporting my recurrent absence, my lack of time and for being a source of courage throughout my journey, this thesis work is dedicated to my wonderful and lovely kids:

Ayman Yohan, Chris Nasser, **Fadela Marielle** and **Cheryl Djalila**

I also dedicate this work to my beloved mother

Mariam Cécile

For giving birth to me at the first place and supporting me spiritually throughout my life

And

To the loving memory of my father

N. Salif

ACKNOWLEDGMENT

This PhD work was realized in the framework of the West African Science Service Center on Climate Change and Adapted Land use (WASCAL) and was fully funded by the **German Ministry of Education and Research (BMBF) in collaboration with the Benin Ministry of High Education and Scientific Research (MESRS)** to which I hereby express my real gratitude.

Writing this thesis has been an intense period of learning in scientific level as well as live arena. I would like to take this opportunity to express my heartily and deep gratitude to all those who have supported and helped me so much across this period. I firstly express my heartfelt thanks to my supervisor Dr Barnabas. A. Amisigo for the continuous support of my Ph.D. study and research, for his patience, motivation, enthusiasm, immense knowledge and his usual understanding. His guidance helped along the research and the writing of this dissertation.

I am also grateful to my co-supervisor Dr Raymond. A. Kasei who was more than generous with his experience and precious time. Full of good will and comprehension, he helped me overcome numbers of difficulties.

I express my sincere thanks to Prof. Dr. Ir. Euloge K. Agbossou who rigorously directed this work with his strong experience and professionalism. I am grateful to Dr Sven Wagner from the Fraunhofer IAO, Mittenwalderstr, Garmisch-Partenkirchen, Germany for agreeing to serve on my committee and for his scientific contribution to this work. I am really fortunate to have performed my work with your collaboration.

I would like also to thank Dr Aymar Bossa for his guidance and the opportunities he has afforded me.

My sincere gratitude goes to the staff of the Groupe of Research Programme on Climate Change and Water resources (GRP-CCWR) in Abomey-Calavi/Benin, Dr Julien Adounkpe our GRP Director and the accountant of the GRP Mr Kore Salem ELEGBEDE. Thanks to Prof. Abel. A. Afouda, our farmer Director, he has been not only a Director but also a “father” to me. My warm thanks also go to Prof. Emmanuel Lawin, the Deputy Director for his spiritual support when things hurt.

My heartily thanks go to the staff of WASCAL Competence Center in Ouagadougou, Dr Boubacar Barry, Dr Mahamoudou Sylla and the others for their usual encouragement.

I would like to recognize my dear fellows of the second batch of the GRP-CCWR who greatly supported me and were willing to help me.

I extend my gratitude to Mr. Vincent Ouedraogo from DEIE, Ouagadougou and to Mr. Yacouba Yra for their always willingness and availability for me whenever I needed help. They enlightened me the first glance of this research. I will always appreciate all you did for me.

I would like to acknowledge my brothers and sisters for their continuous moral support and encouragement. They have never left by my side. I express my warm and sincere gratitude to all my friends for the vast amount of patience, divers support and prayers. Last but not the least my special feeling gratitude is expressed to my dearest husband who has been a constant source of support and encouragement during the challenges of graduate school and life. You always provided me with your love and your presence beside me and I am really grateful for your wonderful presence in my life.

ABSTRACT

In spite of its low emission of carbon dioxide Africa, specifically Sub-Saharan Africa is the most vulnerable to the effect of climate change. Many countries have already moved toward water scarcity and Burkina-Faso is part of the water stress countries.

To supply the water requirements of increasing populations and to meet economic development needs, building small reservoirs seems to be a promising option for water resources development in Burkina-Faso. However, water storage infrastructures may seriously affect, among others, the river flow regime which could worsen under climate change condition.

This study aims at assessing how small dams and/or climate change could impact river basin's hydrology with the case study of the Faga River at Liptougou gauging station located in Burkina-Faso.

For this purpose, hydrological parameters variation and climate extremes were assed in order to understand hydroclimatic behaviour over the basin throughout 1982-2010 using the indices of Nicholson combined to the Hanning filter and the non-parametric Mann-Kendall,Sen's slope test and RClimDex software with three climate stations and one hydrometric station data.

Then we assessed the hydrological changes using the WaSiM hydrological modelled flow for the 1950-1958 as baseline for comparison and the EasyFit software. A field survey were performed to evaluate the environment and the socio-economic impact of small dams on downstream communities

We finally estimate the future changes of the river flow under increasing small dams and/or change climate scenarios over the 2040-2070. Three GCMs' runs under RCP4.5 and RCP8.5 and 15% to 25% increase of dams' number scenarios were used to run the WaSiM model.

Results showed that annual precipitation increased by 18%. flow and potential evapotranspiration slightly increased of 3.48mm and 1.08mm respectively through 1982 2010 while annual mean temperature increased by 0.05^{0}C.

Model simulation under RCP 4.5 showed a decrease flow of about 10.6% and 16.3% for RCP 8.5 for Can_ESM2 while EC-EARTH model simulations under RCP 4.5 and RCP 8.5 showed that the interannual flow will increase by about 4.9 and 8.1 respectively along 2040-2070.

The simulation results showed that future increase in dams' number could reduce the interannual river flow by about 37.40% to 40.03% using 15% and 25% increasing dams' scenarios respectively. Combined dams and climate scenarios, under RCP 4.5 showed an interannual flow decrease of 3.75% for EC_EARTH and 32.8% for MPI_ESM. A decrease of 3.70 to 32.80% is observed for the total flow. RCP8.5 run show a surface runoff decrease of 22.1% with Can_ESM2 while MPI_ESM showed a baseflow decrease of 47.11% throughout 2040-2070.

Key words: Burkina-Faso, Faga, climate change, small dam, hydrological, flow, modeling, scenario.

SYNTHESIS IN FRENCH

Résumé

Malgré ses faibles émissions de dioxyde de carbone l'Afrique et particulièrement l'Afrique subsaharienne est la plus vulnérable aux effets du changement climatique et de nombreux pays font déjà face aux problemes de pénuries d'eau. Le Burkina Faso fait partie des pays ou le problème d'eau est crutial.

Pour satisfaire les besoins en eau de la population et pour répondre aux besoins de développement économique, un nombre important de petits barrages ont été construits le long des cours d'eau au Burkina Faso. Cependant, ces reservoirs pourraient affecter considérablement le régime d'écoulement des rivières pouvant s'intensifier sous l'effet des changements climatiques.

Cette étude vise à évaluer l'impact des petits barrages et des changements climatiques sur l'hydrologie de la rivière Faga au Burkina Faso.

Pour ce faire, nous avons évalué la variabilté des paramètres hydroclimatiques ainsi que les extrêmes climatiques afin de comprendre le comportement hydroclimatique du bassin de 1982 à 2010. Les données de trois stations climatiques et d' une station hydrométriques ont été analysées en utilisant les indices de Nicholson, le filtre de Hanning et le test non paramétrique de Mann-Kendall et Sen ainsi que le logiciel RClimDex.

Les changements hydrologiques dans le bassin aucours de la periode 1982-2010 ont ensuite été évalués en utilisant les débits de la période 1950-1958 simulés par le model hydrologique WaSiM comme débits de référence. Une analyse des fréquences des crues a été realisée à l'aide du logiciel EasyFit et une enquête sur le terrain a été menée pour évaluer l'impact socio-économique et environnemental des petits barrages sur les populations riveraines en aval.

Enfin, les changements hydrologiques futurs du basin sous l'effet d'une probable augmentation du nombre de petits barrages et / ou du changement climatique ont été estimés pour la période 2040-2070. Des données de trois models climatiques tournés sous les scénarios climatiques RCP 4.5 et RCP 8.5 ont été utilisées pour tourner le modèle hydrologique WaSiM avec les hypotheses d'une augmentation de 15% et 25% du nombre de barrages.

Les résultats ont montré que les précipitations ont legèrement augmenté de 18%. Le débit annuel et l'évapotranspiration potentielle ont légèrement augmenté de 3,48 mm et 1,08 mm respectivement entre 1982 et 2010 alors que la température moyenne annuelle a augmenté de 0.050 ^{o}C.

Les simulations de WaSiM sous RCP 4.5 montrent une diminution du débit d'environ 10,6% et 16,3% sous RCP 8.5 pour le model climatique Can_ESM2, tandis que les simulations du modèle EC-EARTH sous RCP 4.5 et RCP 8.5 montrent une augmentation du débit annuel d'environ 4,9 et 8,1 respectivement pour la periode 2040-2070.

Cependant, laugmentation future de 15% et 25% du nombre de barrages pourrait réduire le débit interannuel de la rivière d'environ 37,40% à 40,03% respectivement.

L'effet cumulé du climat et des barrages montre une diminution du débit interannuel de 3,75% selon le model EC_EARTH tourné avec RCP 4.5 et de 32,8% selon le model MPI_ESM. Une diminution entre 3,70 et 32,80% est observée pour le débit total tantis que l'évaporation connaitra une baisse entre 13,63 et 38,80% pour la période de projection. En utilisant le scenario RCP8.5, l'écoulement de surface diminuera de 22,1% selon le model Can_ESM2, tandis que le model MPI_ESM montre une diminution du débit de base de 47,11%.

Mots clé: Burkina-Faso, Faga, changement climatique, petits barrages, hydrologique, débit, modélisation, scenario.

Introduction

L'eau constitue une ressource vitale pour tous les êtres vivants. C'est un élément clé pour la croissance économique et le développement. Cependant, depuis les dernières décennies, la disponibilité de l'eau est compromise en raison du changement climatique ainsi que la variabilité spatio-temporelle des précipitations. "L'Afrique dans son ensemble est l'un des continents les plus vulnérables au changement climatique", selon le GIEC (2001, 2013) et de nombreux pays ont déjà pris des mesures pour lutter contre la pénurie d'eau. En effet, en Afrique de l'Ouest, depuis les cinq dernières décennies, on a observé une des plus grandes variabilités spatiales et temporelles des précipitations dans le monde. Cela a considérablement affecté les ressources en eau à travers la diminution des précipitations annuelles par rapport aux décennies précédentes. En général, depuis les années 1970, les précipitations annuelles totales sahéliennes ont fluctué autour de 400 mm, contre 520 mm pendant la période 1931-1960, comme l'ont indiqué Hulme et al (2001).

La construction de réservoirs d'eau semble être une option prometteuse pour la mobilisation des ressources en eau dans les pays traversant des pénuries d'eau comme le Burkina Faso.

Cependant, ces reservoirs de mobilisation d'eau peuvent affecter considérablement le régime d'écoulement des rivières sur lesquelles ils sont construits. Cette altération du regime d'écoulement pourrait s'intensifier sous l'effet des changements climatique

Cette étude vise à évaluer l'impact des petits barrages et/ou des changements climatiques sur l'hydrologie de la rivière Faga au Burkina Faso.

Zone d'étude

Le bassin de la Faga fait partie du bassin transfrontalier du Niger situé dans la partie Nord-est du Burkina-Faso. D'une longueur de 270 km, la rivière Faga à la station de Liptougou est située entre les longitudes 1 ° 31 'O et 00 ° 17' E et les latitudes 14 ° 23 'N et 12 ° 43' N et draine un bassin versant de 15 700 km2. Il est caractérisé par un climat soudano-sahélien avec une pluviométrie moyenne comprise entre 600-1000mm par an. Le bassin de Faga compte environ 19 stations hydrométriques (avec très peu de stations suivis) et abrite un nombre important de petits barrages (61) qui pourraient avoir un effet sur le comportement hydrologique de la rivière.

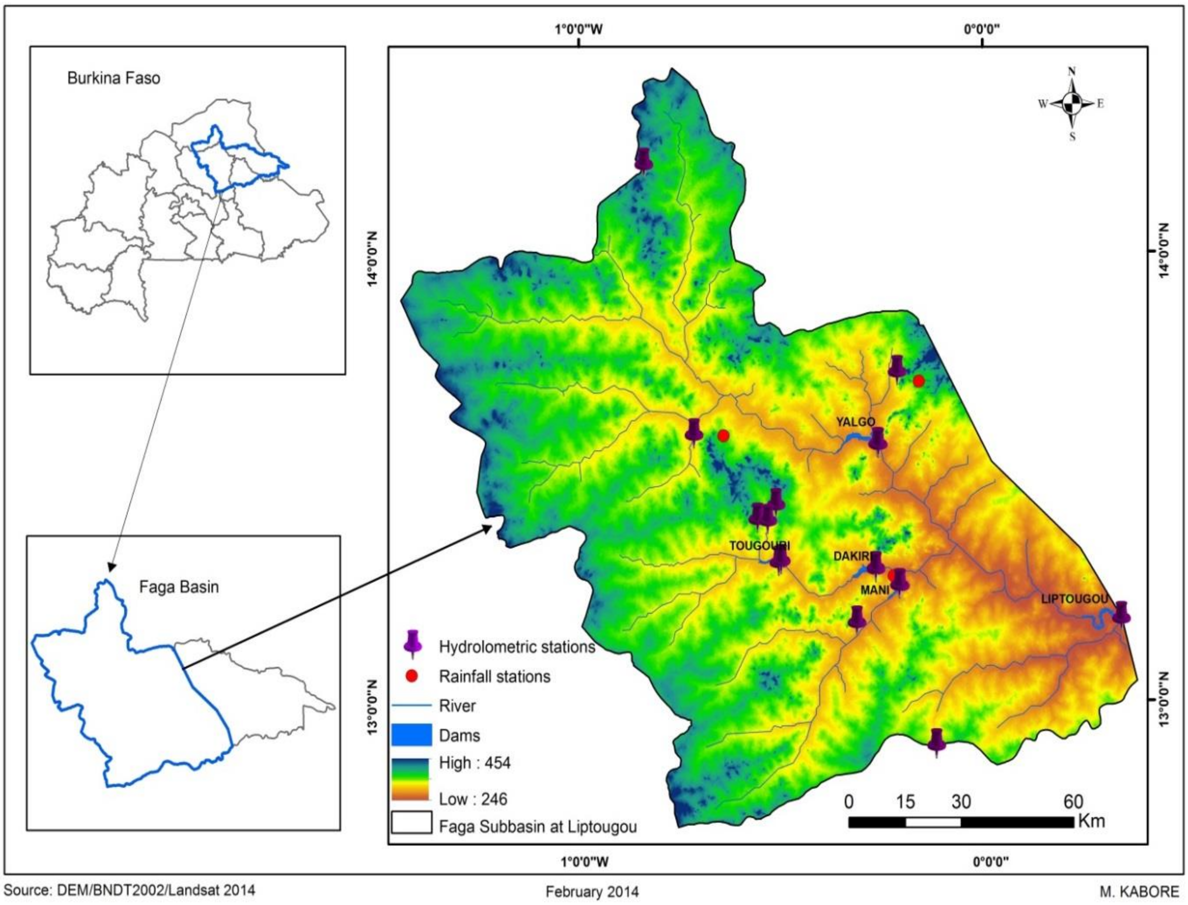

Figure 1 : localisation du bassin de la Faga

Le bassin de Faga est principalement caractérisé par un relief monotone constitué par une séquence de tumulus tabulaires. La végétation est caractérisée par une savane arborée ou arbustive dans la zone agro-écologique nord-soudanien tandis que la partie sub-sahélienne est constituée de steppes à combretum et à herbes annuelles (IGB 2002).

Matériel et méthodes

Afin d'évaluer l'impact actuel et futur du changement climatique ainsi que celui des petits barrages sur l'hydrologie de la rivière Faga à la station de Liptougou, Le modèle hydrologique Water Simulation Model (WaSiM) a été utilisé pour simuler le débit de la Faga à Liptougou avec les données de prélèvement d'eau ainsi que des données de trois modèles climatiques globaux à savoir Can-ESM2-LR, EC-EARTH et MPI-ESM2 qui ont été tournés sous les scénarios RCP4.5 et RCP8.5. Les models RClimDex et EasyFit ont respectivement été utilisés pour l'analyse de la variation des extremes climatiques et de la fréquence des inondations dans le bassin de la Faga. L'analyse des tendances a été réalisée à l'aide de la méthode de Mann-Kendal et de la pente de Sen. Dans la présente étude, les fluctuations interannuelles et saisonnières des variables hydro climatiques ont été effectuées à l'aide des indices de Nicholson à partir des moyennes des variables hydro climatiques annuelles normalisées pour trois stations dans la zone d'étude.

Résultats et discussion

L'analyse de la variabilité saisonnière et interannuelle des paramètres hydro climatiques révèle une augmentation de la température moyenne de 0.050°C entre 1982-2010 en conformité avec l'USGS et l'USAID, (2012) qui suggèrent que la température au Burkina Faso a augmenté de 0.60C depuis 1975. Cependant, la pluviométrie montre une tendance à la hausse de 18% durant la même période.

Aucours de la period 1982-2010 nous avons observé par exemple une diminution de 1,9% du nombre de jours de pluie consécutifs (CWD) ainsi qu'une augmention des valeurs maximales et minimales mensuelles de la température quotidienne (TXx) de 0,02 ºC.

Les débits moyens annuels actuels montrent également une baisse d'environ 54,10% par rapport à la periode de référence (1950-1958) avec une diminution de la fréquences de crues. En effet les crues quinquenales ont par exemple diminué de 15.72%. Celles de 10 ans connaissent une baisse de19.99% tandis que celles de 25-ans diminuent de 20.79%.

Selon 65% et 90% des riverains interviewés les populations en aval font face à une diminution des plaines inondables ainsi qu'une perte des moyens de subsistances respectivement. Aussi environ 28.6% reconnaissent une disparution de certains lieux sacrés.

Le model hydrologique WaSiM tourné sous le scenario climatique RCP 4.5 a montré une baisse du débit d'environ 10,6% et 16,3% sous RCP 8.5 pour le model climatique Can_ESM2, tandis que les résultats ont montré avec le model climatique EC-EARTH sous RCP 4.5 et RCP 8.5 une augmention du débit annuel d'environ 4,9 et 8,1 respectivement pour la periode 2040-2070. Cependant, l'augmentation future de 15% et 25% du nombre de barrages pourrait réduire le débit interannuel de la rivière d'environ 37,40% à 40,03% respectivement. L'écoulements intercirculaire connaitra

une diminution de 9,14% à 12,62% pendant que l’écoulement de surface augmentera de 13,57% à 20,78% aucours de la periode 2040-2070.
Les changements climatiques combinés à l’augmentation du nombre de barrages conduiraient à une diminution du débit interannuel de 3,75% selon le model EC_EARTH tourné avec RCP 4.5 et de 32,8% selon le model MPI_ESM. Une baisse entre 3,70et 32,80% est observée pour le débit total et l'évaporation entre 13,63 et 38,80% pour la periode de projection. En utilisant le scenario climatique RCP8.5 l’écoulement de surface diminuera de 22,1% selon le model Can_ESM2, tandis que le model MPI_ESM montre une diminution du débit de base de 47,11%. Les résultats indiquent ainsi que le régime de River Faga qui dépend de la pluie subit des changements de regime due à l’effet petits barrages ainsi qu’aux changements climatiques.
Une méthode multi-modèles pour l'évaluation des impacts s’avère nécessaire afin de rassembler une large gamme de données hydro climatiques pour soutenir la recherche de mesures d’atténuation et / ou d’adaptation aux impacts climatiques à l'échelle du bassin. De plus, des études d’évaluation des impacts du changement climatique devraient tenir compte des incertitudes liées aux models climatique et hydrologique dans leur modélisation.

Conclusion

La presente étude a évalué l'impact de la variabilité climatique et du changement climatique ainsi que des petits barrages sur l’hydrologie de la rivière Faga située dans la partie Nord-est du Burkina Faso. La fréquence des crues en tant que conséquence de la variabilité du débit de la rivière a également été évaluée. Les conséquences relatives au changement du débit des rivières sur les communautés vivant en aval ont également été évaluées. En outre, les changements futurs que l'hydrologie de la rivière pourrait avoir dans les conditions climatiques changeantes ont été projetés en utilisant trois modèles climatiques tournés sous les scénarios RCP4.8 et RCP8.5. Ctte étude fournit des résultats qui pourraient être le point de départ des études futures dans le bassin de Faga et pourraient être utiles pour l'atténuation et / ou l'adaptation à l'échelle du bassin.

LIST OF ACRONYMS

ACC:	Adaptation to Climate Change
AMAX:	Annual Maximum
AIMES:	Analysis, Integration and Modeling of the Earth System
ASCE:	American Society of Civil Engeneers
ASSAR:	Adaptation at Scale in Semi-Arid Regions
ASTGM2:	ASTER Global Digital Elevation Map
BDOT:	Base de Données d'Occupation des Terre
BNDT:	Base Nationale de Données Topographiques
CanESM2:	Canadian Earth System Model
CARIAA:	Collaborative Adaptation Research Initiative in Africa and Asia
CCCma:	Canadian Centre for Climate Modelling and Analysis
CLE:	Comité Local de l'Eau
CMIP5:	Coupled Model Intercomparison Project Phase 5
DEIE:	Direction des Etudes et l'Information sur l'Eau
DGRE:	Direction General des Ressources en Eau
DMI:	Danish Meteorological Institute
DRM:	Disaster Risk Management
ECEARTH:	Euro-Cordex Earth System Model
ECOWAS:	Economic Community Of West African States
FAO:	Food and Agriculture Organization
GAMS:	General Algebraic Modeling System
GFDL:	Geophysical Fluid Dynamic Laboratory
GIWA:	Global International Waters Assessment.
ICHEC:	Irish Centre for High-End Computation
IGB:	Institut Géographique du Burkina
IPCC:	Intergovernmental Panel on Climate Change
IWRM:	Integrated Water Resource Management
KNMI:	Koninklijk Nederlands Meteorologisch Instituut
LUCC:	Land Use Land Cover Change
MAHRH:	Ministère de l'Agriculture de l'Hydraulique et des Ressources Halieutiques
MATD:	Ministère de l'Administration Territoriale et de la Décentralisation
MM5:	Meteorological Model version 5
MPI:	Message Passing Interface
NAPA:	National Adaptation Program of Action
NGO:	Nongovernmental Organization

OEDC:	Observatoire Estrien du Développement des Communautés
PAGIRE:	Plan d’Action pour la Gestion Intégrée des Ressources en Eau
RCPs:	Representative Concentration Pathways
SDSM:	Statistical Downscaling Model
SMHI:	Swedish Meteorological and Hydrological Institute
SWAC:	Sahel and West Africa Club
UN:	United Nations
UNFCCC:	United Nations Convention on Climate Change
US:	United State
USGS:	United State Geographical Survey
USAID:	United State Agency for International Development
WASCAL:	West Africa an initiative of the West African Science Service Center for Climate Change and Adapted Land Use
WaSiM:	Water Simulation Model
WGCM:	Working Group on Coupled Modelling

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CHAPTER 1 : GENERAL INTRODUCTION

This chapter presents the context in which the study is undertaken, the problem and questions for which there is a need to seek for solutions. The objectives of this study, the research hypothesis, the novelty as well as the scope of the study are also presented in this chapter. The chapter finally presents the conceptual framework and the general configuration of the thesis.

1.1. Context and Problem Statement

Water is essential for every living creature. According to the United Nations World Water Development (2006), “Water is an essential life sustaining element. It pervades our lives and is deeply embedded in our cultural backgrounds”.

Water is needed by all living systems for survival. It is a key element for economic growth and development. However, since the last few decades water availability is compromised due to climate change with temporal and spatial rainfall variability. “Africa as a whole is one of the most vulnerable continents to climate change” as reported in IPCC (2001, 2013) and many countries have already moved toward water scarcity. In fact, in West Africa, since the last five decades, one of the highest spatial and temporal variability of rainfall over the world has been observed. This has significantly affected water resources through the decrease of annual rainfall compared to the preceeding decades. Generally, since the 1970s the Sahelian total annual rainfall fluctuated around the value of 400 mm, compared to 520 mm during the 1931-1960 period, as stated by Hulme et al (2001). This shift is presented as the impact of the global change on the hydrological cycle over West Africa. This observed hydrological cycle disturbance is an effect of the global change in climate pattern mostly due to the net increase of the greenhouse gas emissions. As observed by the United Nations Convention on Climate Change (UNFCCC) the least responsible for climate change are also the most vulnerable to its projected impacts. Indeed, Africa’s emission of carbon dioxide according to Boden et al. (2011), was estimated at 25912 million metric tons of carbon in 1950 and at 311207 million metric tons in 2008. In spite of this observed increase, Africa’s total emission of carbon dioxide emission is still less than for some single countries such as Mainland China, the U.S., India, Russia, and Japan.

Unfortunately, Africa, specifically Saharan Africa is the most vulnerable to the effect of climate change in spite of its low emission of carbon dioxide.

Burkina-Faso where the Faga Basin, our focus basin in this study is located, belongs to Sub-Saharan Africa and is one of the water scarce countries. The mean annual rainfall in the country is around 750 mm with high differences from the North to the South split in three climate zones. Indeed, less than 600 millimeters per year of rainfall are recorded in the sahelian zone in the North while 900 to 1200 millimeters per year are recorded in the sudanian zone located in the southern part of the country. In the sudano-sahelian zone located between the sudanian and the sahelian zone, an average of 600 to 900 millimeters of rainfall is recorded per year. Climate-related stress in Burkina-Faso is likely to worsen in the future, since a gradual trend of increased aridity is observed, adding to the decrease in length of the rainy season by 20 to 30 days and a southward shift of the 100 mm isohyet according to MAHRH, (2006).

This water stress situation is being further exacerbated by the country's rapidly growing population, which has almost doubled in the last two decades, rising from 8.8 million in 1990 to 15.2 million in 2008 (United Nations., 2008). Likewise, access to fresh water constitutes a major constraint for agricultural productivity and poverty reduction in sub-Saharan Africa (FAO., 2008). Some countries have difficulties to reach the Sustainable Development Goal which aims at hunger eradication and poverty reduction (FAO., 2008). So, in Burkina Faso as in most of semi-arid regions, one of the adaption strategies is based on multiplying water storage infrastructures such as small dams because water demand is becoming greater due to increasing food demand. However, water availability from small reservoirs is subject to climate change, which has the potential to alter the relation between small and large reservoirs (Krol et al, 2010). In effect, small water storage infrastructures may affect large reservoirs and other water bodies such as rivers due to water withdrawal.

Furthermore, the evidence of the degree to which and how climate change and climate variability will affect the amount of precipitation in the region is not clear so future change in precipitation and potential change in water resources availability and water use are still highly uncertain.

Population growth, the intensification of human activities and an increased water demand constitute the main drivers of change in stream flow in a river basin. Change in climate conditions may also influence stream flow.

According to Li et al (2007) and Wei and Zhang (2010), human activities such as water abstraction for diverse uses, land use and land cover change (LUCC) caused by forest disturbance, soil and water conservation projects, new dams construction and city expansion alter vegetation retention, soil water infiltration, and surface evapotranspiration and result in significant hydrological alteration. The study basin witnessed a rapid local economic growth due to mining which is a water consuming sector. This economic growth added to climate change led to serious water resources related issues over the basin. Indeed, according to

MAHRH.(2001) the Faga basin experiences great water stress compared to the others. For instance Karambiri et al (2011) has found that the Nakanbe River shows an increase of runoff while precipitation is decreasing.

A better understanding of how climate change and human activities such as building water storage infrastructures over the Faga River basin affect the basin's hydrological processes will be crucial for the planning and management of water resources, and for achieving sustainable development in downstream of the basin. Hence, assessing the impact of climate variability and human activities on hydrological processes in the basin is important for water resources planning and management and for a sustainable development of the Faga hydrological system.

The present study seeks to assess how changing climate conditions and/or water storage infrastructures could affect a river basins' hydrology with a case study of the Faga river basin in the North-eastern Burkina-Faso. It is part of the climate change impact assessment over West Africa, an initiative of the West African Science Service Center for Climate Change and Adapted Land Use (WASCAL).

1.2. Literature review

1.2.1. Climate change

Climate change can be defined as a systematic change in long-term statistics in a given region of climate variables like temperature, wind velocity, humidity and atmosphere pressure over time scales ranging from decades to millions of years. Global warming is described as the increase in global temperature and its consequences on the other climatic variables. Global surface temperature increased by 1.0°C since the pre-industrial society to date and could reach 1.5°C between 2030 and 2052 (IPCC, 2018).

Since 1900 Africa has witnessed a warming climate due to the increase of the greenhouse gas emission. According to James and Washington., (2013), African temperatures will increase more rapidly than the projected change in global mean temperature over the 21st century. We need to note that some African countries are experiencing more warming than others as highlighted in the IPCC Fourth Assessment Report (Boko et al, 2007). A number of studies present different climate change scenarios regarding Africa according to Christensen et al., (2007).

Falkenmark (2007) projected that a warmer and drier environment is expected in the Sahelian region while CARIAA and ASSAR (2015) report that model projections indicate very different responses of the regional climate for the selected future Greenhouse Gas forcing scenario going from drier to wetter increases (over 300mm) in the annual average rainfall. However,

the average annual temperatures are globally projected to rise by 0.3 to 2.5°C by 2050 relative to the 1985 to 2005 average (IPCC, 2013).
The National Adaptation Program of Action (NAPA) which was instrumental in assessing vulnerability and adaptation capacities to climate variability and change showed that Burkina-Faso will experience a 0.8°C rise in average temperature by 2025 and a 1.7°C rise by 2050 compared to 1961-2010.
Rainfall will be affected by a relatively low drop of -3.4% by 2025 and -7.3% by 2050 and this decrease in rainfall would be coupled with a very strong seasonal and inter-annual variability of climatic factors (World Bank, 2011)

1.2.2. Climate Change impact on water resources and river basins

Many studies suggest that in Africa, climate change will have an effect on future water stress. Climate change will amplify existing stress on water availability in Africa and water resources will be subjected to high temporal and spatial variability. This would be a major constraint on the continents' continued economic development. According to Niang et al. (2014), the impacts of climate change on the existing water stressed catchments will be accentuated with the complex land uses, engineered water systems, and a strong historical, socio-political and economic footprint. We must note that the future water scarcity projected to be faced in Africa due to change in climate pattern may be exacerbated by other drivers such as population growth, urbanization, agricultural growth, and land use changes (Abouabdillah et al 2010; Beck and Bernauer 2011; Tshimanga and Hughes 2012; Niang et al 2014).
Indeed, Africa faces the challenge of providing enough water for its people and ecosystems in a time of growing demand and increased scarcity (Africa water atlas, 2010). It has been predicted that the proportion of the African population at risk of water stress and scarcity will increase from 47% in 2000 to 65% in 2025, affecting 18 countries (Bates et al., 2008). ECOWAS-SWAC/OEDC (2008), state that West African countries share their surface water resources which are concentrated in few watersheds. Indeed, the Niger, the Lake Chad, the Senegal, the Gambia and the Volta River Basins constitute the main transboundary watersheds in West Africa. However, following the climate shift since the 1970s in addition to land use changes and water withdrawals, changes in the rivers' flow have been observed. Descroix et al (2013) found that Variations of rainfall have led to strong fluctuations in river discharge with a generally negative trend from 1960 to 2010. For instance, between 1971 and 1989 the Niger River at Onitsha in Nigeria dropped by about 30% and the Senegal and the Gambia by about 60% for the same period (GIWA, 2004). According to Wuebbles and Ciuro (2013), changes in hydrological behaviour may become even more important in the

future due to the observed global warming which will affect the temperature and the rainfall, the key climate variables.

On the other hand, despite the reduction in annual rainfall in the sahelian part of Burkina-Faso, the average runoff and maximum daily discharge have increased since 1970 (Mahé, 2005). The maximum daily discharge has increased by about 100% from 1972 to 1998 (Mahé et al, 2010).

Karambiri et al., (2011) also showed that discharge in the Nakanbe Basin in West Africa will generally increase in the coming decades compared to the 1991-2000.

1.2.3. Uncertainties in climate change impact assessment

Results of climate forecasting and climate change impact assessment studies performed around the world show substantial change in mean runoff, and water availability, etc. with global warming at different rates. However, climate change estimations are burdened by a large amount of uncertainties rising from both climate models and climate scenarios. First, the General Circulation Models (GCMs) output are statistically or dynamically downscaled and suffer not only from uncertainty due to downscaling methods but also GCMs uncertainty. Downscaling is performed in order to bridge the spatial and temporal resolution gaps between what climate modellers are currently able to provide and what impact assessors require (Wilby and Dawson 2007). According to New and Hulme (2000), uncertainty in GCMs is due to the inadequate information about the underlying geophysical processes of global change and variability in the internal parameterizations of each GCM. Another source of uncertainty is that the initial climate state that is the input initial condition, in climate forecasting is almost scientifically unknown. According to IPCC (2007), scenario uncertainty is associated with the unpredictability in the forecast of future socio-economic and human behavior resulting in future uncertainty in hydrological predictions using GCMs output rise not only from GCMs and scenario but also from the hydrological model parameters on which we are interested in. In view of the potential sources of uncertainty in climate forecasting, there is likely a lack of appropriate real-time and future climate information that adequately capture future rainfall projection. Hence, climate change effect on water resources assessment is highly limited by the large uncertainties in climate models regarding West African rainfall predictions. Indeed, climate impact assessment studies results are dependent on the climate model used and the climate scenario that has been considered. For instance, Karambiri et al (2011) using the Regional Atmospheric Climate Model (RACMO) and Regional Climate Model (REMO) and Rossby Centre Regional Atmospheric model (RCA) models to assess the impact of climate variability and climate change on runoff in the Senegal River basin located in Senegal and the Nakanbe River basin located in Burkina-Faso from 1990 to 2050, found different results. Indeed, the RACMO model showed a slight decrease in annual precipitation over the Senegal River basin and an increase in annual precipitation for the Nakanbe River basin. On the other hand the RCA model showed a high upward trend in rainfall for the Senegal watershed (around 25-30%) and a slight downward trend for the Nakanbe basin. A decrease in trend was observed for both basins with REMO model.

Uncertainties seem to be considerable in climate prediction and climate change impact assessment. Nevertheless, uncertainties should not prevent decision-making policies.

1.2.4. Water Resource in Burkina-Faso

Water is one of the current and future main critical challenges facing Africa. Many studies showed that climate change will impose additional pressure on water availability and its access thus leaving a number of African countries in severe water scarcity in the coming decades. The IPCC, (2007) reports that by 2020, a population of between 75 and 250 million and 350-600 million by 2050, are projected to be exposed to increased water stress due to climate change. Climate change and variability are likely to impose additional pressures on water availability, water accessibility and water demand in Africa.

Burkina Faso belongs to water scarce countries where there is a lack of sufficient water due to its location in the arid savannah belt of the Sahel. The amount of the water withdrawal in Burkina-Faso is estimated in 2001 at 54.99m^3 /capita (FAO, 2013). The annual demand exceeds availability of water resources between 10% and 22% depending on the rainfall received that year according to the World Meteorological Organisation.

The average rainfall is around 748 mm/year (Africa Water Atlas 2010).The hydrography network of the region is composed of four main basins inclusive of the nakambe basin. Unfortunately most of the water in these basins is drained outside the country mainly towards Ghana. Andreini, (2002) estimated the annual water towards Ghana at more than 5 km^3. The total renewable water (surface and groundwater) is estimated at 12.5 cubic kilometers/year (Africa Water Atlas, 2010) and only 821 m^3 of freshwater is available per person annually, below the international scarcity threshold. The total water demand is estimated at about 1800 millions cubic meters per year with around 70% used for hydropower production (MEE, 2000). Moreover, the available water has come under pressure in the recent years due to population growth which has almost doubled in the last two decades alone, rising from 8.8 million in 1990 to 15.2 million in 2008 (United Nations, 2008). Projections showed that Burkina-Faso population could reach 56.5 million by 2050 (INSD, 2007). This increasing population provides the physical basis needed to support economically and ecologically sound water management decision-making to meet future needs.

1.2.5. Integrated Water resource management

According to Mahé et al. (2010), rainfall in Burkina-Faso, decreased by 15 to 20% from 1970 to 1998 due to change in climate patterns and is projected to be further exacerbated by future climate conditions. Because climate change could strongly exacerbate the inadequate and inequitable accessibility of the population to water resources, water access is of a great importance in Burkina-Faso.

To ensure water access for its growing population whose key challenge is water scarcity, Burkina-Faso has adopted the Integrated Water Resources Management promoted by the Global Water Partnership (GWP). Since 1988, the policy makers have been aware of the necessity to manage water for present and future generations. A number of actions have been taken and Burkina-Faso is one of the references in terms of water management in West Africa. Indeed, to handle the impact of climate change on water in Burkina-Faso, an Integrated Water Resources Management Action Plan (PAGIRE) was adopted in 2003, with the creation of a Permanent Secretariat (SP/PAGIRE) which is in charge of the implementation of the plan. Local Water Committees (Comité Local de l'Eau/CLE) have been created in each sub-catchment within the country, on which every usage sector is represented. Lately, the policy makers have seen the necessity to manage water resources by basin. The Nakanbe Basin Water Agency is the first to be set up in 2010 and nowadays each of the basins that composed the hydrography of the country has one Water Agency in charge of local water management.

This is to improve water management at the regional and the local levels. These structures work in coordination with each other and co-operate to implement the IWRM principles in Burkina-Faso.

1.2.6. Overview of Small Dams in Burkina-Faso

As mentioned above, Burkina-Faso has witnessed climate-related stress that will probably worsen in the coming decades and water quantity could decrease in the future caused by climate change and climate variability. In this context of uncertainty in future water availability and accessibility, building water storage structures has been identified to be a promising way in response to the growing population water demand. The construction of dams started during the severe sahelian drought between 1974 and 1987 to mainly ensure water for the populations and their livestock and is likely to continue. Around 523 reservoirs have been built between 1974 and 1987 and 335 between 1988 and 2001 according to Cecchi et al., (2009).

Currently, Burkina-Faso has a great number of small dams. In 2012, the National Water Management Directorate (DGRE) of Burkina-Faso inventoried more than a thousand (1000) dams over the country and many others are being built or are projected to be built. The IPCC, (2001) stated that the accumulation of numerous small reservoirs changes the water resources management practices procedures in the present range. It increases the flexibility for adaptation to current climate uncertainty and serves as a precursor to future possible responses with an indefined changing climate. Climate change adaptation constitutes the primary function of small dams. However, they hold an economic character since they are used for livestock production and irrigation. Therefore, they contribute to improve smallholders' standards of living.

1.2.7. Studies within the Faga Basin

The Faga River Basin is part of the shared Niger River Basin located in Burkina-Faso and is of great importance for the country. Following the climate shift observed since the 1970s and the density of small dams in the Basin, river water flow may have been altered with diverse potential consequences like conflicts over water, stream capture and flow interruption. Therefore, there is an evident need of hydrological investigation in this basin. Unfortunately, almost no advanced hydrological study such as climate related impact has yet been done in the basin. Traoré, (1991) elaborated an outline for hydrological assessment of the Faga basin.
Kaboré, (2010) made a synthetic analysis of the available water resource and its uses over the Faga basin. From this analysis he proposed some solutions for a better implementation of the Integrated Water Resource Management (IWRM) strategies over the Faga basin and Ouedraogo, (2011) indicated that it is necessary to prevent flood related events over the basin and reduce their consequences. It is important to have reliable and operational tools to suitably monitor river discharge. Therefore, the hydrological model GeoSFM was calibrated and validated for discharge simulation and found that the model is adapted to flood forecasting in the Faga Basin. These studies that were undertaken in the basin did not point out the hydrological changes that could have been observed through time in the basin due to climate and the increasing number of small reservoirs. This study intends to explore the hydrological behaviour of the Faga River basin following the observed global warning and growth in small reservoirs number.

1.2.8. Assessment of the WaSiM Model Application

The Water Simulation Model (WaSiM) has been widely used in many studies. For instance, Bharati et al., (2008) used the WaSiM model and GAMS to evaluate the conjunctive use of surface and groundwater in small reservoir-based irrigation systems characteristic of the

Volta Basin and got a successful simulation of the catchment hydrology. Indeed WaSiM was able to simulate acceptable water balances from which they developed a decision support system for improving the management of land and water resources in the face of potential environmental change in the Volta Basin. Among others they found that to increase water retention and water use within the catchment, management strategies must focus on reducing losses through evaoporatio and increasing groundwater recharge.

Wagner et al., (2008) using joint meteorological (MM5) and hydrological (WaSiM) models to perform water balance estimations for the White Volta catchment showed that the discharge hydrographs available at near real time show comparable and satisfactory results for different meteorological data sources.

By investigating water balance in the Upper Jordan Catchment using the physically-based model, WaSiM, Kunstmann et al., (2006) showed that the model is able to describe observed river discharges satisfactorily.

WaSiM also permits the simulation of regulated reservoirs, river branching and artificial abstractions including irrigation. It has been useful for simulating a wide range of hydrologic variables required for optimization in a data-scarce environment (Bharati et al., 2008).

The impact of climate change on water resources in the Volta Basin has been modeled by Kasei (2009). He showed that the model was suitable for discharge simulations. Forcing the WaSiM model with the Meteorological Model version 5 (MM5) and the Regional Model (REMO) he found that the mean annual discharge and surface runoff is increasing with MM5 and decreasing with REMO. In many other studies such as Schulla (1997), Jasper et al (2002), Gurtz et al., (2003), and Verbunt et al., (2003), as cited in Kasei (2009), WaSiM has also been used to assess the effect of climate change on hydrological regime satisfactorily within various river basins.

1.3. Thesis Objectives

1.3.1. General Objective

This study aims at assessing the impact of small dams and climate change on the hydrology of the Faga River.

1.3.2. Specific Objectives

Specifically, it will:

Assess the interannual and seasonal variability of the hydroclimatic parameters over the Faga River Basin;

- ✓ Investigate the socio-economic impact that the probable change in river flow may have for local communities over the basin;

- ✓ Investigate the impact of small dams on the river hydrology by evaluating the river flow changes;

- ✓ Assess the projected effect of climate change and dams on the river flow through 2040-2070.

1.4. Research Questions

This study aims to assess how and at what extent small dams under changing climate conditions can impact the hydrological behaviour of river basin in Burkina Faso through hydrological modeling using the Faga River Basin as a case study.
From this goal emerge the following research questions:

- ✓ How does climate vary in the Faga Basin and how this affect the Faga River's hydrology?

- ✓ Do small dams have significant impact on the hydrology of the Faga River? And

- ✓ How and what extent do small dams and climate change affect the Faga river flow over 2040-2070?

1.5. Hypothesis

To date, relatively few studies have assessed the impacts of climate change on hydrological regimes in West Africa and a clear picture of possible changes is lacking (Roudier, Ducharne and Feyen, 2014).
The present study hypothesizes that hydrological responses of a given river may be significantly influenced not only by existing small dams but also climate change with adverse effects in river flow regime and the socio-economic activities of riparian communities in the future .
Changes in river basin's hydrology result not only from hydro-climatic change but also from land use/land cover change. Indeed, studies such as Mahé et al., (2010); Karambiri et al., (2011) showed an increase runoff over the Sub-Saharan Africa owing to land use/ land cover

change. However, in this study impact of land use/land cover change on the Faga River flow was neglected. Indeed, we assume that modelling the impact of land use/ land cover change on large basin (>100Km^2) as the Faga River Basin may be difficult to discern owing to various land use and land cover(e.g. presence of multiple secondary vegetation), rainfall spatial variations and the existence of sustainable land management usages that may be observed in some parts of the large basin (Bruijnzeel , 2004).

Novelty

Most of the hydrological studies conducted in Burkina-Faso were focused on the Volta River Basin portion especially on the Nakanbe River. Very few studies and almost not any hydrological studies have been done with regard to the Faga River.
The particularity of this study lies on the fact that it is the first time a study involving hydrological assessment in the Faga Basin is being performed.

1.4. Scope of the Thesis

This work was able to detect the relative changes of the Faga river flow due to small dams and/or climate change. It also analyzed the variation of the hydroclimatic parameters through the 1982-2010 as well as change in extreme events. However, for dams' impact assessment, hydrological data recorded before and after the construction of the infrastructure to quantify the hydrologic changes imposed by dams and reservoirs on downstream river basin were used. Due to scarcity of hydrological data in the basin, pre-dams construction (1950-1958) flow was simulated from the calibrated and validated hydrological model and this may increase uncertainty in the results. In addition, water availability assessment was not done to exhibit awareness on the impact that dams and climate may have on the availability of water in the basin.

1.5. Expected results and benefits

The present study is expected to provide:

- ✓ A comprehensive analysis of hydroclimatic parameters variability over the Faga Basin;
- ✓ A quantification of the effect of the ensemble of small dams on the river flow

- ✓ Proper evaluation of the combined effect of dams and future change in climate on the projected changes in river flow.

These outcomes will increase the understanding of how and to what extent human activities such as small dams' construction as well as climate change could impact a sahelian river flow regime especially for decision-makers. They will also provide an outline for future studies in the basin.

1.6. Conceptual Framework

The aim of this section is to summarize the different steps followed by the present study to reach the objectives. It helps readers have an overview on what is going on in the study.

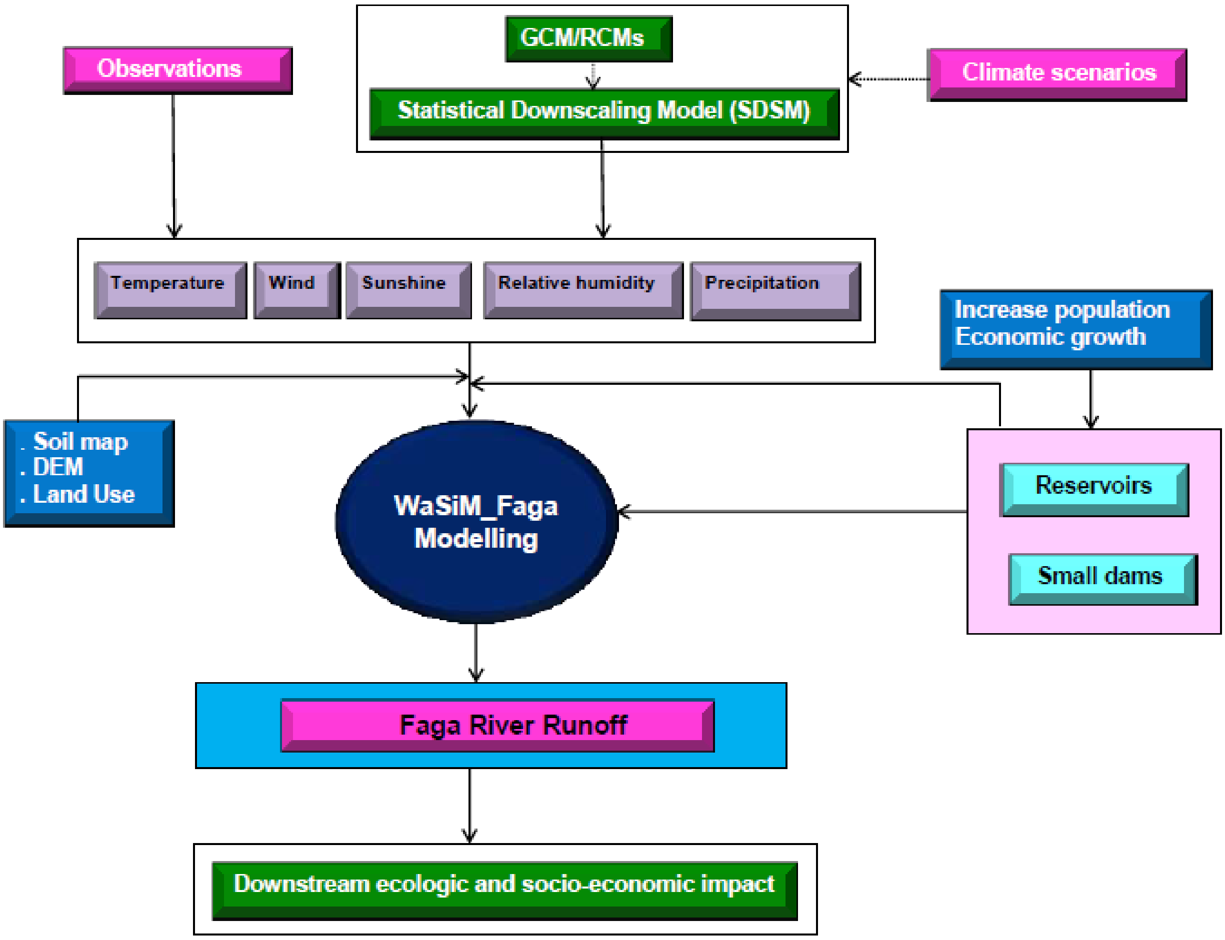

Figure1.1: Conceptual framework of the study

1.7. Outline of the Thesis

The structure of this study which is described in Chapter 1 comprises a general introduction to change in climate and water resources over the region. It also provides the research questions as well as the aim and objectives of the present study. It also contains the review of previous studies, the research questions, the scope of the study, the novelty and the study hypothesis. Chapter 2 describes the research area, giving specifically the physical aspects of the catchment. The hydrological and climatic data and their quality and suitability for running the hydrological model WaSiM are discussed in Chapter 3, and this section also discusses the materials and the methods used to perform the study. Chapter 4 presents the results of the assessment of the seasonal and interannual variability of the hydroclimatic parameters. Chapter 5 describes the hydrological impact of small dams on the River flow regime. The projected effect of small dams and change in climate on the Faga River behaviour is stated in Chapter 6. The last Chapter outlines the general conclusion of the work and perspectives for further research studies.

CHAPTER 2: STUDY AREA

This section describes the area in which the study was conducted. It indicates the geographical location of the area and describes the climate, the geography and the geology which characterize the basin. It also presents the hydrographic network as well as the social and economic aspects.

2.2. Localization

The hydrographical network of Burkina-Faso as shown in Figure 2.1 is made of three main international river basins: the Comoe basin with a watershed of 17 590 km², the Volta basin composed by the Nakanbe river (White Volta) with a watershed of 172 968 km² and the Mouhoun (Back Volta) basin with an area of 91,036 km² and the Niger basin (83 442 km²) with its tributaries including the Faga river. These basins are presented in Figure.2.1.

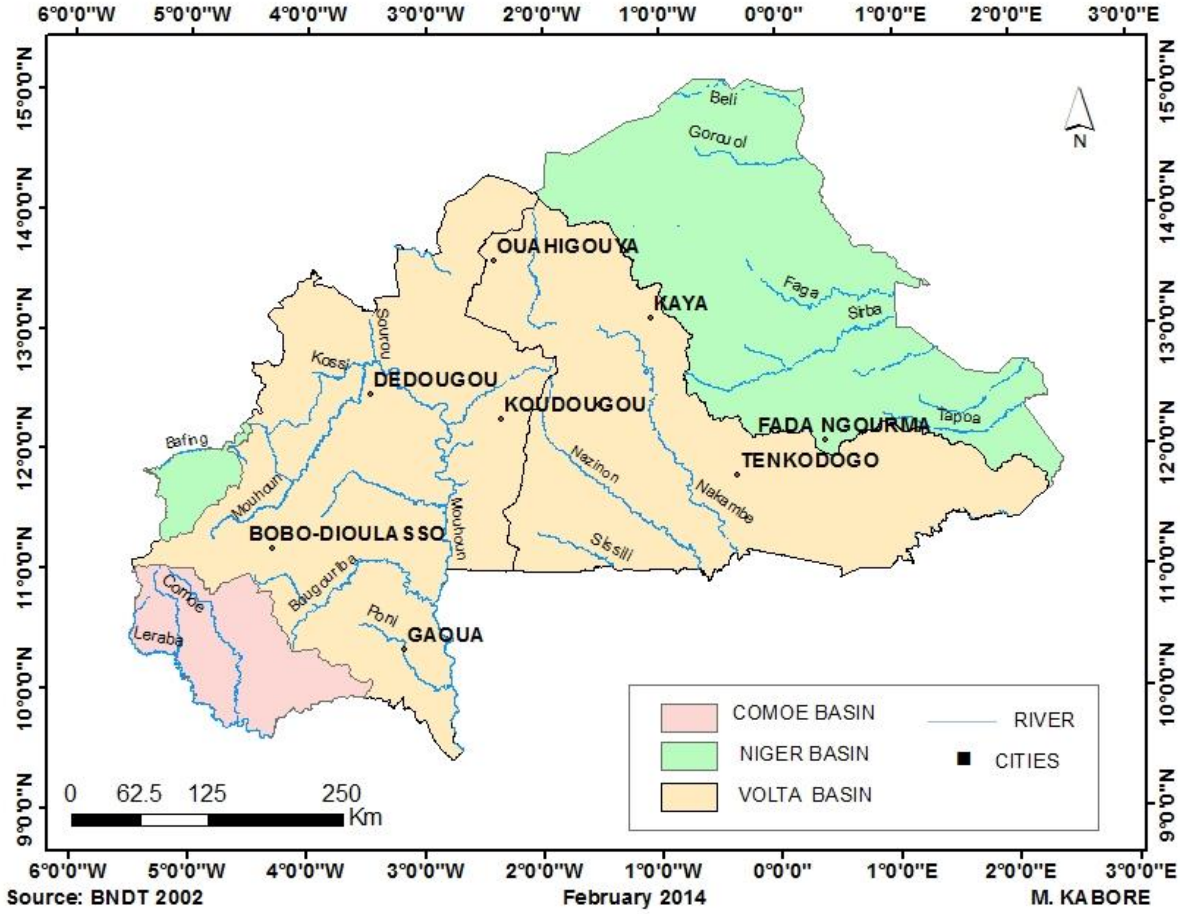

Figure 2.1: Tranboundary basins of Burkina-Faso

The area of interest in this study is the Faga Basin (Figure 2.2) which is a tributary of the Niger transboundary watershed situated in the North-eastern part of the country. With a length of 270 km, the Faga River at Liptougou station located between longitudes 1°31' W and 00° 17' E and latitudes 14°23'N and 12°43'N drains a watershed of 15,700 km^2. It is characterized by a Sudano-Sahelian climate with an average rainfall between 600-1000mm per year. The Faga Basin has around 19 hydrometric stations (with very few monitored ones) and hosts an important number of small dams (61) which may have effect on the main river behaviour.

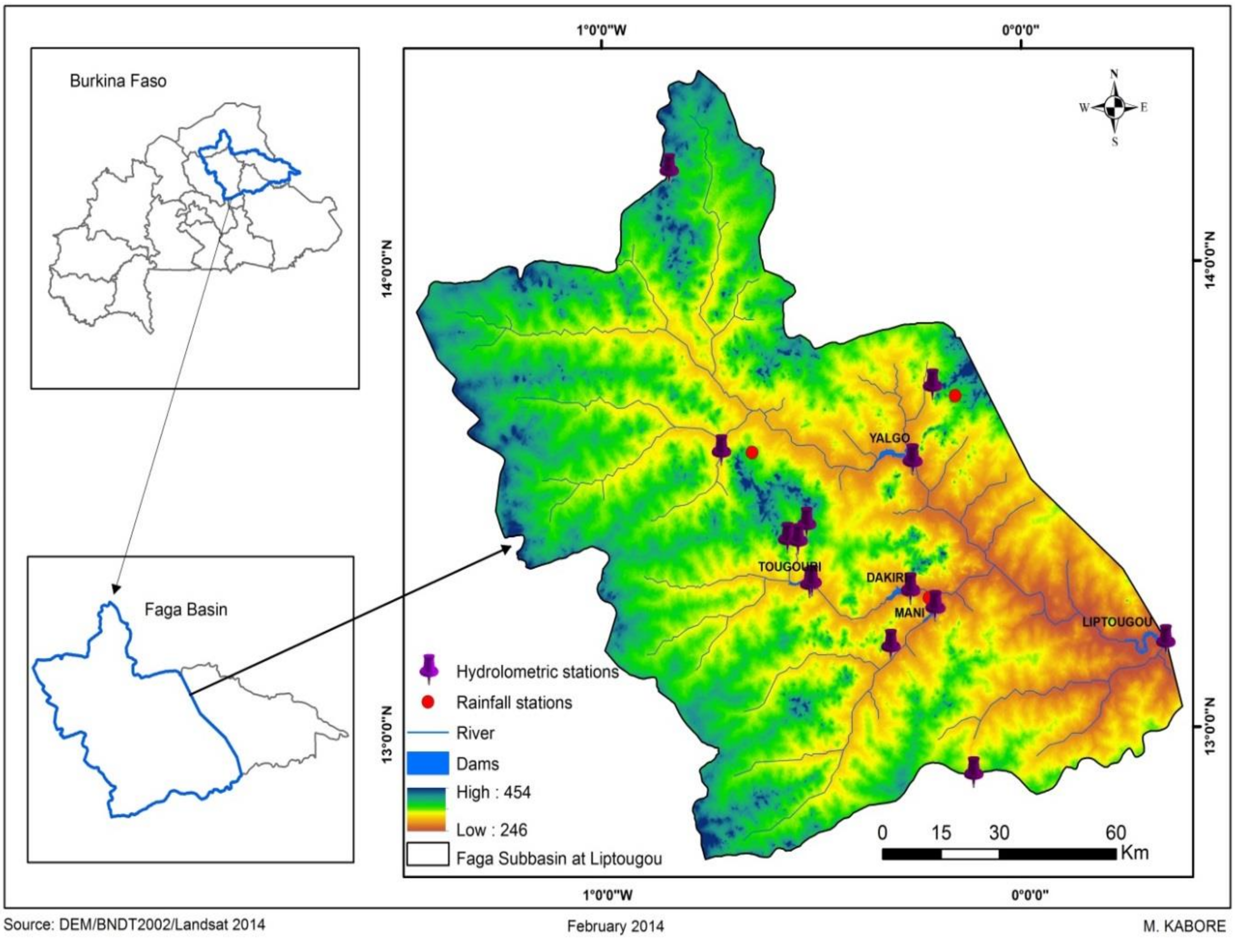

Figure 2.2: The Faga Basin at Liptougou and hydrometric stations

Moreover, it suffers nowadays from high degradation due to the combined effects of climate change and variability and anthropogenic activities such as agriculture, deforestation, over-grazing and mining (FAOWATER, 2010).

2.3. Relief and geology

The morphology of the Faga Basin is mainly characterized by a monotonic relief that is constituted by a sequence of battleship tabular mounds.

Characterized by a crystalline plinth, the Faga Basin's geology is mainly dominated by schistose and granitic formations. Figure 2.3 presents the geological formations found in the basin.

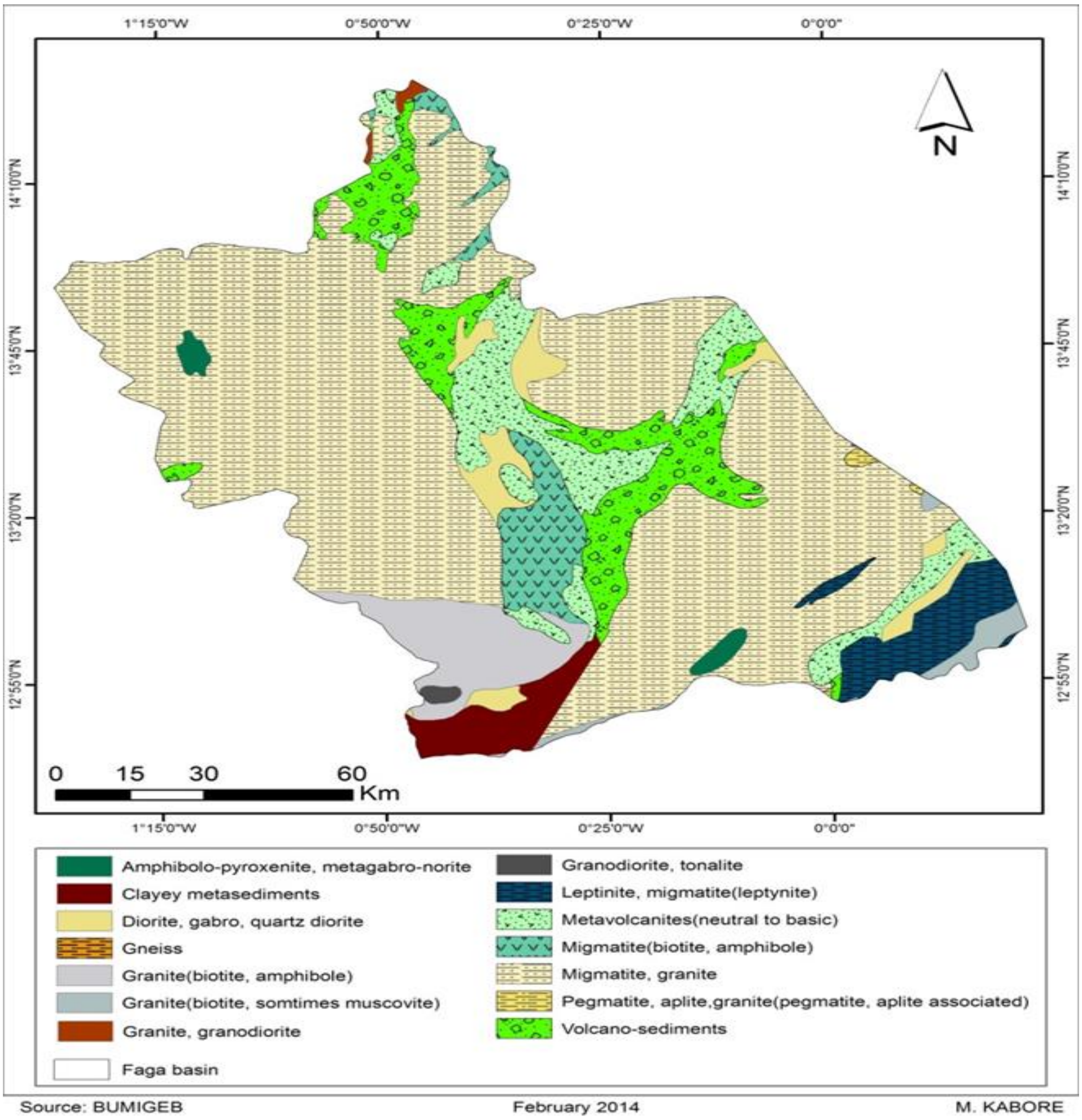

Figure 2.3: Geological formations of the Faga Basin

Such formations proceed from the geological history of Burkina Faso which is marked by Precambrian volcanic activity, Eburnean faulting and folding and fluctuations of sea levels, notably those contemporary with Hercynian movements (Zoungrana, 1991) cited in Kagone, (2006).

These geological events, followed by successive erosion cycles of the plinth which is later filled by Birimian formations, give rise to the relief basis that comprises an immense peneplain and sandstone plateaux. The Birimian formations consist of shale, quartz, sandstone and volcanic rock which constitute sedimentary formation and grano-diorite, grano-biotite rock with plutonic formation elements.

2.4. Vegetation

The vegetation is characterized by a savanna with trees or shrub in the north-sudanian agro-ecological zone while the sub-sahelian one is constituted by steppes with combretum and annual grass. According to Fontès and Guinko (1995), the steppes are usually shrubby, dominated by thorn-bushes of the genera Acacia and Balanites. They are under heavy pressure from livestock and the fodder trees and shrubs are overexploited by browsing, lopping for fodder and hacking off branches. The grass cover is sparse which protects them from bush fires. Ponds and their surroundings are covered by humid or aquatic grassland. In the Sub-Sahelian zone numerous ubiquitous sudanian and sahelian plants are found. The most characteristic are: *Acacia laeta*, *Acacia nilotica* var. *adansonii, Acacia senegal, Aristida hordeacea, Bauhinia rufescens, Combretum glutinosum, Cenchrus biflorus, Diheteropogon hagerupii, Andropogon gayanus.*

In the north Sudanian zone the savannas are dominated by trees which have been retained for mainly economic reasons *Adansonia digitata*, *Butyrospermum paradoxum, Parkia biglobosa, Tamarindus indica*. Some Sahelian elements are still present but the most typical grasses are the annuals *Andropogon pseudapricus, Loudetia togoensis, Pennisetum pedicellatum*, and the perennials *Andropogon gayanus* and *Cymbopogon schoenanthus*.

2.5. Climate

The Faga Basin is characterized by a Sudano-Sahelian climate. The West African Monsoon mainly drives an alternate short rainy season (about 04 months) and a long dry season (about 08 months).

The mean monthly temperature of the Faga basin varies between 25 (˚C) and 33 (˚C) as shown in Figure 2.4 and Figure 2.5. In general the mean monthly precipitation is estimated at around 230 mm at Bogande and 220 mm at Fada.

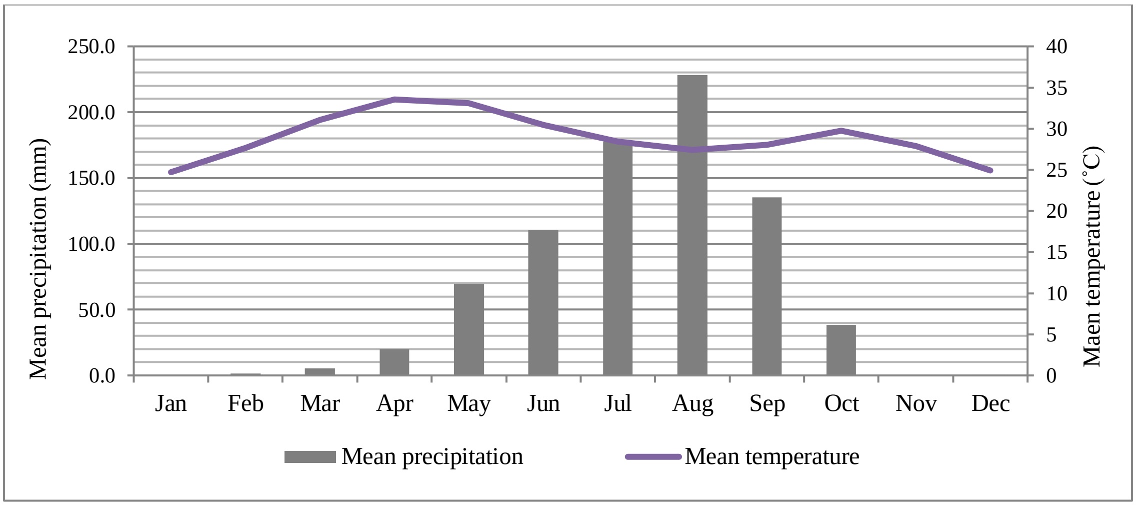

Figure 2.4: Mean monthly temperature vs. mean monthly precipitation at Bogande (1980-2010)

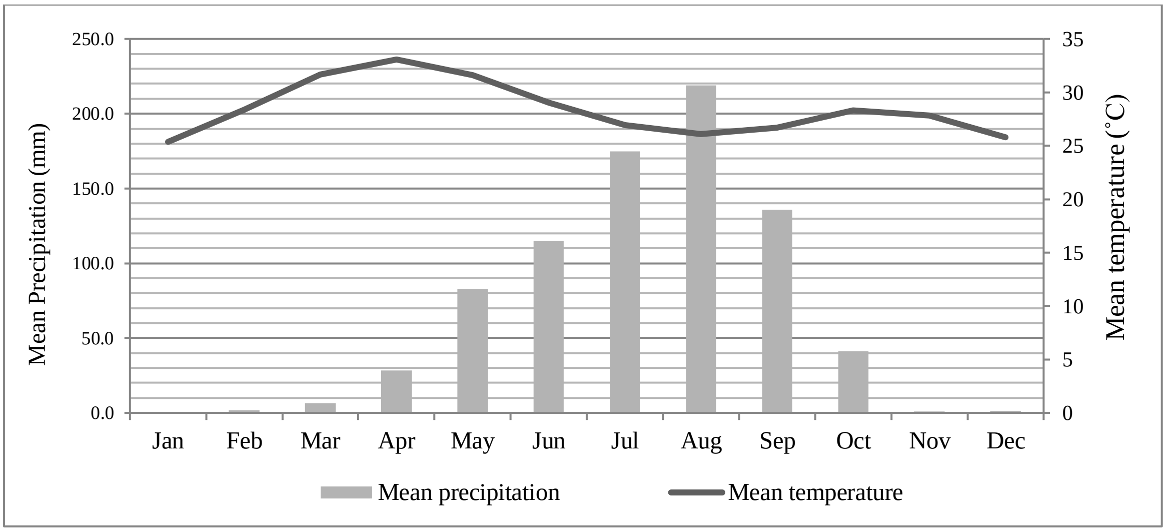

Figure 2.5: Mean monthly temperature vs. mean monthly precipitation at Fada N'Gourma (1980-2010).

2.6. Hydrography

The Faga River Basin is part of the Niger Transboundary River that flows in Burkina-Faso. It is well-drained with four main tributaries the Gouya, the Yali, the Kanbi and the Tengo rivers. The hydrographical network flow and its intermittent nature makes the Faga an ephemeral river where flow occurs only in the rainy season. Degradation due to sporadic floods and the relative long dry season modifies the Faga River network thus creating a number of floods spreading ponds. The runoff is characterized by a sahelian flow regime which begins with sporadic flow in May and increases in July-August where regular flow is observed. The river dries up around October leaving a string of ponds. Around 93.12% of the mean annual flow at Liptougou is observed between July and September. The mean monthly flow in this period is estimated at 41m^3/s in July, 86m^3/s in August, and 42m^3/s in September (Kabore, 2010).

2.7. Soil and Land Use

According IGB (2012), the Faga River Basin is characterized by eight main types of soil which are the following as presented in Figure 2.6.

The **Leached ferruginous** *soils* cover the greatest areas; basically they are found in the central part of the Precambrian peneplain, in the South of the thirteenth parallel. These soils have a variable texture, generally tending to be sandy in their surface horizons and clayey in the deeper one (below 40 cm). They drain badly, in accordance with their physical characteristics (low porosity and permeability). They all have a poor cation exchange capacity. They are regularly associated with gravelly soils.

The **Poorly evolved erosion soils** are mostly found in the northern half of the country. They are found over the granites and migmatites from which they are derived. They have a sandy surface horizon (15–20 cm) and an underlying clay horizon. The denseness and impermeability of that second horizon affects root penetration and the water regime.

The **Hydromorphic soils** are found on river alluviums or on fine weathered material. They have poor drainage and are regularly waterlogged in the rainy season. They are mostly developed in the west of the country.

The **Brown eutrophic soils** are characterized by their high clay content. The presence of swelling clays gives them a high exchange capacity and cation saturation. These are generally well drained soils; their surface structure is variable from crumby to prismatic. This is the characteristic that governs their fertility. They are found, in small patches, throughout the country.

The **Vertisoils** have the same textural parentage as the brown soils. They are distinguished from brown soils by the prismatic structure of their B horizon; a characteristic influenced by their low topographic position which makes them poorly drained. They are particularly developed in the south-east and south-west (valley of the Sourou).

The **Raw mineral soils** are poor, shallow and found on bed-rock or ferralitic pans. The vegetation found on them may be sparse or, contrarily, dense because they are not suitable for cultivation which keep them free from human intervention.

The **Halomorphic soils** are found in the north of the country. Their texture varies; their structure is frankly degraded. They are poor soils which are covered by a weak shrubby steppe.
The **Ferralitic soils** are found in the south of the country. Their area is very limited. Their profile is related to that of ferruginous soils but their physical and chemical properties are clearly different. They are distinguished by the kaolinitic texture of their B horizon which gives them satisfactory permeability. They are good agricultural soil; their natural vegetation is wooded savannah.

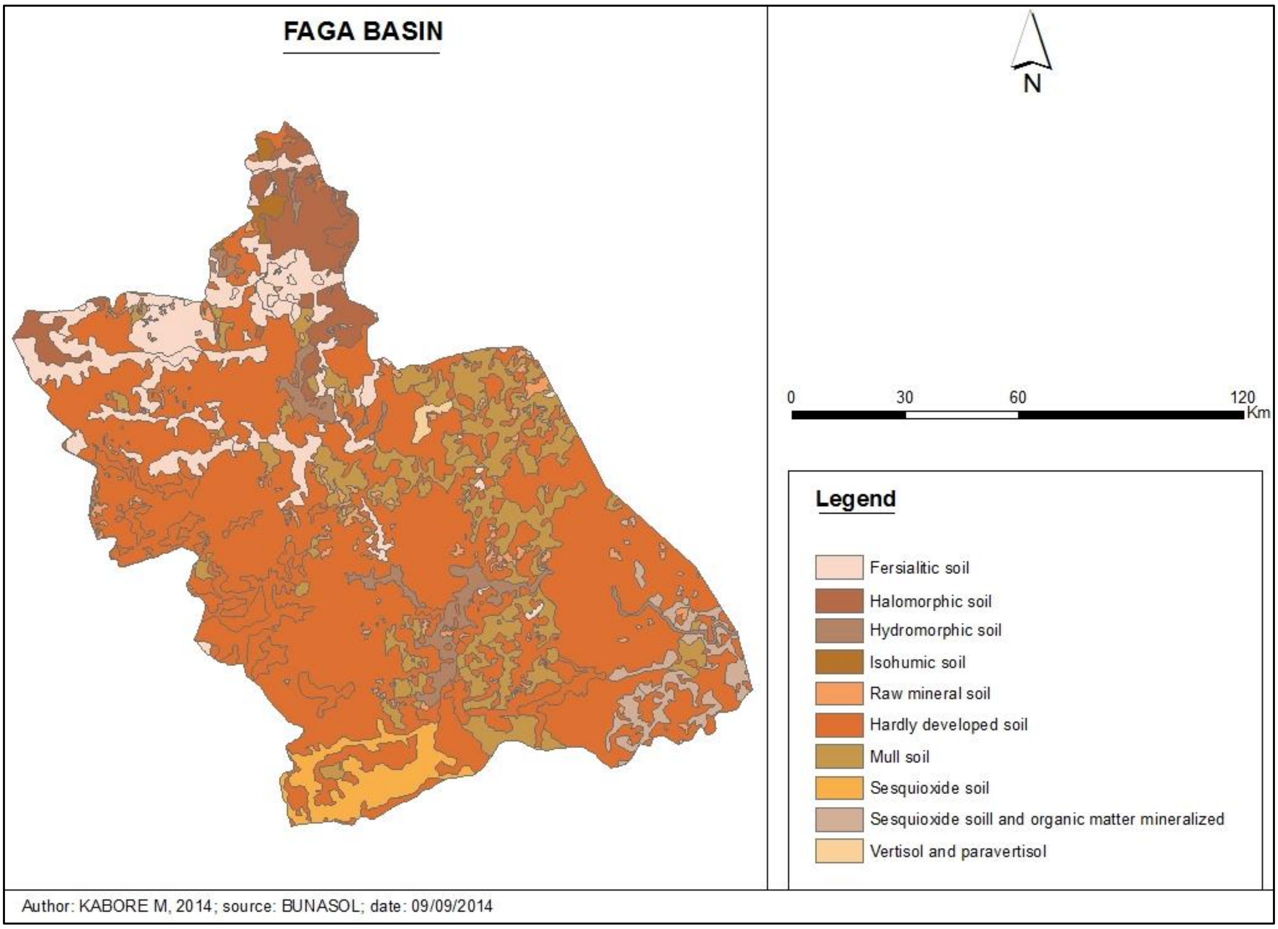

Figure 2.6: Soil types in the Faga Basin

The Basin, like the rest of the country, is mostly composed of agricultural land. Mostly made up of farmers, the population practices subsistence farming based on millet, sorghum and cowpea in the Sahelian part of the basin. In the North-sudanian part, the agriculture is based on sorghum, millet, cowpea and groundnut with some cotton.

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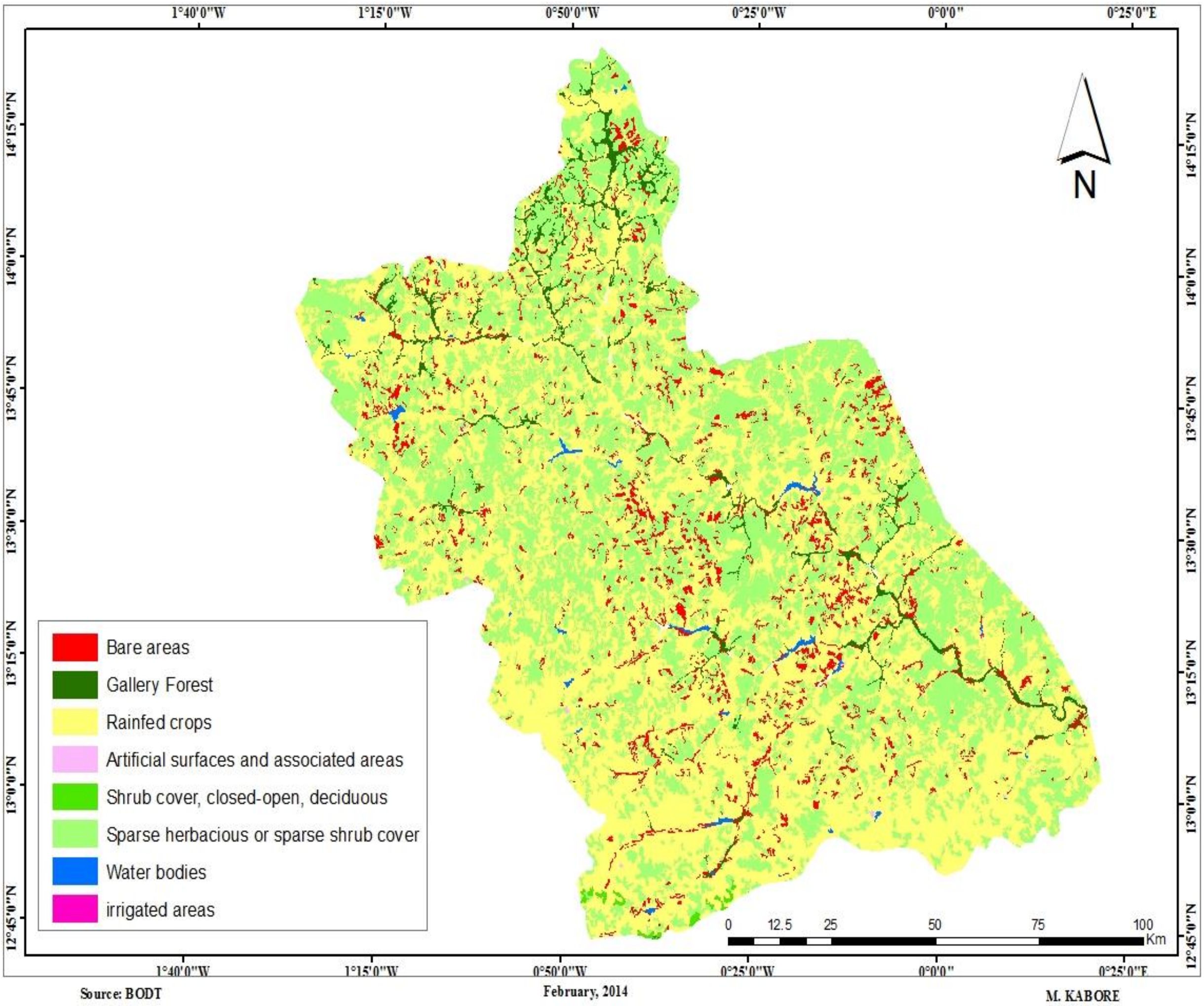


Figure 2.7: Land Use/Land Cover of the Faga Basin

Land cover types of the study area include irrigation land, water bodies, bares soil, gallery forest, rainfed forest, artificial surface and associated areas, shrub cover (closed, opened and deciduous), sparse herbaceous or sparse shrub cover as shown in the Figure 2.7.

2.8. Small dams and reservoirs overview

Dams and Reservoirs Census conducted in 2001 by National Water Management Directorate (DGRE) revealed that around 1 450 reservoirs were built between 1910 and 2001 in Burkina-Faso. Figure 2.8 shows the location of dams and reservoirs in 2001. However, the 2011 census registered about 1 794 dams and reservoirs consisting of 1001 dams and 793 reservoirs.

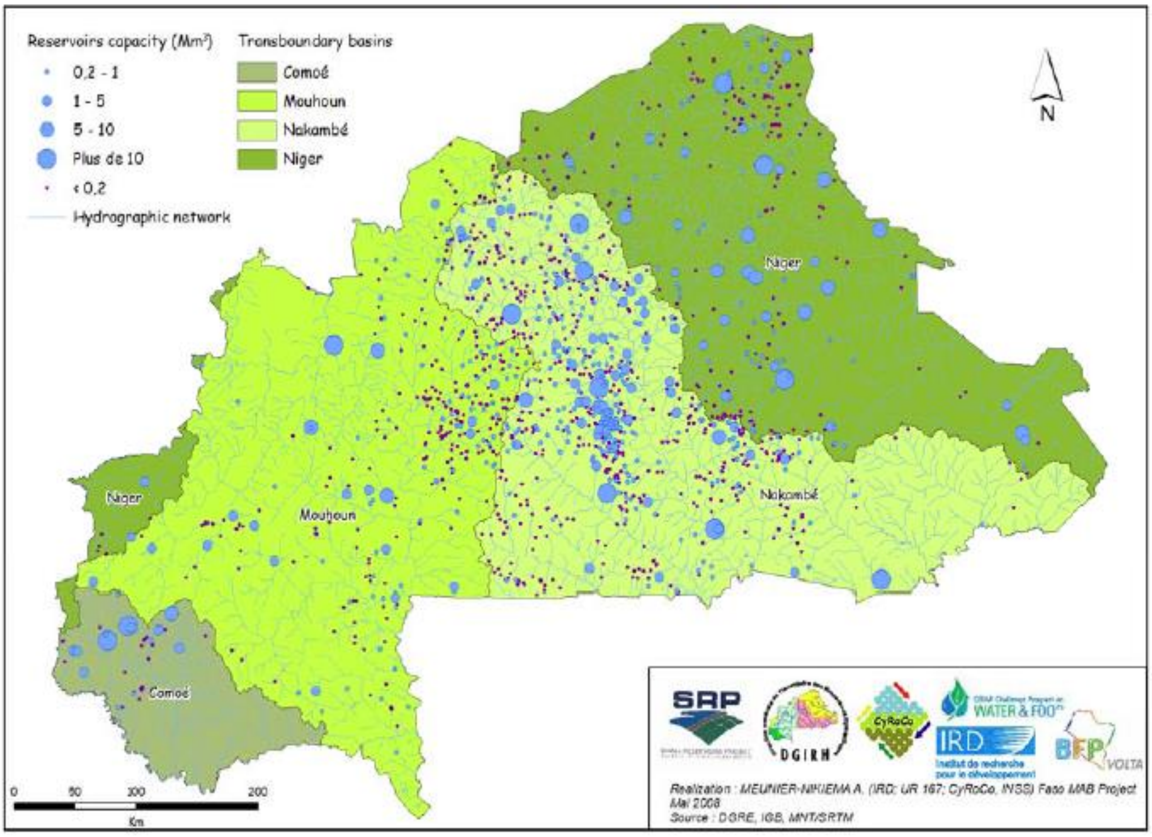


Figure 2.8: Dams and reservoirs location in Burkina-Faso (UNEP-UNESCO-MAB-GEF)

A total of 344 water storage infrastructures were built between 2001 and 2011 leading to an increase of 23.72%. When we analyze these figures, we estimate that around 34.4 infrastructures were built every year throughout the 2001-2011. The area of interest holds 61 water infrastructures with one underground dam. Water infrastructures' building started in 1941 in the Faga Basin and was intensified in the 1990-2000 decade as stated by Sally et al.,(2011).

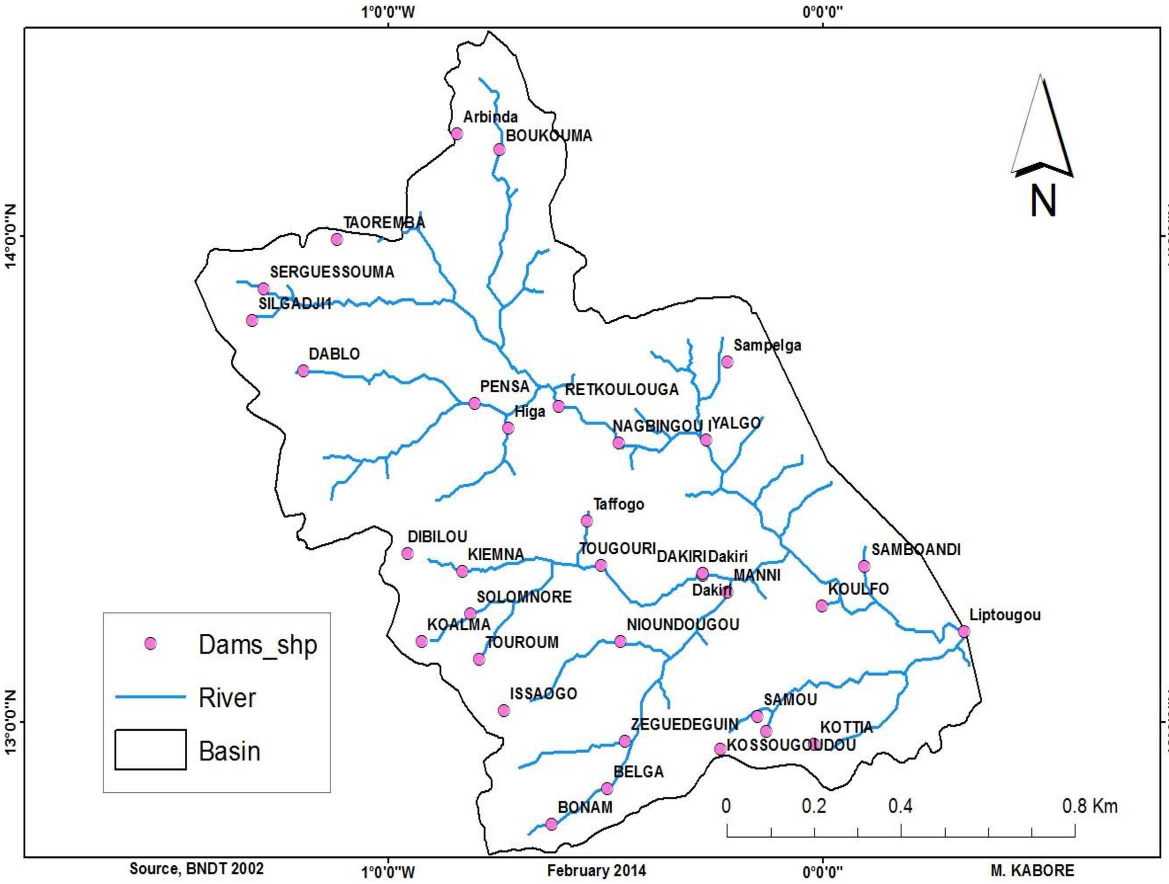
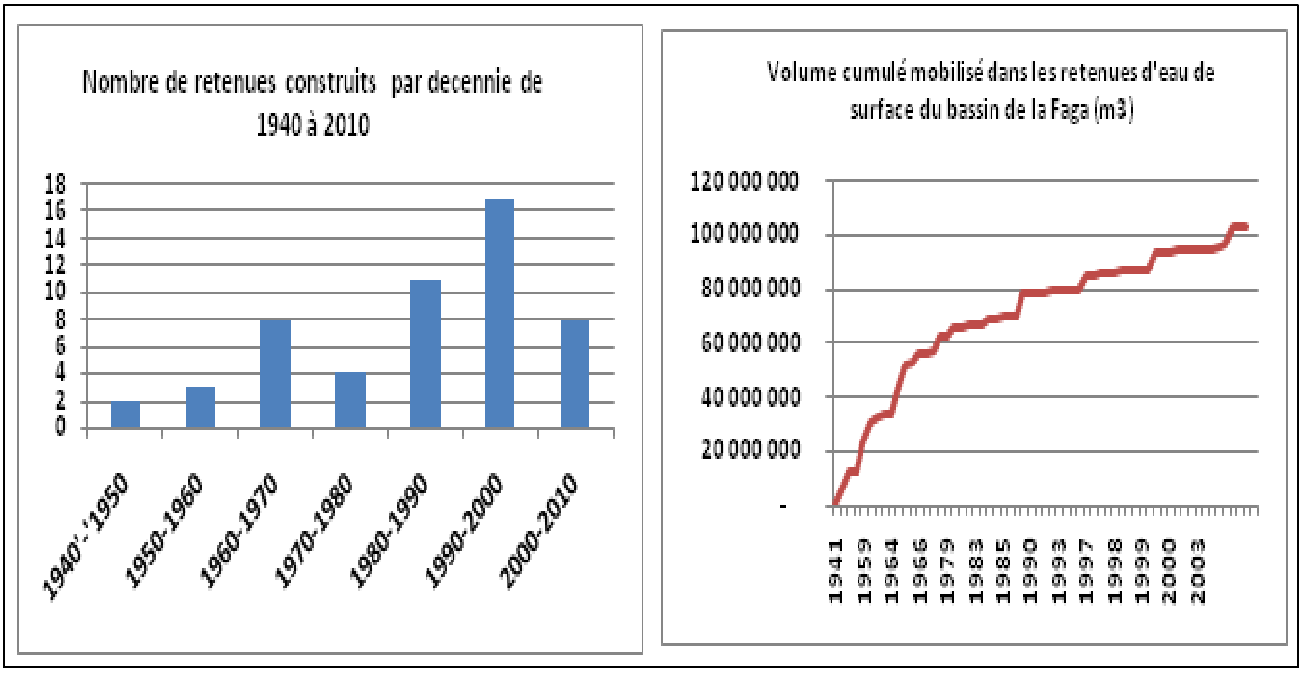


Figure 2.9: Dams in the Faga Basin

Water storage infrastructures are mainly for agricultural and pastoral purpose and their storage capacity is between 5 000 and 10 400 000 m^3.

In Burkina-Faso, these infrastructures store more than 103 673 459 m^3 of water as we can see in figure 2.10 (b). The total storage capacity of the dams and reservoirs is estimated at about 5 billion m^3 and 2.7 billion m^3 are stored each year (DGRE/DEIE, 2011). the remaining water is flowing towards Ghana.

A great number of dams is built in the country to fill water demand requirements but very few of them are monitored. According to DEIE, only 35 dams are monitored among the thousand dams constructed over the country and this constitutes a big problem in reservoirs impact assessment.



(a) (b)

Figure 2.10: (a) Number of infrastructures built per decade, (b) Cumulative quantity of water stored form 1941 to 2010, (Gislain Kabore, 2010).

2.9. Demography, environmental, social and economic activities

The Faga basin is populated by diverse ethnical groups mainly constituted by the Mossi, the Gourmantché, the Rimaîbés and Kurumba Fulani distributed in six (06) provinces: Gnagna, Namentenga, Sanmatenga, Seno, Soum and Yagha. Following the INSD (2006), population census the population of the Faga Basin is estimated at 2,107,981 inhabitants on the giving population by province. Following the rapid rate of population growth estimated at 2.8 (UNDP, 2007) the population may double by 2050. The livestock mainly comprises some pack animals (oxen), small ruminants (sheep, goat) and poultry. Transhumant herding and transhumant pastoralism constitute the livestock production system in the Basin.

2.10. Partial Conclusion

The growing population and the important number of dams over the Faga River Basin may result in high pressure on water resource. This pressure could worsen particularly due to the recent mining sites (2 Industrial and many artisanal) and market gardening development in the basin.

The data, the materials and the methods used to assess this probable pressure will be described in the following chapter.

CHAPTER 3: DATA, MATERIALS AND METHODS

This chapter aims to describe the methodology applied to achieve the study goals. It also presents the description of the data required as well as the model and softwares used in the study. The methods used to obtain the presented results are also provided in this section.

3.1. Data

3.1.1. Data availability and quality assessment

Before running the WaSiM model, input data which are precipitation, wind, temperature, relative humidity and sunshine duration were processed and imported into it for further internal data interpolation and correction. Precipitation and temperature were spatially interpolated from point data to average areal precipitation and temperature ready to be used for WaSiM run and its calibration.

Very few hydrological studies have been done within the Faga Basin even though the Faga River is one of great importance for the country. These studies used specifically the archived gauged data from the meteorological and hydrological agencies. However, assessment of the available gauged data showed that hydrological data and some meteorological data that exist for the Faga River Basin have long periods of gaps. The periods with data are strewed with missing data affecting the quality of the usable data. For the meteorological data the monitoring of some of the parameters needed in WaSiM like the Wind speed and the Sunshine started later than other parameters. For the nineteen hydrological stations existing in the Faga Basin, only three have some series with very different starting dates and with gaps. The others are not monitored and therefore no runoff data exist for them. For the whole Faga Basin, the Liptougou station had continuous daily runoff data with a few gaps and questionable values. So, for this study, three meteorological stations and only one hydrological station have been considered due to the lack of adequate data in the basin. The hydrogeological informations like horizontal hydraulic conductivities, storage coefficient and aquifer thicknesses needed for the WaSiM model calibration were provided by the Bureau de Mines et de la Geology du Burkina (BUMIGEB).

3.1.2. Climate data and scenarios

The National Meteorological Services (NMS) is mandated to collect precipitation and the other meteorological data in Burkina-Faso. They also regulate, plan and implement the policy related to meteorological and climatic activities. The NMS provided the historical daily data for precipitation and mean temperature recorded within the basin from 1955 to 1958 and 1982 to 2010 with some few missing data for all the station. To provide climate inputs to the WaSiM model for climate change impact assessment, the first step is to select greenhouse gas emissions scenarios and a group of Regional Climate Models (RCMs).

RCMs downscale the Global Circulation Models (GCMs) simulations output from the global scale to the regional scale. These simulations are carried out by a number of independent research groups worldwide, and use emissions scenarios generated for the Intergovernmental Panel on Climate Change (IPCC) as inputs. A number of meteorological variables are the key inputs to hydrologic models from which precipitation, relative humidity, temperature, duration of sunshine and wind speed are used within the WaSiM hydrological model.

In this study a set of the mean values of each climate variable of the hydrological models are obtained for the Faga Basin for 2100 using output of the current generation coupled climate models run at the Geophysical Fluid Dynamic Laboratory (GFDL) of the Princeton University's Forrestal Campus in Princeton, New Jersey. GFDL model runs are employed within the phase 5 of the Coupled Model Intercomparison Project (CMIP5) coordinated by the World Climate Research Programme in support of the IPCC AR5. CMIP5 is the most recent activity, and is built on the CMIP3 and data from the Message Passing Interface (MPI) models.

The GCMs models output runs run under the IPCC Representative Concentration Pathways RCP 4.5 and RCP8.5 which were downscaled at regional scaled by Regional Climate Model namely: Can_ESM2, EC_EARTH and MPI_ESM respectively. the output of these simulations were then downscaled at the station point using the Statistical Downscaling Model (SDSM).

The RCP8.5 assumes a rising carbon concentration in 2100 and RCP 4.5 stipules a stabilization of carbon concentration without overshoot after 2100.The aim of these two RCPs is to assess the response of the Faga river flow under rising and stabilized carbon emission scenarios. The overall range across the RCP scenarios is larger because for the first time a low-emission mitigation scenario is included.

3.1.3. Hydrological Data

The Faga River discharge data were acquired from the DEIE database (Direction des Etudes et de l'Information sur l'Eau, 2014). In order to find the suitable data set for the study, data from five hydrometric stations in the sub-basin were used for the calibration and the validation process of the hydrological WaSiM model. Based on the data quality we have in each station, the most suitable data set has been selected for the calibration of the model. The Liptougou gauging station located in the extreme downstream of the sub-basin was found to have the most suitable data set for calibration. Moreover, the station is the most monitored among the others and possesses the longest discharge time series data set. This station record begins in 1973 and ends in 2011. Daily values of stage height are available from 1973 to 2014 but not for all the gauging stations.

3.1.4. Spatial gridded data

The computation of the WaSiM-ETH model requires meteorological data as well as spatial gridded data such as digital elevation (DEM) data, spatial gridded distribution of soils properties and land with hydrogeological information (Martin and van de Giesen, 2005).
The DEM of the Faga Basin was derived from the Shuttle Radar Topography Mission (SRTM) subset at 30m resolution using ArcGIS tool.

3.2. Materials

3.2.1. Climate models

To assess the present and the future climate change impact on the Faga River hydrology, an ensemble of simulations were examined using three widely used GCMs simulations output from the CMIP5 described above The First GCM we considered is the Second Generation Earth System Model (CanESM2) used within the Canadian Centre for Climate Modelling and Analysis (CCCma). The second model is the Euro-Cordex Earth System Model (EC-EARTH) used within the Irish Centre for High-End Computation (ICHEC).The users of the model include the Koninklijk Nederlands Meteorologisch Instituut/Royal Netherlands Meteorological Institute (KNMI), the Swedish Meteorological and Hydrological Institute (SMHI), the Irish National Meteorological Service (MetÉireann), the Danish Meteorological Institute (DMI), the Norwegian Meteorological Institute (Meteorologisk Institutt), and the Swiss Federal Institute of Technology in Zürich (ETH Zürich). The third model is the Message Passing Interference (MPI) Programming Model. These GCMs' simulations output were downscaled for the Coordinated Downscaling Experiment (CORDEX) using the version of the Rossby Centre regional atmospheric model, RCA4. We used only the same RCM downscaling output of the three different GCMs because we assume that this may ease the comparison between models and may reduce uncertainties in impact assessment.

3.2.2. Hydrological model

The impact of dams and climate change on the hydrology of the Faga River was assessed using the Water Simulation Model (WaSiM) which is a fully distributed, deterministic and physically- based hydrologic model which requires digital elevation data, gridded soil properties, land use, and hydrogeological information (Martin and van de Giesen, 2005). The model grid is constructed from square grid cells, the side length of which may be set from a few hundred meters up to several kilometers. The computation starts from a given initial state and advances through the defined computation period using time steps from one second to one day. For each time step and grid cell, the model first computes meteorological variables from the given input data, and then proceeds to compute land use, soil, river network, water balance, etc. Figure 3.1 shows the outline of the structure of the WaSiM model. The WaSiM version used for this study has a physically based soil model using the RICHARDS-equation for modeling the fluxes within the unsaturated soil zone (Schulla , 2012). Physically based models such as the WaSiM hydrological model have the advantage that they calculate the complete terrestrial water balance, i.e. the processes of land-surface flow aggregation, infiltration in the unsaturated zone, evapotranspiration by open water bodies, plants or bare soil, up to the consideration of groundwater recharge, groundwater flow and its re-infiltration in surface waters. Due to the solution of mostly physically based equations, a high prognostic capability, e.g. under climate change or land use change conditions, is assumed for these kind of models (Kunstmann et al., 2006).

The potential evapotranspiration is calculated using Penman–Monteith equation. Surface runoff is routed to the sub-catchment outlet using a subdivision of the catchment into flow time zones (Wagner et al. 2008).

According to Kunstmann et al (2006), WaSiM model is able to describe observed river discharges satisfactorily. In addition, it enables the simulation of regulated reservoirs, river branching and artificial abstractions including irrigation.

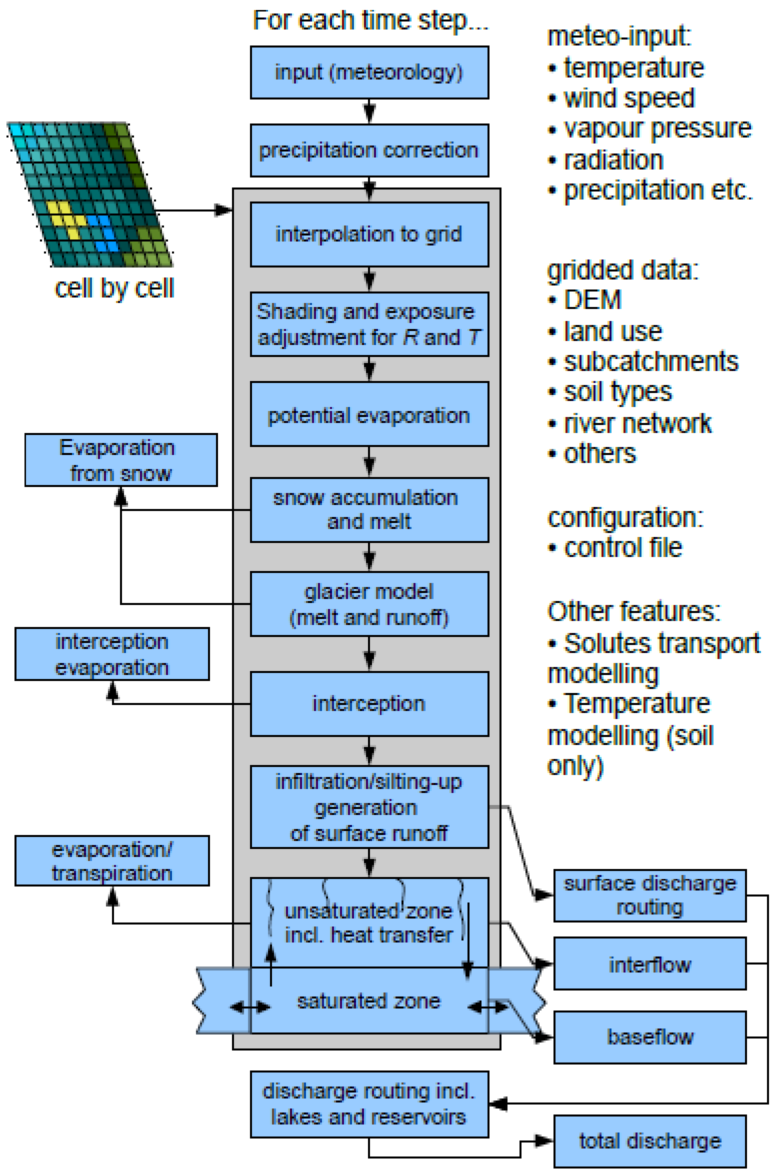


Figure 3.1: WaSiM-ETH model structure (Schulla, 2014)

The WaSiM-ETH model is constituted by an ensemble of sub-models as described below. Each of these sub models possesses mathematical and empirical equations which are fully stated in Schulla (2014).

- ✓ Interception model

Interception is the fraction of precipitation caught up by canopy formed by the vegetation above the ground. For WaSiM, a simple bucket approach is used for the computation of interception storage, which depends on the leaf area index (LAI) and the maximum height of the water on the leaves. This precipitation fraction is obtained from equation (3.1) after Schulla (2014):

$$SI_{\max} = vcf * LAI * h_{SI} \qquad (3.1)$$

With:

SImax: maximum interception storage capacity [mm]

Vcf: degree of vegetation coverage [m^2/m^{-2}]

LAI: leaf area index [m2/m-2]

hsi: maximum height of water [mm] on the leaves

In WaSiM model, the extraction of water out of the interception storage by evaporation is assumed to be at a potential rate. In case there is a sufficient amount of water in the storage, the storage content is reduced by the potential evaporation, and no evaporation water will be taken from the soil. However if the storage content is smaller than the potential evaporation rate, the remaining rate will be taken from the soil on condition that the soil is not too dry or too wet. The interception evaporation will then be:

EI =ETP (for SI ≥ ETP in mm), ETR = 0 and EI = SI (for SI < ETP in mm), ETR = ETP –SI

With:

EI: the interception evaporation [mm]

ETR: remaining evaporation from soil and vegetation

SI: content of the interception storage [mm]

- ✓ Potential and actual evapotranspiration model

In WaSiM, the potential transpiration from plant leaves, the evaporation from bare soil and the evaporation from interception surfaces are calculated separately (with separate interception evaporation as an option only). However, the algorithms are identical for each type of evaporation. Only the input and/or some parameter estimation vary. Also, for multi-layer vegetation, the algorithms for transpiration and interception evaporation are identical for each layer, but the radiation input will vary.

The Penman-Monteith approach is used in WaSiM to calculate the evaporation. This approach according to MONTEITH (1975) is most sensitive to the properties of the plants used for transpiration and should be used where possible. The potential evapotranspiration after Penman-Monteith is given by Equation (3.2):

$$\lambda E = \frac{3.6 * \frac{\Delta}{\gamma P}(RN\_G) + \frac{\rho * CP}{\gamma ra}(es - e) * ti}{\frac{\Delta}{\gamma P} + 1\_ {}^{rs}/_{ra}} \qquad (3.2)$$

With:

: latent heat of vaporization = (2500.8 - 2.372.T) KJ□Kg-1, T: temperature in °C

E: latent heat flux (kg.m-2)

: tangent of the saturated vapor pressure curve [hPa.K-1]

RN: net radiation, conversion from Wh.m^{-2} to KJ-m^{-2} by factor 3.6 [Wh·m^{-2}]

G: soil heat flux [Wh·m^{-2}]

P: density of dry air (kg·m³) p (RL ·T) (at 0°C and 1013.25 hPa: p =1.26)

cp: specific heat capacity of dry air (KJ· (Kg·K)-1) at constant pressure = 1.005

es: saturation vapor pressure at temperature T [hPa]

e: actual vapour pressure (observed) (hPa)

ti: number of seconds within a time step

: psychometric constant [hPa·K-1]

rs: bulk-surface resistance [s·m-1]

ra: bulk-aerodynamic resistance [s·m-1]

- ✓ Infiltration and the unsaturated zone model

As described in Schulla (2014), the infiltration model is an integrated part of the soil model, but implemented in the Top model version only. It uses an approach after (Peschke 1977, 1987) which is based on the approach of GREEN and AMPT (1911). The soil is assumed to be homogeneous and not layered. Matrix flow is assumed to dominate and the wetting front is approximated as a step function. The precipitation intensity (PI) is assumed to be constant over the entire time step. The approach consists of two phases. Within the first phase the time of saturation is calculated (if any saturation will occur within the time step at all). Within the second phase, the cumulative infiltration until the end of the time step is calculated. If the soil surface is saturated at the end of the time step, in the next time step only the cumulative infiltration will be calculated (if the precipitation intensity is sufficiently high) without calculating the saturation time. The exceeding amount (the not infiltrated water) is surface runoff. Using a parameter the amount of re-infiltrating water can be controlled. This may be important to consider in homogeneities of the soil properties if using larger grid cells (e.g. for grid cell sizes of some hundreds of meters).

If PI > Ks (otherwise there will be no saturation at all), the saturation time ts is calculated by:

$$t_s = \frac{I_s * n_a}{P_i} = \frac{\dfrac{\dfrac{\Psi_f}{P_i}}{\dfrac{P_i}{K_s}-1}}{P_i} \qquad (3.3)$$

With:

ts = saturation time from the beginning of the time step [h]

ls = saturation depth [mm]

]

ks = [mm] saturated hydraulic conductivity [mm/h]

PI = precipitation intensity [mm/h]

The infiltrated amount of water up to this time FS is given by:

FS = lS Ψ na= tS Ψ PI

Finally, the cumulated amount of infiltration after saturation until the end of the time step is calculated after PESCHKE by:

$$F = \frac{A}{2} + \sqrt{\left[\frac{A^2}{4} + AB + F_s^2\right]} \quad (3.4)$$

With

A = ks (t-ts)

B = Fs + 2.na. f

The exceeding amount of precipitation PI.Δt - F - Fs is surface runoff QD.I.

The unsaturated zone as the groundwater model is encapsulated in an extra loop. In the Richards-version of WaSiM used in this study the POND-grid is processed with no interflow, no exfiltration, no snow accumulation etc. Groundwater exfiltration and re-infiltration from rivers as well as macro pore infiltration are suppressed for such cells,, too. Within the unsaturated zone each cell is divided into layers of uniform thickness and the percolation and capillarity rise are computed according to the properties of the soil and the vertical moisture profiles and fluxes. In case the top of the unsaturated zone is constituted by bare soil, this leads to evaporation and soil covered by vegetation leads to the water uptake from other soil layers for transpiration. According to Van Genuchten (1980) the hydrologic conductivity with decreasing water content is calculated using the Van Genuchten equation below built on the water release curve of soils which is a function of the saturated (θs) and residual (θr) soil water contents, the soil matrix potential Ψ and the parameters α and n.

$$\theta_{(\Psi)} = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + \left(\alpha/\Psi\right)^n\right)^m} \quad (3.5)$$

With:

θ = actual water content [-]

Ψ = suction [hPa]

θs = saturation water content [-]

θr = residual water content at k (θ)= 0 [-]

α,n = empirical parameters (m = 1-1/n) [-]

The interflow and the base flow are passed through from unsaturated zone model in the way that the observed flow retention leads to linear storage. The recession constants KD and KI should therefore be calibrated.

- ✓ Runoff routing model

The runoff in WaSiM is the ensemble of the base flows, the interflow and the direct runoff. The base flow is the flow generated by exfiltration into the channel network and the interflow is the flow generated at soil layer boundaries possible when there is a slope angle > 0 and a drop in hydraulic conductivity. Translation to the sub-basins outlet is done using a flow time histogram (isochronic method). The direct flow is that part of precipitation that directly runs off the soil surface after rainfall occurrence.

The generated runoff in each cell is directed to the outlet of a basin with respect to flow times that are calculated by the preprocessor TANALYS for the entire catchment considering the distances to specific routed outlets (Kasei, 2009). WaSiM uses the kinematic wave approach to model the surface runoff or to describe the runoff or a flood plain routing for the combination of a main river bed.

- ✓ Lake Model

Artificial and natural reservoirs or lakes can fully be incorporated into WaSiM using the Lake model as an integral part of both, the unsaturated zone- or Richards-model and the routing model with detailed feedback from one model component to the other. Each lake is coded with its unique ID in the lake grid. The lake model contains a set of parameters which should be used in case the lake cells contain water- regardless of the defined land use. The internal time step of lake balancing model should be much smaller than the constant model time step due to the probable change in small reservoirs volumes during flood events. The lake model affects the other sub-models of WaSiM specifically the evaporation model. The potential evaporation has to be calculated depending on the water content of the actual pond--cell if the lake model is considered.

So, if there is water in the POND-cell, then some default-parameters are used from the control file section “[lake_model]”. However, if there is NO water in the POND-cells, then the land use code from the land use grid is used and the evaporation will be calculated in the traditional manner. A full description of the lake model can be found in Schulla, (2014).

3.2.3. RClimDex 1.1 software

The RHtestV3 software which is incorporated into RClimDex 1.1 was used to control the quality of the rainfall and the temperature time series and to test their homogeneity.
We examined the variability within the analysis of the climate extremes calculated from the RClimDex software (1.1). It computes all 27 core indices recommended by the World Meteorological Organization Commission for Climatology research project on Climate Variability and Predictability (WMO-CCl /CLIVAR) Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI) as well as some other temperature and precipitation indices with user defined thresholds (Zhang and Yang, 2004). Interannual variability of annual rainfall within the study area is analyzed using the coefficient of variation in percentage in order to provide an indication of annual fluctuations.
The percentage coefficient of variation is expressed as followed:

$$C_V = \frac{\sigma}{\mu} \times 100 \qquad (3.6)$$

Where:
= Coefficient of variation in percentage
= Standard deviation
= Mean
The magnitude of change is given by Sen's slope computed by the software.

3.2.4. Easy-Fit software

Flood frequency analysis was conducted using the annual maximum (AM) flow time series which is the most frequently used series. The annual maximum flow was extracted from the baseline and the current period (1982-2010) time series. Only flow peak exceeding the average annual were considered for flood analysis in this study. The Easy-Fit software was used to select the best fitted distribution for the two data sets.
The software automatically calculates the goodness of fit statistics and ranks the fitted distributions from the best to the least fitted distribution. Anderson-Darling, Chi squared, and Kolmogorov-Smirinov (KS) goodness of fit tests were used to measure the compatibility of our data sets with a theoretical probability distribution function.
The best fitted distribution function formula was used to calculate the probability of exceedence of flood and the return period for each data set and to estimate the maximum flow

which corresponds to each return period. We then compared the estimated baseline maximum flow and the dams' run maximum flow for the same return period to see how dams are affecting the Faga River flow peaks. The Generalized Extreme Value (GEV), Frechet (3p), the Log-Pearson 3 and Pearson5 (3p) were used to perform the fitting test.

3.3. Methods

3.3.1 Model selection

Hydrological models constitute an inescapable tool for water resource and environment management and for impact of climate and land use change on the water resources and rivers' hydrology assessment. The appropriate model that was able to capture with high enough precision the essential features of a river basin such as runoff, land use and soil characters was selected through a review of hydrological models. Several models have been developed to perform hydrological modeling over the world. They are classified as empirical models, conceptual models and physically based models. The empirical models involve mathematical equations that do not imply the physical processes of the watershed but only input and output time series. The conceptual models incorporate the physical elements of the watershed. However there is less confidence in land use change impact prediction due to the difficulty in calibration results interpretation which consists of curves fitting. The physically based models are qualified as the idealized mathematical representation of the real phenomenon according to (Gayathri et al, 2015). In addition, due to the solution of mostly physically based equations, a high prognostic capability, e.g. under climate change or land use change conditions, is assumed for these kind of models (Kunstmann et al., 2006).

Many previous studies as presented in section 1.2.9 above successfully applied the physically distributed WaSiM within several watersheds to assess hydrological changes.

In our view, the WaSiM model was a suitable model for the assessment of climate and reservoirs induced impact on river's hydrology as it is able to describe observed river discharges satisfactorily. In addition, it enables the simulation of regulated reservoirs, river branching and artificial abstractions including irrigation according to Kunstmann et al (2006).This motivated the selection of the WaSiM model tor performing our hydrological modeling.

3.3.2. Modelling process

3.3.2.1 Model set up

Once the hydrological model selected and the study area delimited, the first step was to set the WaSiM input folder. Observed meteorological data, spatial gridded data such as digital elevation (DEM), spatial gridded distribution of soils properties and land with hydrogeological information (Martin and van de Giesen, 2005) were incorporated into the input folder. Climate data from Regional Climate Models were statistically downscaled and assigned to the input folder for climate change impact assessment.

The DEM of the Faga Basin was derived from the Shuttle Radar Topography Mission (SRTM) subset at 30m resolution using ArcGIS tool.

WaSiM runs from the command line with a control file that contains all the informations required for the WaSiM run. The second step was to adapte the WaSiM control file to the selected study area by incorporating parameterization and initial condition. Three parameter types are defining the control file as followed:

1. Parameters controlling the model run such as grid write codes, statistic file write codes, output lists etc.).
2. Input and output streams files format names and paths names.
3. WaSiM model parameters and property tables (for land use, soil types, tracers), static model parameters.

In order to assess the effect of water storage into dams, an abstraction rule (detailed in section 3.3.4) was written in WaSiM control file for each dam. Abstraction rule can be defined as a relation between dam content and allowed outflow (Schulla, 2014). Abstracted water included irrigation water and household water supply and was taken from the lowest dams of each sub-basin collected from the field survey. Indeed, in WaSiM, abstraction water should be taken from the last reservoir even in case of multiple reservoirs within the sub-basin.

If there is multiple abstractions, WaSiM simulates the abstracted water in such a way that water is abstracted in the first dam until the satisfaction demand or until the remaining water in the dam is not sufficient to satisfy the demand before it simulates the second dam abstraction. This abstraction rule was used to simulate the projected changes of the Faga River flow.

3.3.2.2. Sensitive parameters analysis of the model for the Faga Basin

Sensitivity analysis aims amongst others to (i) define which factor most needs better determination, and (ii) identify the weak links of the assessment chain (those that propagate most variance in the output). Sensitivity analysis in this context is often performed using regression techniques, such as standardized regression coefficients (Saltelli et Al; 2006). The sensitive parameters of the hydrological model for the study basin were determined through the sensitivity investigation. In the current study, this analysis was carried out specifically using the Monte Carlo method to determine which factors have the greatest influence on the runoff (Alan Ristow at al, 2004). Thus the model was run

by varying independently the mean of each soil model and the unsaturated zone parameter values which need to be calibrated by ±15% from their nominal value instead of ±10% as used in the Monte Carlo method.
The sensitivity was calculated using the following equation (modified after Cullmann, 2006):

$$S = \frac{(P(+15\%) - P(-15\%))}{P} \qquad (3.7)$$

With,
S sensitivity measure [–]
P+15% = peak discharge for the considered flow parameter +15%
P −15% peak discharge of the considered flow hydrograph for the parameter −15%
P peak discharge of the considered flow hydrograph for standard parameter set

3.3.2.3. Calibration and validation of the WaSiM model

After setting up the WaSiM input folder and the control file, the model calibration was performed to obtain computation parameters which fitted the Faga River Basin conditions and to obtain the best fit and an acceptable correlation between the computed and the observed runoff. Indeed, the main purpose of the model calibration is to obtain a parameter set for a catchment which gives the best possible fit between the computed and observed hydrographs for the calibration period (Ndiritu and Daniel 1999, E.Mutekenya-Mwelwa 2004).
In this study, WaSiM was calibrated only for the main river at Liptougou station located in downstream Faga Basin due to the inadequacy of the hydrological data sets within the area. Data from 1982-2010 was used for the hydrological modelling processed to come out with results obtained in chapter 5 and 6. However, the WaSiM calibration parameters were successfully calibrated using flow data set for 1992 to 1994 period which was found to be suitable as calibration period.
Calibration and validation time periods were selected based on the comparison the means of precipitation and river flow for the two periods using the two-samples t-test.
This test is used to compare two small independant samples. The principle is based on *the* computation of two-samples t-test directly from Means, Standard deviations and sample size. It is assume that each of the two data sets are sampled from normal distribution (from -1.96 to +1.96 (see normal distribution plot in Annex 4) with a p-value < 5%.
For comparing two means, the basic null hypothesis is that the means are equal,
H_0: $m_1=m_2$ (m_1 and m_2 respectively the mean of sample 1 and sample 2)
with three common alternative hypotheses,

H_a: $m_1 \neq m_2$,

H_a: $m_1 < m_2$,

or H_a: $m_1 > m_2$

A slightly different set of null and alternative hypotheses are used if the goal of the test is to d₂etermine whether m_1 or m_2 is greater than or less than the other by a given amount.

T- statistics which is Δ / S_d is computed and compared with the normal distribution (t_α =1.96).

We have:

$\Delta = m_1 - m_2$ (3.8)

and (3.9)

With $$S^2 = \frac{(N_1-1)S_1^2+(N_2-1)S_2^2}{N_1+N_2-2}$$ (3.10)

Where: N_1 and N_2 are the two sample sizes

S_1 and S_2 are the two samples standard deviations

Table 3.1 below preents the most important parameters used to calibrate the WaSiM model. A detailed table of the calibration parameters is found in Schulla, (2014).

WaSiM-ETH calibration process that normally is not a “trivial problem which requires hydrological expertise as well as a sufficient knowledge of the model structure and the model reactions” as mentioned in Schulla (2014) was quite a big task for the Faga River. This was due not only to the observation data set accuracy but also the fact that WaSiM was being calibrated for the first time for the Faga River Basin.

Table 3.1: Main calibration parameters of WaSiM

Parameters	**Unit**	**Description**
K_i	[h]	Recession constant for interflow
K_D	[h]	Recession constant for direct runoff
d_r	[m-1]	Drainage density
K_{rec}	[-]	Recession constant for saturated hydraulic conductivity with Depth

3.3.2.3. Performance analysis of WaSiM-ETH for the Basin

An ensemble of statistical measures was used in order to assess the model performance and the adequacy of the calibration. The Pearson’s statistic, the Nash–Sutcliffe Efficiency, the efficiency index and the Willmott’s index of agreement were evaluated from the simulated discharge values and the available observed runoff for selected time periods.

3.3.2.3.1. Pearson's R^2

A common approach to consider the fitting to data of a statistical model is the determination of the coefficient of determination R^2 which indicates how the data fit the selected model by measuring the strength of the relationship between the data. It is defined as the square of the coefficient of correlation and is calculated by the following equation:

$$R^2 = 1 - \frac{\sum_i (y_i - x_i)^2}{\sum_i x_i^2 - \frac{1}{n}\left(\sum_i x_i^2\right)} \quad (3.11)$$

With

- yi = simulated value (e.g. runoff [mm])
- xi = observed value (e.g. runoff [mm]),
- n = number of time steps used for calculating R^2

If the fit of the regression is good, e.g. R^2 is larger than, 0.7, this means that the regression model is able to represent a large part of the variation of Y. (ref, please).

3.3.2.3.2. Explained variance EV

Another performance criterion is the explained variance (EV) which may eliminate the impact of too large or too small computed data on the performance criteria. A comparison between the EV and the R^2, which itself does not consider systematic shifts, may show these effects. If the explained variance EV is larger than the corresponding R^2, then it is highly probable that there are systematic errors in the modeled data. (ref, please

$$EV = 1 - \frac{\sum_i (\varepsilon_i - \mu_\varepsilon)^2}{\sum_i (X_i - \overline{X})^2} \quad (3.12)$$

With:

ϵ_i = deviation of the modeled from the observed value

μ_ϵ = mean deviation of the modelled from the observed values

n = number of time steps used for EV-calculation

$x_i, \bar{x}$ = observed value at time step i (e.g. runoff [mm]), mean observed value

3.3.2.3.3. Mass balance error

The minimization of the errors in the mass balance is considered the most important objective in calibration after the water balance is fairly correct. This is derived from the fact that the processes within the unsaturated zone and evapotranspiration are considered the core of the model, and the processes are responsible for keeping the mass balance as realistic as possible Kasei, (2009).Good estimations of the parameters of infiltration process (unsaturated zone), lead to very likely good estimations of runoff starting time and good matches between simulated and observed surface discharge may also be obtained according to David et al., (1991).

3 3 2 3 4. Index of Agreement (d)

Another approach to compare the closeness or agreement between data sets X and Y is the index of agreement (d) which has also been used to evaluate the agreement between the estimated and the observed runoff (Willmott, 1984). Many widely used indices of change do not give indication of how similar the values of - time series are in magnitude (Duveiller et al, 2016). According to Willmott, 1981 and 1984, the index of agreement is developed to overcome the insensitivity of correlation-based measurements that were based on difference in sampled means and variances of the observed and model-simulated outputs
It is defined as followed:

$$1-\frac{\sum_{i=1}^{n}\left(O_i-P_i\right)^2}{\sum_{i=1}^{n}\left(\left|P_i-\overline{O}\right|+\left|O_i-\overline{O}\right|_i\right)^2} \qquad (3.13)$$

Where:

- O_i is the observed data;
- Pi is the model-simulated values of Oi,
- $\overline{O}$ is the mean of O; and
- n is the length of data O.

3 3 2 3 5. Nash-Sutcliffe efficiency index

Nash and Sutcliffe, (1970) proposed the efficiency coefficient E which is a normalized measure that compares the mean square error generated by a particular model simulation to the variance of the target output sequence. The Nash–Sutcliffe model efficiency coefficient is widely used to assess the predictive power of hydrological models. Among others, Kasei, (2009) and Kalin, (2003) used the index as goodness-of-fit statistic respectively for the calibration and validation of WaSiM and for a storm event model. Nossent and Bauwens, (2011) used this coefficient for another purpose as they successfully applied it to improve the accuracy of the Sobol' sensitivity analysis of a hydrological model.
The Nash- Sutcliffe is defined as “one minus the variance of the residuals between the predicted and observed values normalized by the variance of the observed values for the period under investigation. . It is calculated as:

$$E = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \qquad (3.14)$$

Where:

P_i and O_i are predicted and observed discharge at time i,

$\overline{O}_i$ is the mean observed discharge over the entire simulation period of length n.

E can range from $-\infty$ to 1. An efficiency $E = 1$indicates the model perfectly simulates the target output. Anefficiency $E = 0$indicates that the model predictions are as accurate as the mean of the observed data, while an efficiency $E < 0$ occurs when the observed mean is a better predictor than the model. The choice of the model is then questionable.

Essentially, the closer the model efficiency is to 1, the more accurate the model is.

3.3.2.4. Validation of the model

The period of data set used in model calibration may provide parameter set that give satisfactory goodness-of-fit criteria but for another period with different conditions, the goodness-of fit may not be satisfactory for the same parameter set.

Hence, once the calibration of the model was completed we found appropriate to check the usefulness of the parameter values previously obtained for computing other periods. The model performance was then estimated again for the validation step. The model was said to be validated when the model performance of the validation period was similar to the performance given by the calibration. The validation of the model is then judged from the performance criteria like in calibration. Then the calibrated parameter values were considered satisfactory and used to simulate any other events and climatic conditions. Depending on the observed data availability, the period from 1998 to 2000 was used for the validation.

3.3.3. Sensitivity analysis results

The sensitivity analysis showed that the soil layer thickness parameter that is a numerical parameter used to discretisize the solution of the Richards-Equation, the recession constant *Krec* for the saturated hydraulic conductivities (recession with depth), the drainage density *dr* for interflow, the storage coefficient *Kd*, for surface runoff, the scaling factor *Q0* for base flow, the storage coefficient *Ki* (recession constant) for reservoir are respectively the main parameters influencing the runoff generation processes.

It also showed that the sensitivity of the parameters in a daily time step simulation differ in intensity from the sensitivity of the hourly time step simulation as we can see in Figure 3.2. This result is in accordance with the ones of Cullumann J. (2006) in the study of WaSiM-ETH – model parameter sensitivity at different scales.

We also found that running the WaSiM-ETH for the Faga River Basin with a quite small value of *dr* and *Q0* and a quite big *Krec* and a deep soil layer impacts on the occurrence time of the simulated runoff as showed in Figure 3.3. We assumed that the computed runoff occurs later than the observation starts due to an existing latency time for the ground to be saturated after the rain falls. This implies that the soil layer thickness is the most sensitive parameter of the WaSiM model calibrated for the Faga River basin and the model needs to be recalibrate for different time steps simulations.

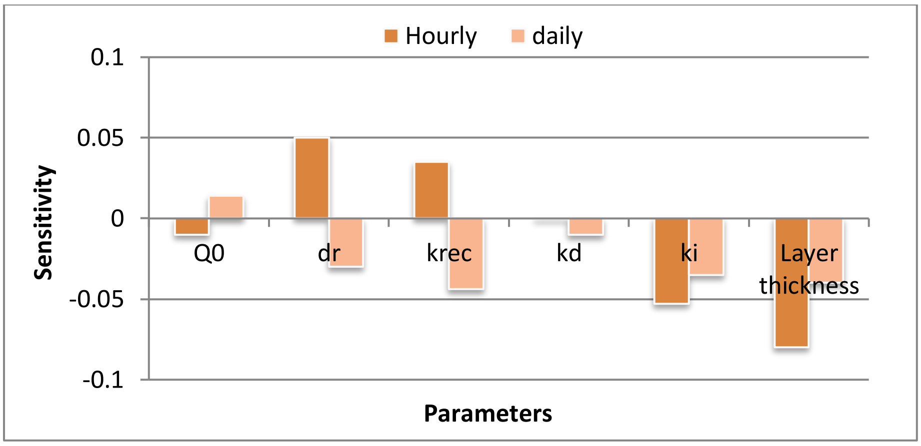


Figure 3.2: Sensitivity of soil and unsaturated zone parameters

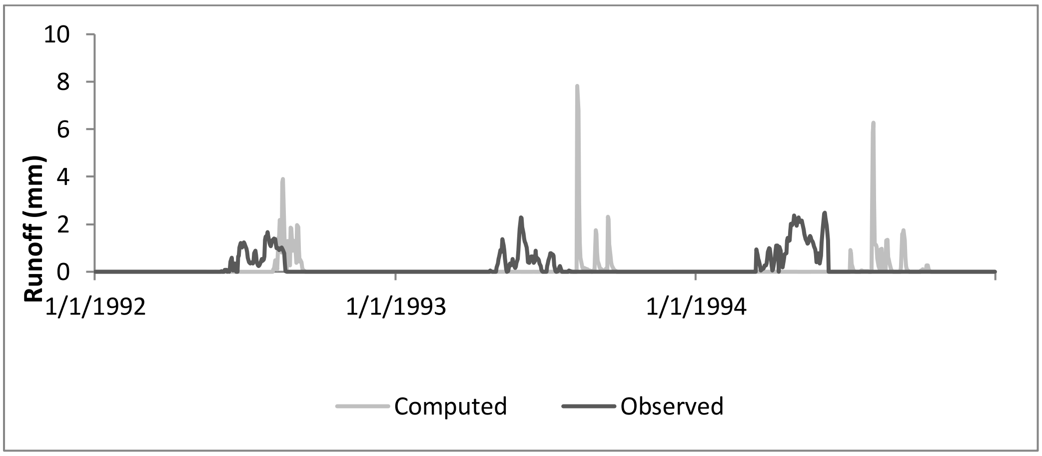


Figure 3.3: Sensitivity result showing shift of computed runoff from daily observed runoff of the main Faga River at Liptougou due to small *dr* and *Q0* values and high *krec* value

3.3.4. Calibration and validation results

3.3.4.1. Student t-test results

The following annual rainfall (mm) and river flow (m^3/s)data set for calibration period (1992-1994) and validation period (1998-2000) was used to determine t-statistics.

Calibration flow (1992-1994)	933.5	893.4	990.6
Validation flow (1998-2000)	926.7	832.6	865.2

Calibration flow (1992-1994)	11	19	45.3
Validation flow (1998-2000)	30.8	18.8	7.3

t = Δ / Sd $$t = \frac{\Delta}{\sqrt{\frac{S^2}{N_1} + \frac{S^2}{N_2}}}$$

For annual rainfall we have $$t = \frac{939.17 - 874.83}{\sqrt{1556.45}} = 1.63$$

For annual flow we have $$t = \frac{25.10 - 18.97}{\sqrt{153.37}} = 0.50$$

Results of the computation of t- statistics for two time periods showed that the values of t are 1.63 and 0.50 respectively for annual rainfall and river flow. Both of the values are less than 1.96 (tα).

One can not reject the null hypothesis (H0). There is not significant difference between calibration and validation periods' rainfall means and river flow means as well. The observed difference may probably due to hazard. Results showed that the two parameters pesents a similar characteristics for the two periods. Therefore, the chosen time scales (1992-1994and 1998-2000) are sweetable for calibration and validation of the hydrological model.

3.3.4.2. Calibration results

Results for three years of calibration period for the Faga at Liptougou station are shown in Figure 3.4, Figure 3.5 and Figure 3.6 for daily, weekly and monthly runoff, respectively. The figures show a quite good similarity between observed and computed runoff in accordance with the statistics in Table 3.2.

The performance criteria R^2 as shown in the Table 3.2 get better from the daily to the monthly aggregation. The monthly aggregation has a better R^2 followed by the weekly one and the daily aggregation possesses the lowest R^2. These results may be due to two possible reasons. We can firstly assume that since WaSiM is calibrated for the first time for the Faga River Basin the model was extremely sensitive to the basin properties and was then not able to take into account some of the parameters. These results may also lead to the observed data accuracy. Actually, the quality of any measured parameter such as precipitation, temperature, etc. depends on its precision and accuracy Kasei, (2009) which can influence the performance of the model. As previously mentioned, the study basin is not well gauged with a discontinuity in observed data time series.

The plots for the calibration period show that the agreement between the observed and the computed runoff gets better from the year 1992 to the year 1994.. The R^2 rose up from 0.75

for the year 1992to 0.95 for the year 1994 of calibration and this may due to the fact that the model was not warmed up enough to give a better response (runoff) to precipitation occurring at the beginning of the calibration. The model is then warming up as it is running from year to year so that validation step gave better simulation results than the calibration.

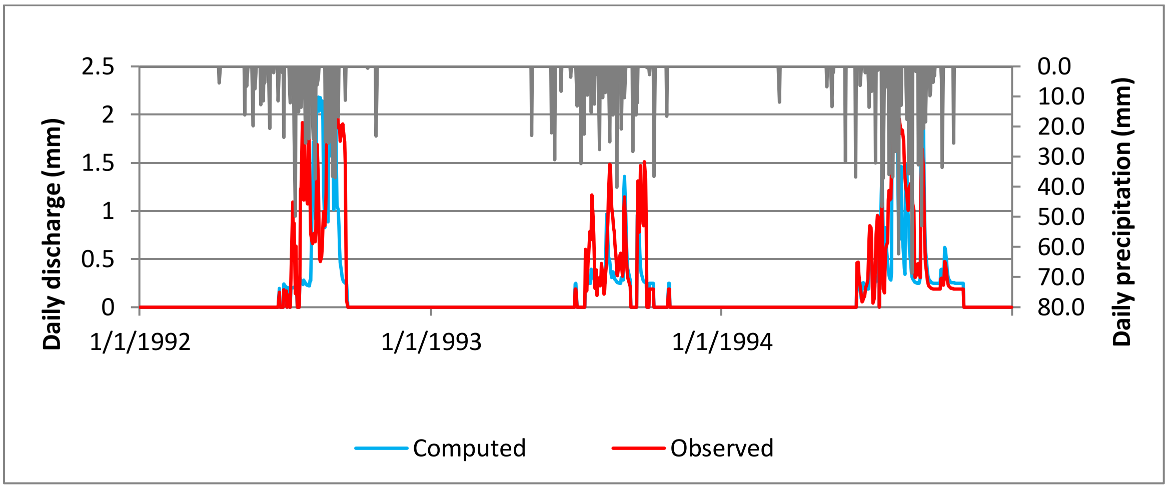


Figure 3.4: Calibration results of daily observed versus computed runoff for the main Faga River at Liptougou against daily precipitation

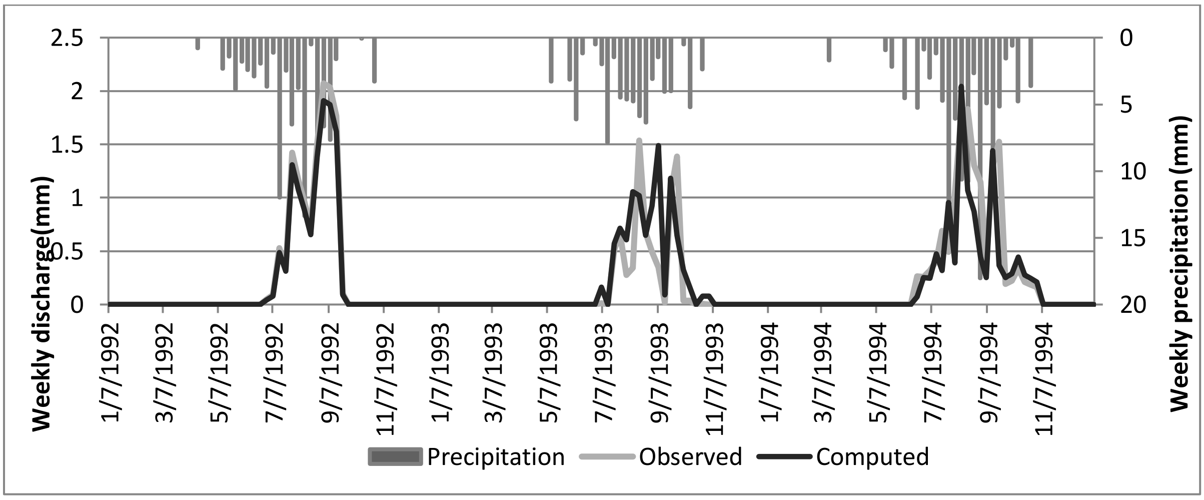


Figure 3.5 Calibration results of weekly observed versus computed runoff for the main Faga River at Liptougou against weekly precipitation.

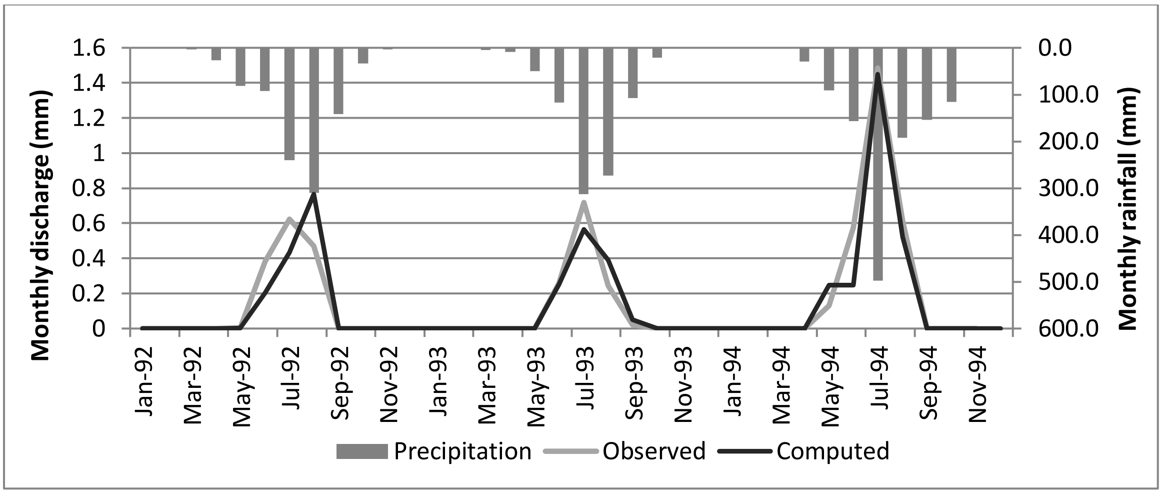


Figure 3.6 Calibration results of monthly observed versus runoff computed for the main Faga River at Liptougou against monthly precipitation.

Table 3.2: WaSiM-ETH estimated performance for the Faga Basin at Liptougou for the calibration period using daily, weekly and monthly aggregation.

<u>Aggregation</u> Frequency	<u>Performance criteria</u>			
	R^2	Model efficiency	Mass balance error [%]	*Index of agreement*
Daily	0.72	0.75	0.90	-8
Weekly	0.81	0.82	0.92	
Monthly	0.92	0.86	0.94	

3.3.4.4. Validation Results

The observed and simulated hydrographs for the validation time period are similar to those of the calibration . In effect, validation results for the Faga Basin as shown in the Figure 3.7, Figure 3.8 and Figure 3.9 indicate that the model performed better for the validation period comparatively to the calibration period. This confirms the statement made in part 5.7.2 that the model at the beginning of the simulations was not warmed up enough to give better performance. The model parameter values are generally equally suitable for both calibration and validation periods. This suggests that there is some reasonable degree of confidence that the results obtained in the calibration process are significant for the full observed record of the Faga river basin. Table 3.3 summarizes the WaSiM-ETH performance for the Faga Basin at Liptougou for the validation period using daily, weekly and monthly aggregation as in the calibration process.

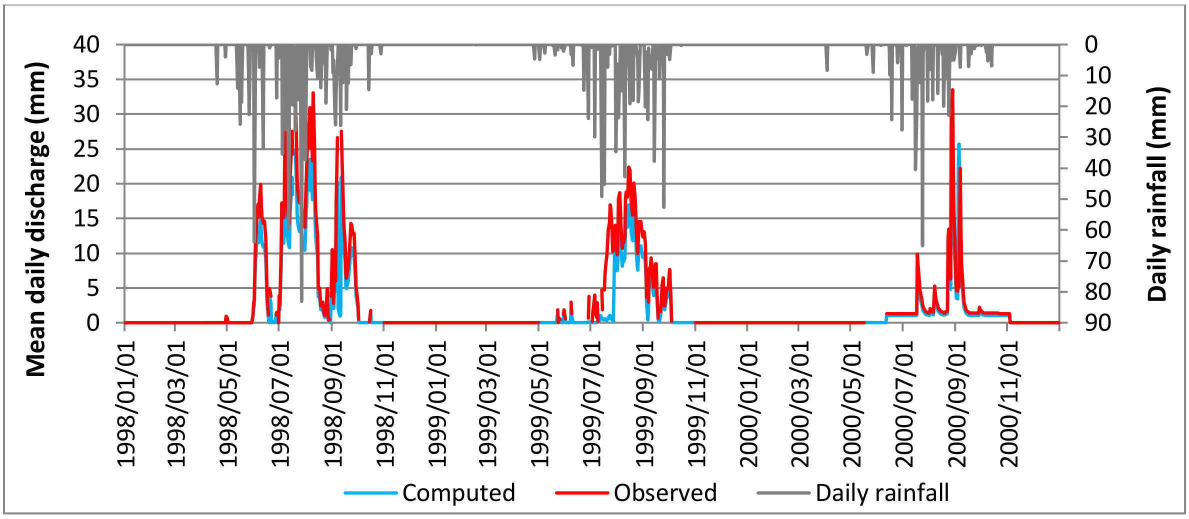


Figure_3.7 Validation results of daily observed versus computed runoff for the main Faga River at Liptougou against daily precipitation.

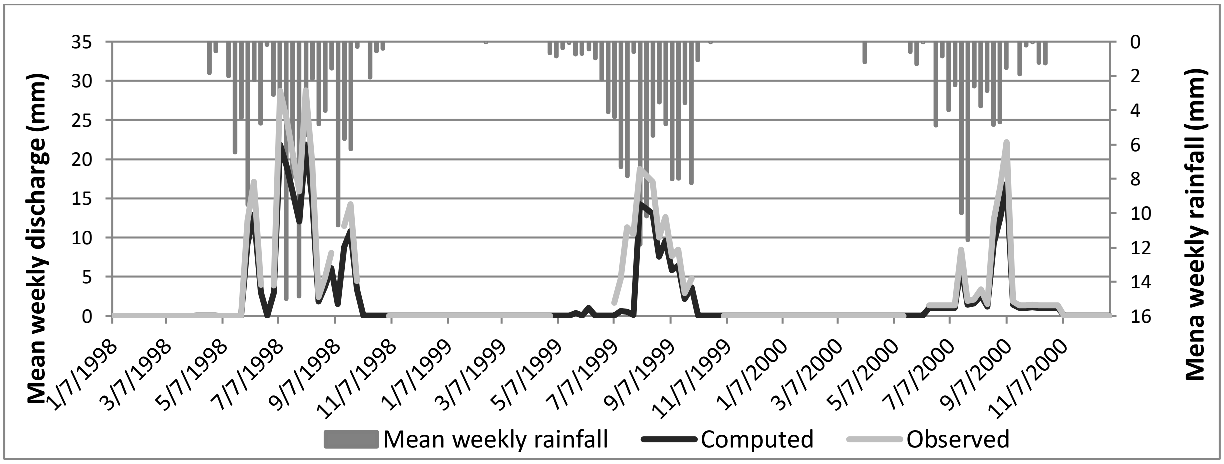


Figure 3.8 Validation results of weekly observed versus computed runoff for the main Faga River at Liptougou against weekly precipitation.

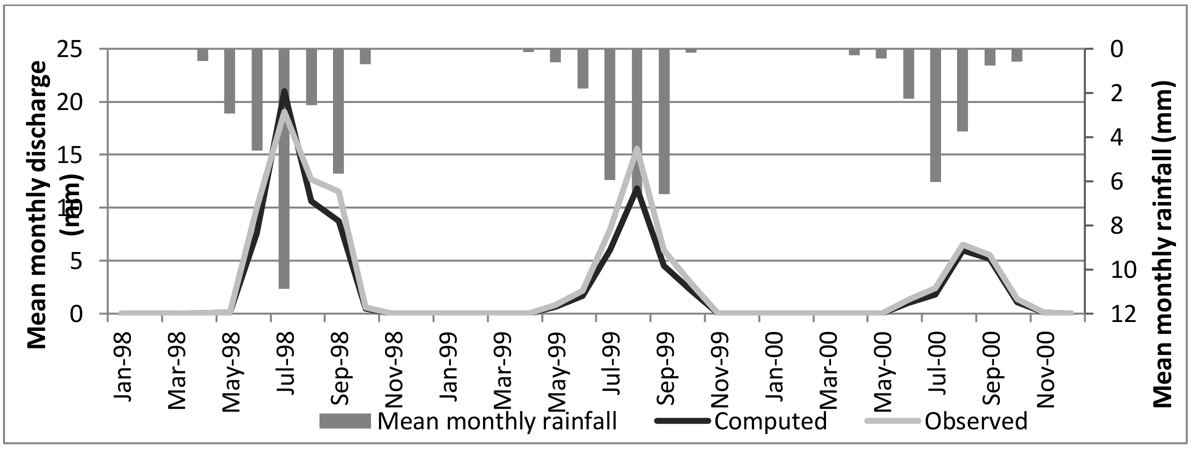


Figure 3.9_Validation results of monthly observed versus computed runoff for the main Faga River at Liptougou against monthly precipitation.

Table 3.3: WaSiM-ETH estimated performance for the Faga Basin at Liptougou for the validation period using daily, weekly and monthly aggregation

Aggregation Frequency	**Performance criteria**			
	R^2	*Model efficiency*	*Mass balance error [%]*	*Index of agreement*
Daily	0.87	0.89	0.93	-6
Weekly	0.89	0.94	0.94	
Monthly	0.95	0.95	0.96	

3.3.5. Hydroclimatic parameters variability assessment

There is a need to understand the role of climate parameters variability in determining the hydrologic parameters mean variability. In the present study, the interannual fluctuation of the hydroclimatic variables monitoring and detection were carried out using the indices of Nicholson which are averages of standardized annual hydroclimatic variables for three stations within the study area. The index of Nicholson is widely used to diagnose wet or drought periods over the study area within a study period and is expressed by the following equation:

$$I_i = \frac{X_i - \overline{X}}{\sigma} \qquad (3.15)$$

I_i .= Annual index of rainfall or hydrological variable

: Annual mean of the variable over the study period

: Annual variable recorded during the year i

: Standard deviation of hydroclimatic series in the study period

The Hanning filter is commonly used to better characterize the hydroclimatic variability, in many studies including Goula et al. (2006), Kanohin et al. (2009), Yao et al. (2012) and Maléki et al (2014) In order to identify the different periods where change occurs and to have homogeneity in results plot, extremes have been standardized using Equation (3.13).

The seasonal variability of the hydroclimatic parameters was assessed using the same approach as the interannual analysis with a study time scale of June, July, August and September (JJAS) which cover the wet season with almost very low precipitation in the rest of months in the study area.

The widely used non-parametric Mann-Kendall (MK) (Mann, (1945), Kendall, (1975), Gilbert, R.O., (1987)) combined with Sen's slope estimation is used in this study for trend analysis test. The MK is chosen for the reason that it statistically assesses if there is a consistent increase or decrease trend of the variable of interest over time even if the trend may or may not be linear. The Mann-Kendall also has less assumptions than the usual parametric test such as Student's t-test, Fisher's F-test , (Zhang et al., 2014).

The Mann-Kendall test statistic S is calculated as follow:

$$S = \sum_{k-1}^{n-1} \sum_{j-k+1} \operatorname{sgn}\left(x_j - x_k\right) \quad (3.16)$$

Where:
S = trend
n = length of the data set
x_j = observation at time j
x_k = observation at time k
With:

$$\operatorname{Sgn}(x) = \begin{cases} 1 , & \text{if } x_j - x_k > 0 \\ 0 , & \text{if } x_j - x_k = 0 \\ -1 , & \text{if } x_j - x_k < 0 \end{cases}$$

The Mann-Kendall test tests whether to reject the null hypothesis and accept the alternative hypothesis, where

(H_0) = No monotonic trend

(H_a) = Monotonic trend is present

The initial assumption of the MK test is that is true and that the data must be convincing beyond a reasonable doubt before is rejected and is accepted.

The variance of S is computed using equation (3.17) which considers tied values may be present:

$$\text{VARS(S)} = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p (t_p - 1)(2t_p + 5)\right] \quad (3.17)$$

Where:

q = the number of tied groups and

tp = the number of data values in the pth group.

n = number of time periods

p = Prob [S ≥ x] = Prob [S ≤ −x]

The Mann-Kendall test is performed using the Z statistic (normal approximation) and the 95% and 99% confidence intervals for the Sen's slope estimates are calculated. The z-statistic is therefore:

$$Z = \frac{|S|}{\sigma^{(0.5)}} \quad (3.18)$$

The nonparametric Sen's method was used for estimations assuming that the time series has a linear trend. It gives the true slope of an existing trend and was used to estimate the magnitude of change in the hydroclimatic variables per unit time over the period of study.
After the hydroclimatic parameters variability assessed, we examined the variability of the climate extremes within the Faga Basin using the RClimDex software (1.1).

3.3.6. Small dams impact on the Faga river flow regime assessment

The calibrated and validated WaSiM model was used to simulate the river flow and the Easy-Fit software was used for flood frequency analysis. The WaSiM model and the Easy-Fit software are described in section 3.2.
The Faga River flow data collection started in 1973. However, from the 4 dams we considered in this study, the oldest one was built in 1959 where there was no recorded flow data. We then considered the period 1950-1958 as the reference period taking into account the starting point of climate parameters records (1950).
The WaSiM model was then run using input data for the baseline period to simulate the Faga River flow since the model does not need flow data as input for simulation. This output considered as the baseline flow was then compared to the current observed flow of the period 1982-2010. The period 1982-2010 was considered for flow change assessment because the majority of the dams were built during this period and the year 1982 is the starting point of irrigation in the basin. In. addition, the recorded data of this period is quite better than the other periods.
In order to assess the effect of dams and the water abstraction from dams on the river flow, an abstraction rule containing the volume of water abstracted in cubic meter (m^3/s) was written in WaSiM control file for each dam. An abstraction rule can be defined as a relation between dam content and allowed outflow (Schulla, 2014)
Abstracted water included irrigation water and household water supply and was taken from the lowest dams of each sub-basin collected from a field survey. WaSiM simulates the abstracted water from the lowest dam to the upper one in such a way that water is abstracted in the first dam until the satisfaction demand or until the remaining water in the dam is not sufficient to satisfy the demand before it simulates the second dam abstraction. This abstraction rule was used to simulate the projected changes of the Faga River flow.
Flood frequency analysis was conducted using the annual maximum (AM) flow time series which is the most frequently used series. The annual maximum flow was extracted from the baseline and the current period (1982-2010) time series. Only flow peak exceeding the average annual were considered for flood analysis in this study.

Anderson-Darling, Chi squared, and Kolmogorov-Smirinov (KS) goodness of fit tests were used to measure the compatibility of our data sets with a theoretical probability distribution function. The best fitted distribution function formula was used to calculate the probability of exceedence of flood and the return period for each data set and to estimate the maximum flow which corresponds to each return period. We then compared the estimated baseline maximum flow and the dams' run maximum flow for the same return period to see how dams are affecting the Faga River flow peaks. The Generalized Extreme Value (GEV), Frechet (3p), the Log-Pearson 3 and Pearson5 (3p) were used to perform the fitting test.

Trend analysis was done by comparing the average flow of the baseline and the current periods using equation (3.19):

With: = Rate of change

BAMf = Baseline annual mean flow (3.19)

CAMf = Current annual mean flow

3.3.7. Prediction of future flow changes over the Faga River

3.3.7.1. Regional Climate Model selection

Regional climate Models (RCMs) output are used as basis for hydrological modelling. End users of RCMs with regard to hydrological changes require informations regarding the quality of the predictions. However, the use of RCMs output is often challenging as there are expected changes in climate patterns that RCMs should be able to very well capture. This suggests a need for RCMs performance evaluation by hydrological modellers because there is no given RCM performance information. A wide range of methods are used to assess climate model performances. Since there is no accepted climate models performance evolution method, we assumed that RCMs had the same probability and they can substitute each other IPCC, (2010).

Among many other methods, climate models can be evaluated based on the quantification of models errors using statistical measures. Indeed, Reichler and Kim, (2008) considered the performance index of climate models as the aggregated errors of the observed climatological simulations of the mean states of many climate variables. Gleckler et al, (2008), performed their evaluation using simple statistical metrics such as bias, correlation, root-mean-square error and standard deviation. For these methods models are evaluated against observations on a global scale for given variables.

In this study RCMs were selected using the standard deviation of models and temperature and precipitation changes. This method is a straightforward measure estimation using the MultiModel Mean (MMM). Indeed the MMM was found to be the best way in determining

RCMs that better capture the future climate compared to the observed (Reichler and Kim, 2008) and (Gleckler et al, 2008). A total of 15 GCMs (presented in Table 3.2) widely used within the Couple Model Intercomparison Project Phase 5 was use for the purpose of this study. These GCMs data included historical and future temperature and precipitation for both the high and moderate representative concentration pathways RCP4.5 and RCP8.5, respectively.

GCMs projections of temperature and precipitation changes were calculated as the difference between future and observed mean temperature and total precipitation. Then the standard deviation members of the 15 GCMs was calculated for the temperature as well as for the precipitation. Then, temperature changes are plotted against precipitation changes and the standard deviations (± standard deviations) are used to define the zone of acceptable models (red circle). Models that fall within this zone are representative models that capture well climate projections for the study region. However, the best fitted models are GCMs whose temperature and precipitation changes fall closest to the center of the acceptable zone (here represented as a circle as one can see in figure 3.10). Therefore, better performing models for the purpose of this study were found to be: MPI-ESM_LR (Yellow), Can_ESM2 (green) and EC-EATH (red).

Table 3.4: CMIP5 GCMs used in this study

Models	**Institutions**
CanESM2	Canadian Centre for Climate Modelling & Analysis
EC-EARTH	Euro-Cordex Earth System Model
MPI-ESM-LR	Max Planck Institute (MPI) for Meteorology (low resolution)

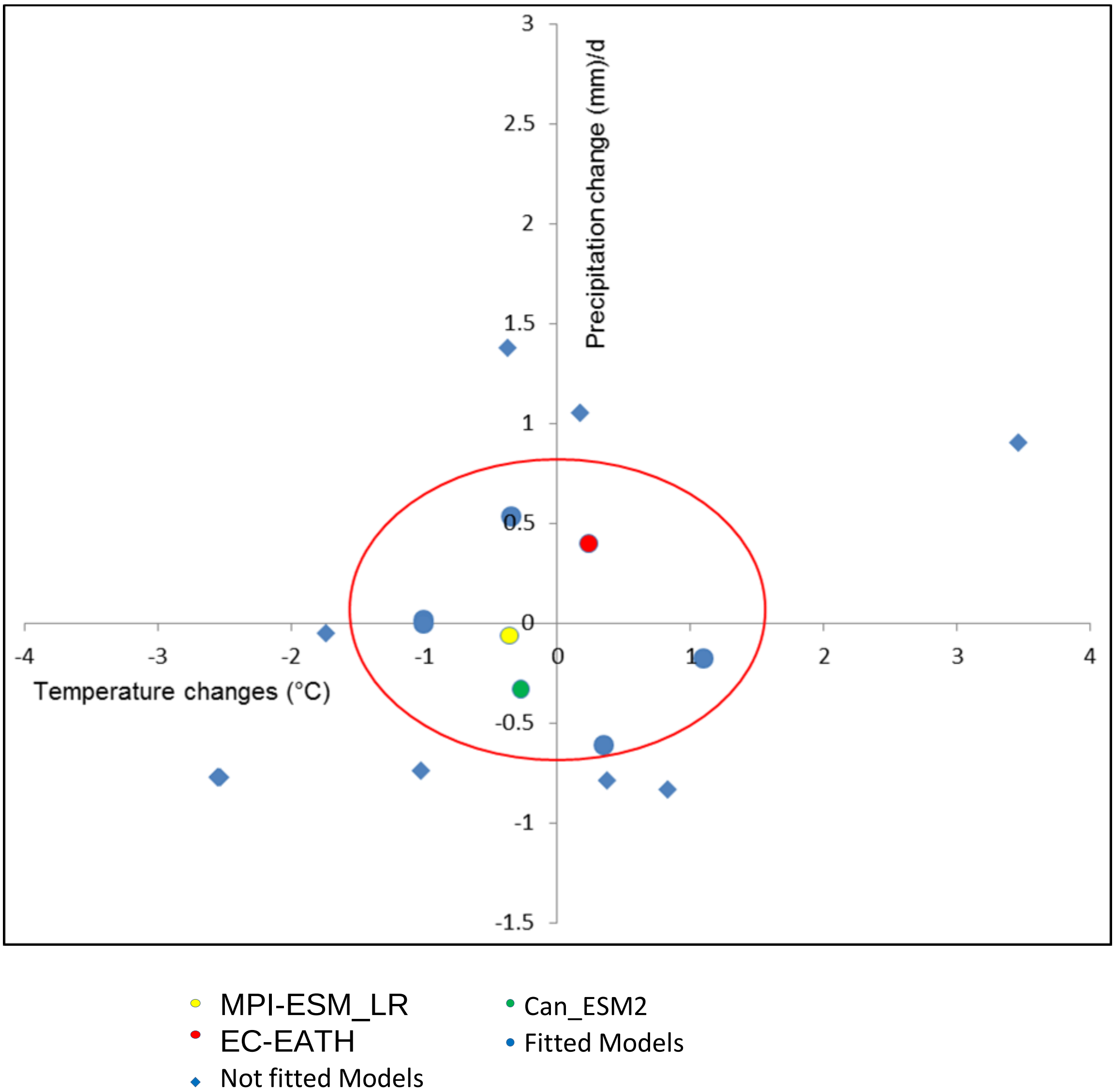


Figure 3.10: Zone of acceptable climate models

To assess the future changes in the Faga River Basin, climate variables from the Can_ESM2, EC_EARTH and MPI_ESM regional climate models were downscaled at the station point using the Statistical Downscaling Model (SDSM).The output of this downscaling runs were used to run the hydrological model, WaSiM. A standalone simulation was first done using the projected climate variables from the different RCMs to assess impact of only future climate change (without dams) on the Faga River. The cumulative impact of existing and the planned future small dams and future climate was then assessed by running WaSiM with the projected climate variables from RCMs and the activated lake sub- model containing dams operation rules previously detailed. In this study, assessment of future river flow change will focus on comparing the projected change to the observed flow with and without dams' effect. This is to understand how the Faga River flow from nowadays will respond to the probable change of climate parameters. RCP4.5 and RCP8.5 were used as emission scenarios in this assessment

The Regional Climate Models output were downscaled from large scale to local scale using the version 5.2 of the Statistical Downscaling Model (SDSM). The SDSM is a software package used to statistically downscale climate output from GCMs' simulations. It allows the synthetization of daily time scale series using the incorporated weather generator methods. SDSM is used in this study for it may be employed any time there is a need to assess small-scale effects of climate scenarios and can be used for all locations. A quite easy to use software, the SDSM possesses a set of use instructions and is widely used for climate impact assessment. Among others, Crawford, et al. (2007), used the SDSM to analyse the GCM grid box choice and predictor selection. Bootsma, A. et al.(2005) used it to assess the impacts of potential climate change on selected agroclimatic indices in Atlantic Canada. Prudhomme, C., Reynard, N. and Crooks, (2002) analyzed flood frequency through downscaling of global climate models. It has also been used by Diaz-Nieto and Wilby, (2005) to compare statistical downscaling and climate factors methods impacts on low flow in River Thames in United Kingdom. Downscaling daily precipitation with SDSM software constitute a big challenge due to the conditional character of the precipitation.

3.3.8. Socio-economic impact assessment

In the discussion on climate change, trends in the hydrological cycle are of particular interest since they are expected to have severe consequences for societies and ecosystems. In this study the socio-economic effect of small dams was assessed throughout a field a field survey. This survey based on interview was interested in irrigation abstraction around four main dams since they were built for water supply and agricultural purposes. Data related to the quantity of water used for irrigated parcels and household use, the number of days the parcels are irrigated, the start and end day of irrigation for instance were collected. These data was used to establish the reservoir abstraction rule used in the Lake sub-model of WaSiM for dams' impact on river flow assessment. Furthermore, the survey focused on downstream riparian's perception on the effect of existing dams on their social and economic environment over the last 25 years. These informations include their perceptions on change in their daily livelihood, change in rivers' banks, crop yield and their customary sites such as sacred places. Local adaptation strategies used to cope with the observed changes were collected as well.
For this purpose a questionnaire was administered to a total of 500 market gardeners from 40 to 80 years old within the four (4) main dams' sub-basins.

3.3.9. Partial conclusion

This chapter provided an overview of the methodology used for the hydrological modelling. It gave details on the data and the models and softwares utilized for the study goals achievement. Each method, data and material enumerated will use in the results descriptions. The following chapter deals with the results obtain for assessment of the seasonal and interannual variability of the hydroclimatic parameters over the Faga River Basin.

CHAPTER 4: INTERANNUAL AND SEASONAL VARIABILITY OF THE CLIMATE AND HYDROCLIMATIC PARAMETERS OVER THE FAGA RIVER BASIN

4.1. Introduction

Hydroclimatic parameters such as rainfall, temperature, evapotranspiration and river flow may be subject to global change and their analysis may contribute to a better appreciation and understanding of how climate and hydrodrological variables behaved from 1982 through 2010 in the Faga basin. Indeed, Burkina Faso which is a Sahelian country, has a rainfed agriculture system, which employs over 90 percent of the workforce according FAPDA (2014) and strongly depends on the amount of precipitation received over the rainy season and how this amount is distributed. Like the other agricultural countries, the economy of Burkina-Faso heavily depends on the agriculture. However, change in mean climate condition as well as extreme climate conditions (warmer or wetter) could impact on crop productivity leading to food security issues. Other risks may be the increase of diseases; death due to increased heat stress; increase water stress, etc.

Hence there is an important need to study how climate variables are changing at local scale in order to reinforce agriculture and water related adaptive capacities. In addition, many essential sectors on which economy depends including agriculture, water, transportation and energy are highly vulnerable to climate extremes. The sustainability of economic development and living conditions depends on our ability to manage the risks associated with extreme events (Albert M.G. Klein Tank, 2009). The motivation for analyzing climate variability and climate extremes is that these changes may be risky to all the socio-economical domains. Indeed, deficit or excess rainfall or temperature may cause enormous losses. For instance, eleven (11) deaths, over 25000 affected persons and an important number of damaged infrastructures were numbered on the 1st September 2009 where an amount of 261 mm of rainfall according to Karambiri et al. (2011) was recorded in Ouagadougou in one day.

The purpose of this chapter is to examine the interannual and seasonal variability of rainfall and temperature. It also aims to analyse change in climate extreme in order to contribute to the appreciation and the understanding of how rainfall and temperature extremes over the Faga watershed located in the North-Eastern part of Burkina-Faso varied from 1982 through 2010. Another interest of this section is to assess the relative effect of climate variables change on the Faga River runoff through the study period.

4.2. Interannual fluctuation of climatic variables

4.2.1. Rainfall variability

The precipitation times series analyzed with the index of Nicholson combined with the moving average for three stations reveal distinct rain periods. Figure 4.1 to Figure 4.3 show the annual variation of rainfall at each station. One should note that a sequence of positive index indicates a period where annual rainfall is above the average rainfall of the study period and it is qualified as a wet period. The period is qualified as drought in case of negative index sequence where the annual rainfall recorded is below the average rainfall of the study period.. The coefficients of variation of rainfall for the three stations are estimated at 1.03%; 30% and 17% respectively for Dori, Bogande and Fada. This support the finding that rainfall distribution is spatially variable over the study area and this variability is high in the region witnessing sahelian regime of rainfall.

We assess how the climatic data generally varies within the Faga. The mean values of rainfall and temperature data were computed by calculating the global mean of each parameter.

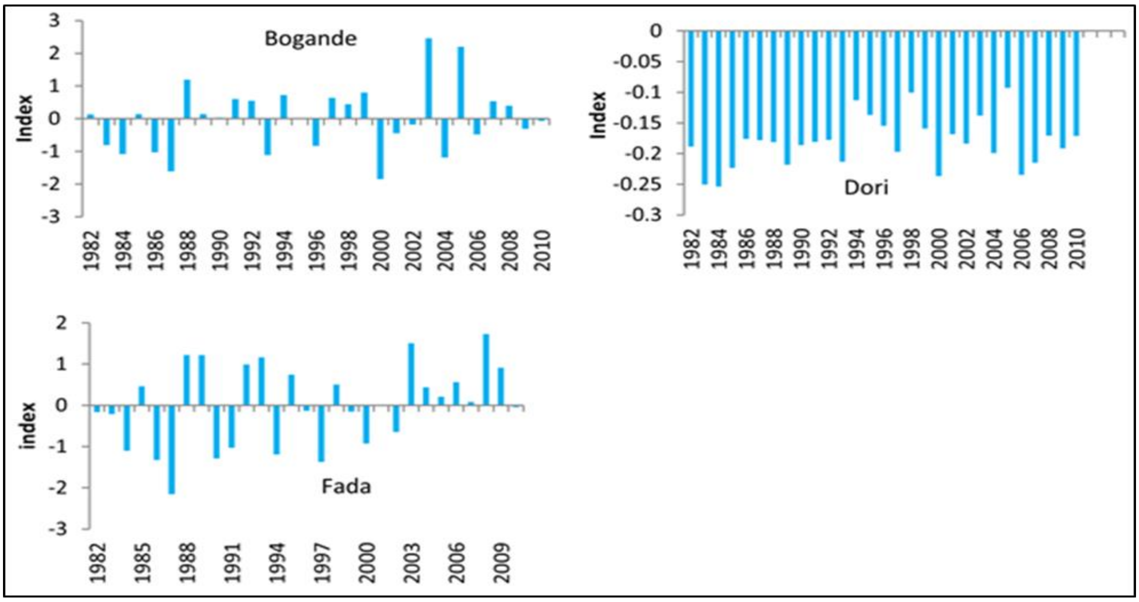


Figure 4.1: Rainfall vatiability at Bogande, Dori and Fada stations

Globally, the whole basin presented a deficit rainfall from 1982 through 2010. This is in accordance with the general rainfall trend over the Sub-Saharan Africa since the 1970s. Indeed, from 1982 through 2010 mean annual rainfall over the Faga basin is 684.5mmwith a standard deviation of 120.34mm. The coefficient of variation is estimated at 18%. The highest rainfall is observed in 2003 is as 946.6mm and the smallest is 480.8mm observed in 1997.

4.2.2 Temperature variability

While the rainfall time series shows different interannual variability depending on the station, the mean temperature time series showed for the two stations an increase temperature from 1982-1987 while relatively lower temperature is observed from 1988 to 1994 follow by a clear increase from 1995 to 2010 as one can observe in Figure 4.5. Two stations, Fada and Dori, time series were considered for temperature variability analysis. The reason is that the third station contains about 28% of missing data and may not be useful for variability assessment. Along the study period, temperature has been increased by 0.05^{0}C for Dori station and by 0.04^{0}C for Fada station. However this value that could be very high already. These results aline with the observed global warming trend over the West Africa. Indeed, according to Morice et al., (2012), West African region witnessed an increase temperature of about 1^{0}C since 1950. Riede et al., (2016) gest that temperature has increased at about 0.5^{0}C over the Africa and some regions have had more increase between the last 50-100 years.

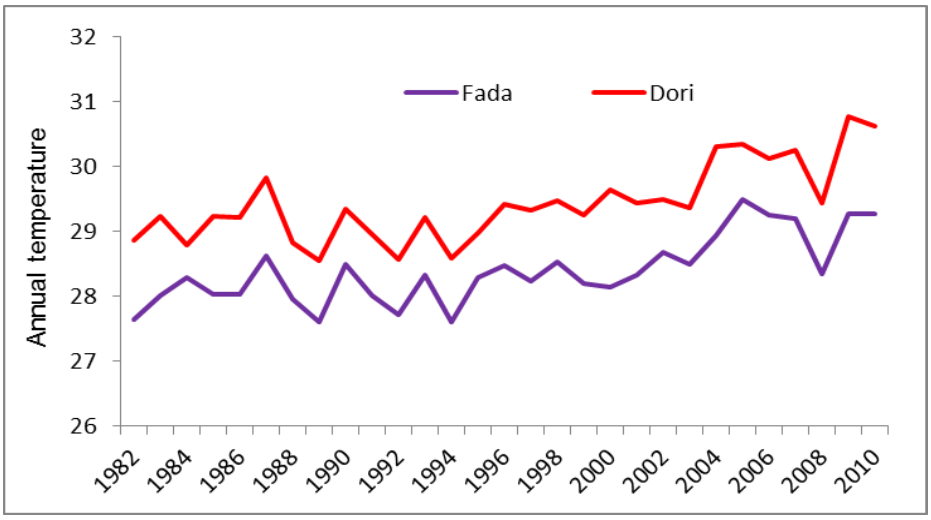


Figure 4.2: Interannual variation of temperature

4.2.3. Flow and potential evapotranspiration fluctuation

Flow variation analysis was done using flow time series recorded at the Liptougou station in downstream Faga. The average flow value is estimated at 215.25 m^3/s recorded in 2000.
The interannual variability of the river flow is estimated at 60% for the study period. Flow index analysis showed adverse annual through the study period (Figure 4.3).

The potential evapotranspiration (PET) was only available for the Fada station and was used in this study as reference. As shown in Figure 4.4 below, the PET is high for almost the whole period with few years of low evapotranspiration. Through the study period the minimum and the maximum are respectively 1,454.8mm recorded in 1996 and 3,097mm recorded in 1997.

The mean monthly PET is about 635.99mm per month while the mean annual PET is estimated at 2,817.49mm per year from 1982 through 2010.

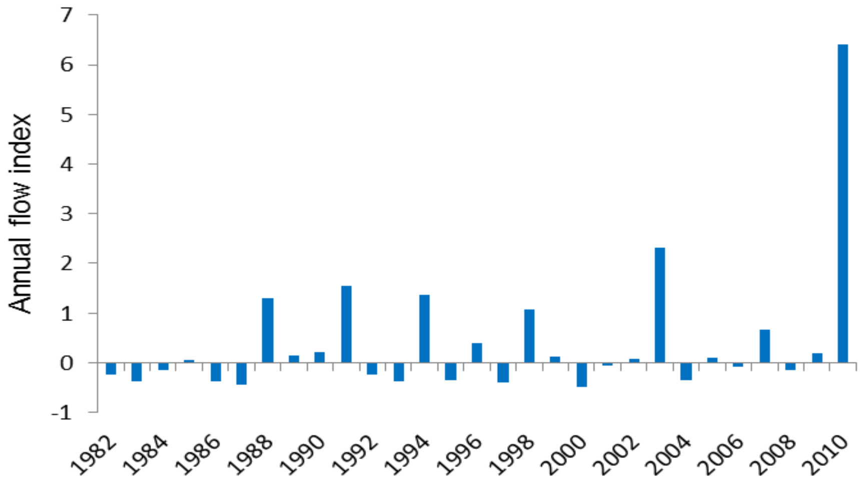


Figure 4.3: Annual flow variation

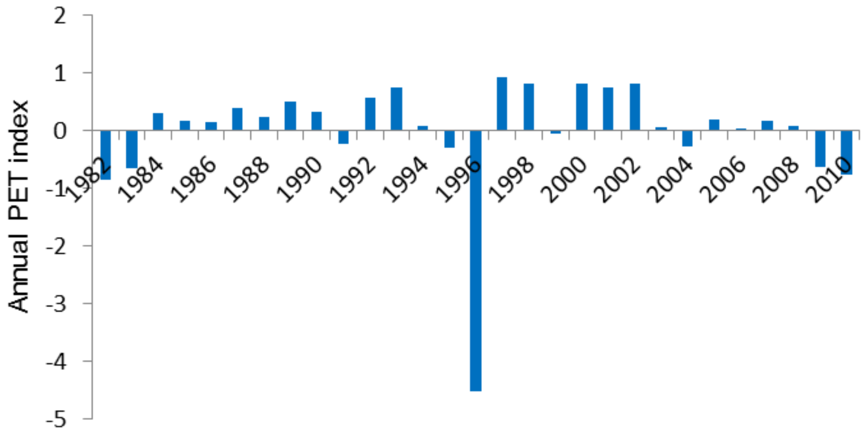


Figure 4.4: Annual PET variation

4.3. Seasonal fluctuation of climatic variables

4.3.1. Rainfall variability

Monthly rainfall time series for the three stations were used to analyse the seasonal variation of rainfall. The seasonal mean rainfall was also determined to assess its seasonal variability over the basin. The minimum rainfall for the seasonal time scale of June-July_August_September (JJAS) for Bogande, Dori and Fada were 80.3mm in 1987, 55.95mm in 2000 and 84.23mm in 1984 respectively. The maximum values were observed in the same order in 2008 with 223.1mm, in 2003 with 164.62mm and in 2005 with 193.5mm.

The assessment of interseasonnal variability of rainfall reveals deficit years where the JJAS indices are negative and excess years with positive indices. Figure 4.9 presents the variation of JJAS rainfall . The first decade is marked by a deficit in JJAS rainfall as found in all the stations followed by an excess decade for Bogande. The last decade is fairly watered with almost the same number of years with negative and positive indices. The second decade for Dori and Fada showed contrasted rainfall. However the third decade is watered for Fada whereas the Dori one is dry.

Generally indices of the whole Faga basin reveal for the first decade a deficit in JJAS rainfall. The remaining period seems to be fairly watered with alternation of dry and wet years.

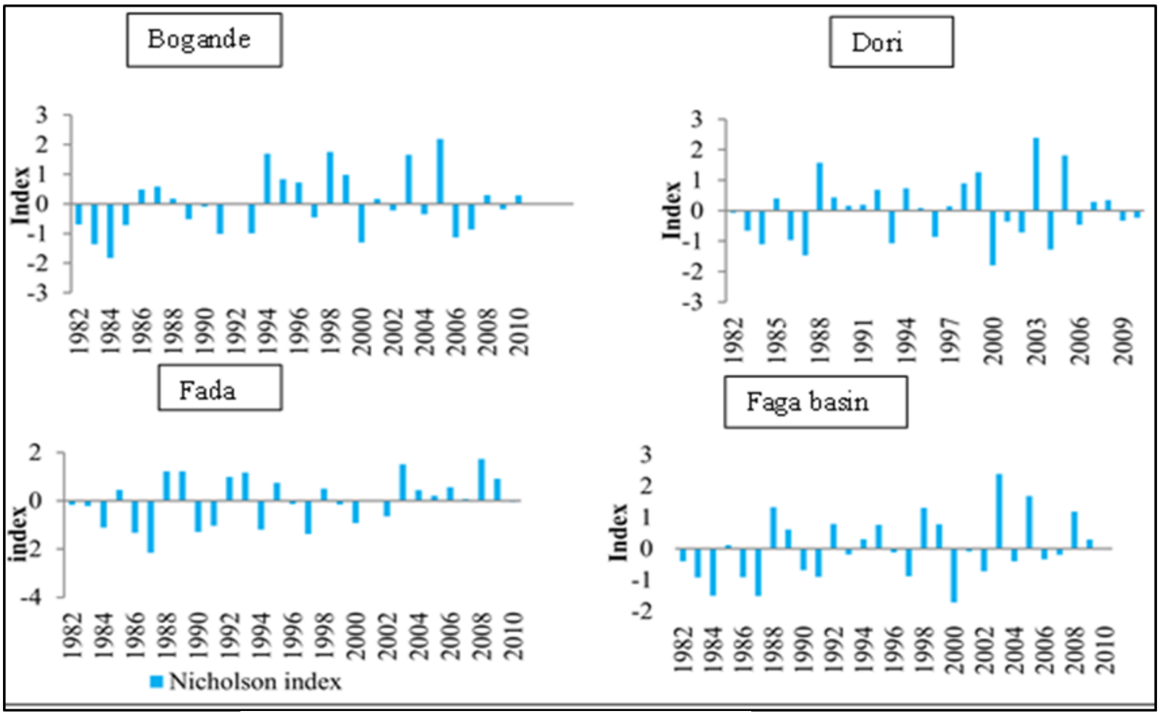


Figure 4.5: Seasonal rainfall variation

The mean seasonal rainfall for the Basin is estimated at 132.23mm per JJAS time scale with a coefficient of variation from one JJAS to another at around 17%. However the highest rainfall for all the stations is recorded in August around 33% of the JJAS rainfall, 40.87% and 33.70% respectively for Fada, Dori and Bogande.

4.3.2. Temperature variability

For the temperature analysis the monthly mean temperature is used due to the reason mentioned above. The mean seasonal temperature for the Basin is 28.7°C and the coefficient of variation is estimated at 1.68%. One can note that during the two first decades the mean temperature is generally lower than the mean of the period 1982-2010. The last decade presents positive indices meaning that the temperature is above the general mean observed for the period in contrast with the first decades as showed in Figure 4.10 below. The variation of the temperature is low in comparison with the rainfall variation.

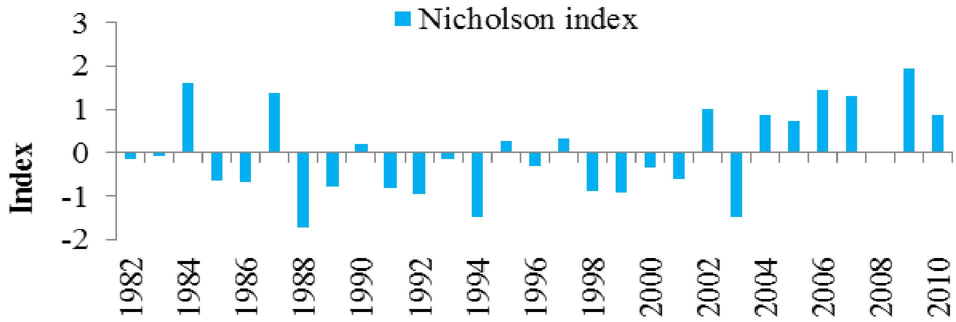


Figure 4.6: Seasonal temperature variation

4.3.3. Flow and potential evapotranspiration fluctuation

Figure 4.11 shows that a general low flow is observed from 1982 through 2010 along the Faga River and very little high flow with low intensity is recorded in each JJAS time scale. From the total amount of water flowing each year, the minimum and the maximum flow were 7.36m3/s observed in 1987 and 57.9m3/s observed in 2009 respectively. The mean JJAS flow from 1982 to 2010 is 53.34m^3/s with a coefficient of variation estimated at 98%. Contribution of JJAS flow to the annual flow is estimated as 96.66% with the highest flow observed in August. The mean flow is estimated as 43.12M3/s from 1982 through 2010.

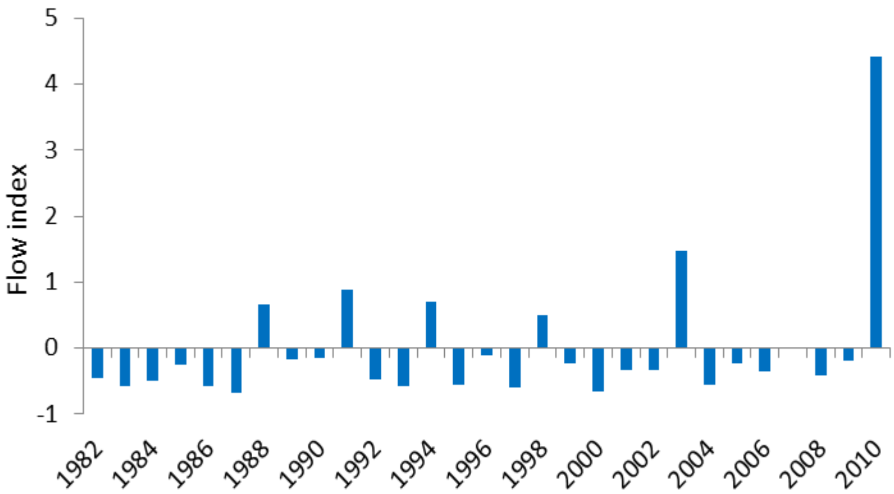


Figure 4.7: Seasonal flow variation

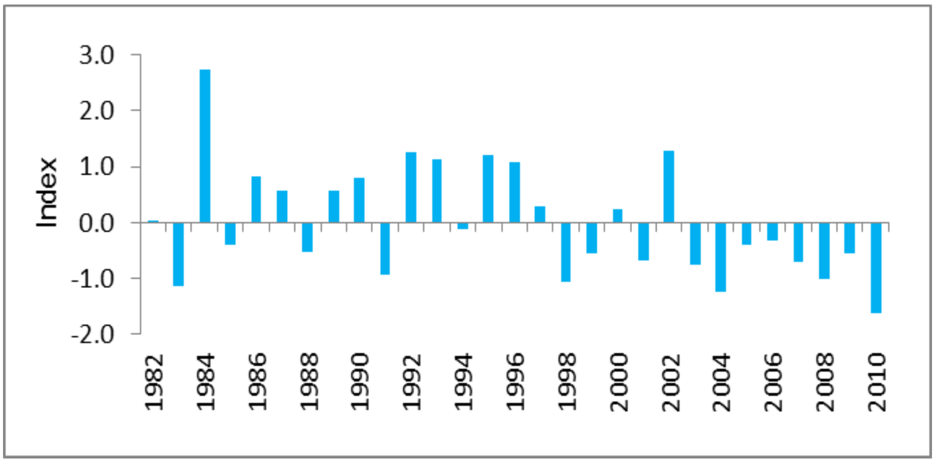


Figure_4.8: Seasonal PET variation

Analysis of seasonal potential evapotranspiration showed a coefficient of variation estimated at 11% and the mean value was 625.05mm.

The maximum PET value was observed in June with 210.46mm and minimum in August with 128.92mm. The lowest JJAS PET value was 377.9mm observed in 1996 and the higher value was observed in 1984 with 785.2mm.

4.4. Trends analysis

Trend analysis of seasonal and interannual time series was done using Mann-Kendall test and estimation of Sen's slope. The calculations of the Mann-Kendall statistics, Sen's slope and p-values derived for each of the hydroclimatic variables and the Faga River basin area using the mean recorded values of the variables over the basin are summarized in Table 6.3 below. The P-value of 5% was used in this study as criteria level with 95% of confidence in slope estimation and the related trend is then significant if the P-value is below 0.05.

4.4.1. Interannual trends

The Mann-Kendall test of the annual rainfall time series reveals an upward trend with two statistically significant ones for Bogande and for the whole basin. The magnitude of the observed increase in annual rainfall is estimated through Sen's slope test. It indicates all the stations have a weak upward trend which is estimated at 4.94 mm, 2.39mm and 11.8mm per year for Fada, Dori and Bogande respectively. A weak upward trend is observed for the whole Faga basin in the annual rainfall which increases at about 6.62mm per year. This result is in accordance with the observed trend of all the stations.

Over the whole study period from 1982 through 2010, annual flow and potential evapotranspiration showed no significant upward trend at the 0.05 of confidence level, which slightly increased by 1.44m3/s (3.48mm) and 1.08mm per year respectively. Significant increasing trends were detected in annual mean temperature at the same confidence level, which increased by 0.05^{0}C per year.

4.4.2. Seasonal trends

The total amount of rainfall through JJAS ranges between 321.2mm and 892.4 for Fada. In Dori the range is between 230.8mm and 753.2mm while for Bogande the range is between 433.8mm and 737.5mm. The JJAS rainfall ranges from 328.6mm to 819.9mm for the whole Faga. The coefficients of variation of JJAS are 23.05%, 32.35% and 24.46% for Fada, Dori and Bogande respectively. Table 4.1 presents the trend observed in the two time scale of the study, with significance statistic at 95% confidence level

Table 4.1: Mann-Kendall and Sen's test on hydroclimatic variables

Annual rainfall time series	**Sen's Slope**	**Z Test**	**P-values**	**Significance**
Fada	4.944	1.46	0.1	
Dori	2.389	0.62	0.54	
Bogande	11.800	3.09	0.002	**
Whole-Faga	6.6	2.19	0.027	*
Annual flow	1.44m3/s (3.48mm)	0.22	0.15	
Annual PET	-1.08	-0.21	0.83	
Annual Temperature	0.055^{0}C	3.35	0	***
JJAS rainfall time series	**Sen's Slope**	**Z Test**	**P-values**	**Significance**
Fada	5.48	1.63	0.001	*
Dori	2.39	0.62	0.54	
Bogande	3.76	1.37	0.17	
Whole-Faga	3.79	1.87	0.63	
JJAS Flow	1.57m3/s (3.02mm)	1.33	0.38	
JJAS PET	-2.84	-2.16	0.03	*
JJAS temperature	0.02^{0}C	1.63	0.10	

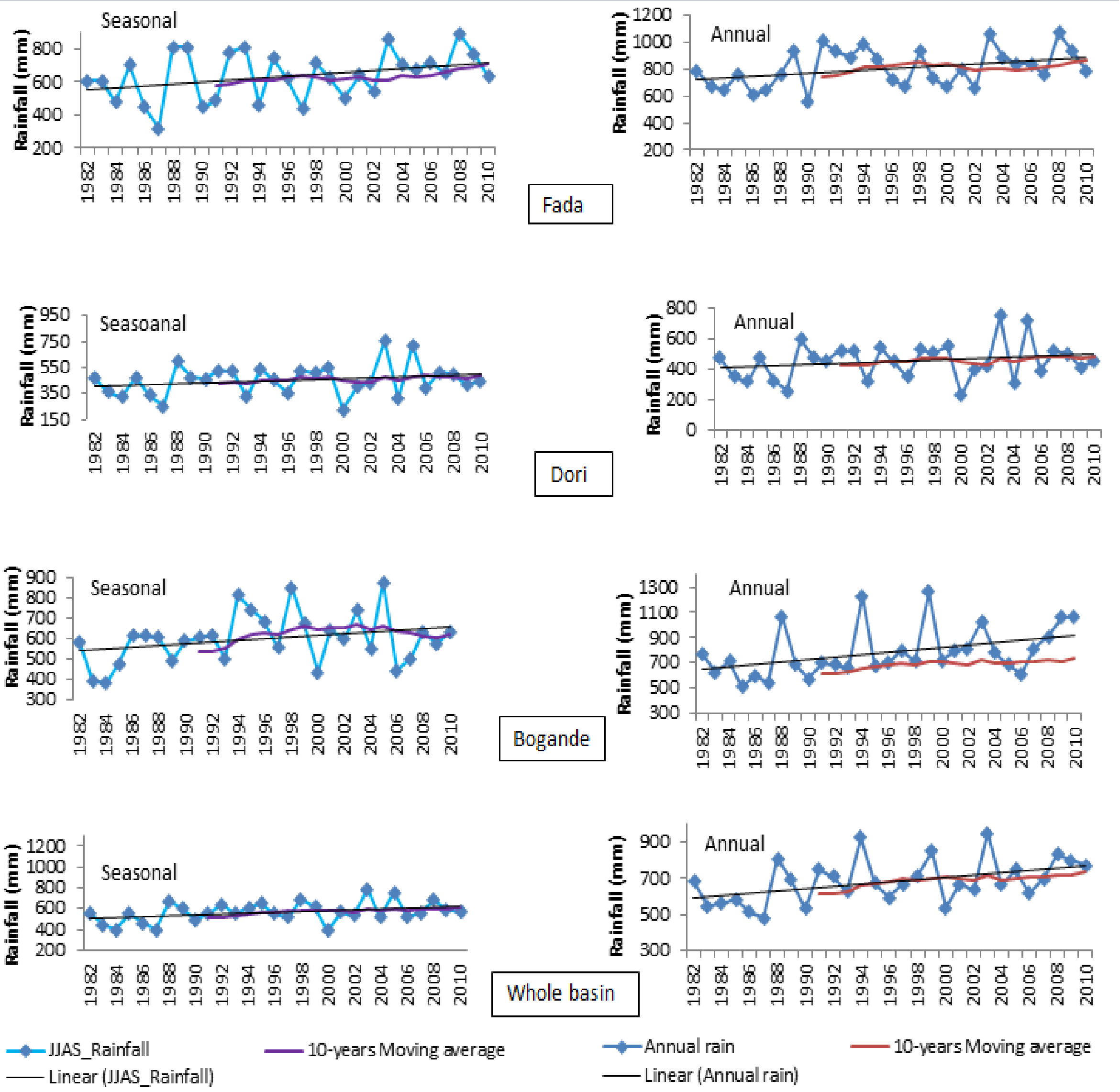


Figure 4.9: Seasonal and interannual rainfall variation

Seasonal rainfall of the Faga basin shows almost the same trend as the one observed in the three stations as represented in Figure 4.12. Statistics reveal a general upward trend in all the three stations. Only Fada presents a statistically significant trend among the three stations.

Over the whole study period from 1982 through 2010, JJAS flow and temperature showed not significant upward trend at the 0.05 of confidence level, by 1.57m3/s (3.02mm) and 0.02^{0}C per year respectively. However, the JJAS potential evapotranspiration showed a significant trend estimated at 2.82mm per year.

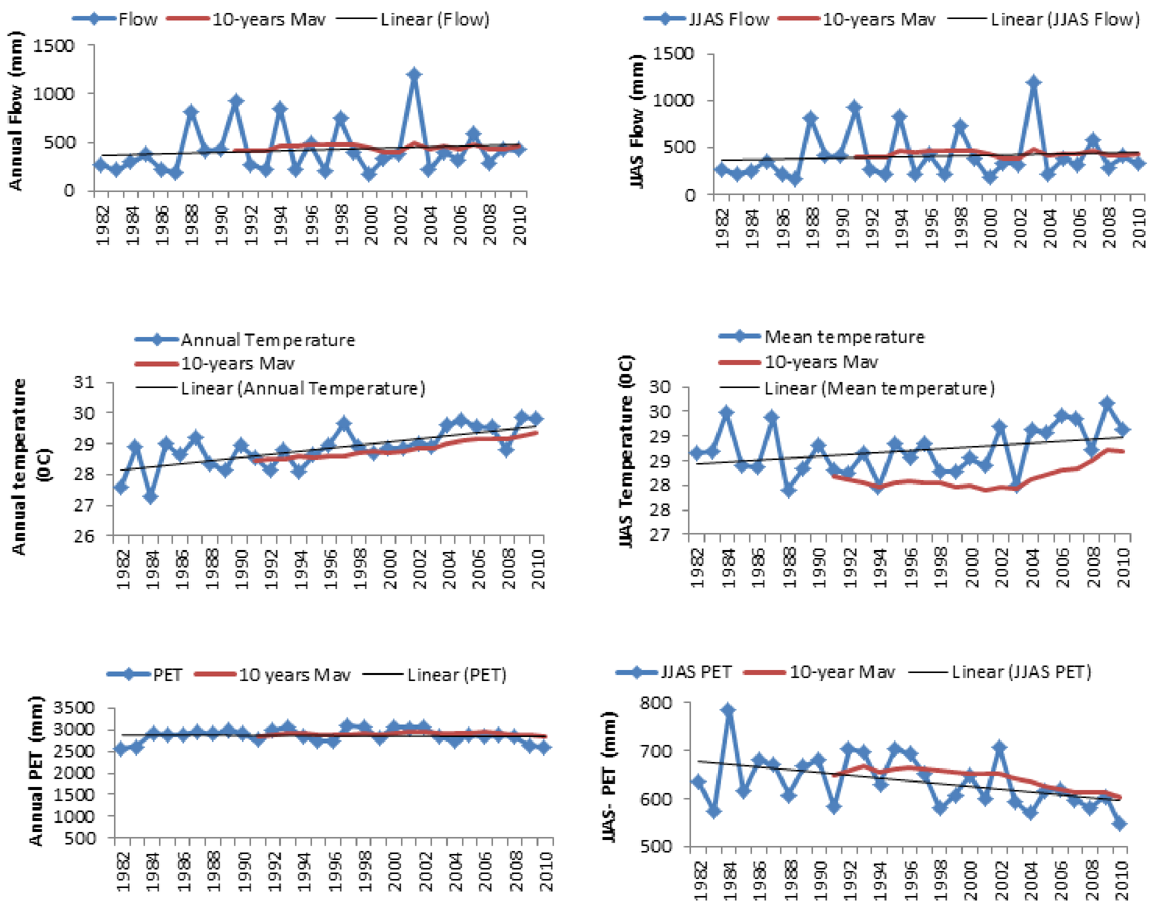


Figure 4.10: Seasonal and interannual Flow, temperature and PET variation

While a general slight upward stations trend is detected for the JJAS rainfall, analysis showed a downward trend at the end of the last decade between 2005 and 2010 as presented in Figure4.9 above. In this period, rainfall decreased about 16.5mm per JJAS for the whole basin and 6.2mm for Fada, 28.1mm for Dori. In contrast to the two first stations a spectacular upward trend of 36.3mm is observed for Bogande in the same period.

4.5. Change in climate extremes over the Faga Basin

4.5.1. Change in rainfall extremes

From 1982 through 2010, a downward trend was detected in the number of consecutive wet days (CWD). Figure 4.11 (b) The maximum 5-days rainfall (RX5day) also shows a downward trend Figure 4.11 (j) though the linear trend line due to the fact that decrease goes from very low positive index to the negative one

Table 4.2: Rainfall trends statistics (1982-2010)

Indices	Slope	STD_of_Slope	P_Value
RX1day (mm)	0.069	0.378	0.857
RX5day (mm)	-0.022	0.646	0.973
SDII (mm/day)	0.035	0.048	0.471
R10mm (days)	0.033	0.104	0.752
R20mm (days)	0.148	0.077	0.065
R50mm (days)	0.059	0.03	0.061
CDD (days)	2.089	0.785	0.013
CWD (days)	-0.019	0.03	0.535
R95p (mm)	3.065	2.05	0.146
R99p (mm)	0.781	1.333	0.563
PRCPTOT (mm)	5.206	3.021	0.096

Indeed, the consecutive wet days (CWD) and the maximum 5-days rainfall (RX5) day slightly decreased by 1.9% day per year and 2.2%mm per day within the study period (Table4.2). The maximum 1-day (RX1day) and the simple daily intensity index (SDII) which is the quotient of the annual rainfall by the total number of wet days in the year Figure4.11 i and k) showed a slight increase respectively by 0.069mm and 0.035 mm. Bontogho et al. (2015) also found an increase trend in the same index for the Massili basin in Central Burkina-Faso. The number of "heavy precipitation events increased over most areas during the second half of the twentieth century, leading to a larger proportion of total rainfall in a year from heavy falls" according to the (IPCC, 2007). This has also been noted in this study. Indeed, results showed that heavy to very heavy rainfall days which are days with rainfall more than 10mm (R10mm), 20mm (R20mm), and 50mm (R50mm) also showed an upward trend. An increase of 0.035mm was observed for the R10mm, 0.148mm for the R20mm and the R50mm rose by 0.0 59mm per year.

The trend of the consecutive dry days (CDD) which determine the dry spell length showed an increasing trend. Indeed, the number of consecutive days without rain during the rainy season rose from 1982 to 2010 by 2.089 days per year. This increase is in accordance with the work of Karambiri et al., (2011) indicating an increase trend in dryness in the Nakanbe basin. It also alines with results found by Badou, (2016) and M'Po et al., (2017) for the Oueme basin.

The fraction of annual precipitation due to very wet days (R95p) and extremely wet days (R99p) increased from 1982-2010 by 3.065mm and 0.781mm respectively The trend is also observed for the total wet days precipitation (PRCPTOT) which observed an increased of 5.20mm. These results lines up with the (IPCC, 2007) report on change in extremes which indicated that "the index R95pTOT representing the fraction of annual precipitation amount due to very wet days shows positive trends for the majority of stations".

The slight increase in rainfall observed in the basin is in agreement with the observed recovery of rainfall over the Sahelian region since 1990s as stated in (Lodoun et al. 2013, Wang and Gillies, 2011). The USGS and USAID, (2012) also reported that rainfall in Burkina-Faso recovered in the 1990s after a rapid decline between 1950 and the mid-1980.

4.5.2. Change in temperature extremes

Trends analysis of temperature extremes highlighted in Table4.3 and Figure 4.12 indicate that the cold days number (TX10p) showed a negative trend by 0.11 days while the number of warm days (TX90p)) rose by 0.12 days.

The number of cold nights (TN10p) decreased by 0.44 day whereas the number of warm nights (TN90p) increased by 0.48 day.

A non-significant very low decrease is indicated for the cold spell duration indicator (CSDI) with a rate of 0.06 day.

The warm spell indicator (WSDI) showed a slight increase with 0.06 day of rate.

As far as the monthly maximum and minimum value of daily temperature are concerned, the maximum value of daily temperature (TXx) increased by 0.02 ºC.

The same trend was detected for the monthly minimum value of daily maximum temperature (TNx) increased by0.03ºC. The monthly minimum value of daily minimum temperature (TNn) also increased by 0.08ºC. However, the Monthly maximum value of daily minimum temperature (TXn) showed a very insignificant downward trend with very low magnitude estimated at 0.004 ºC.

This analysis shows a clear warming climate for the Faga Basin in Burkina Faso from 1980 to 2010 with greater temperature extremes accompanied with an increase in the warm spell duration and a decrease of the cold spell duration. This observed increase in temperature extremes lead to general warming of the climate at the end of last century with greater warm extremes and less cold extremes Tebaldi et al, (2006). The warming trend in daily temperature extreme over the Faga Basin is in accordance with other findings in West Africa's climate assessment such as New et al., (2006) and Ly et al., (2013). This positive trend in temperature has also high impact on the basin's agriculture which is as the whole country qualified as rainfed agriculture. This increase in temperature may lead to an increase plant disease. Temperature extremes may negatively affects agriculture specifically when they occur during the growing period. Sarr et al.(2015),

also found that temperature increase accelerates maturation of seedlings in nurseries of lettuce, cabbage and onion. The carbon dioxide of the net ecosystem is likely to be disturbed by the increase temperature. Indeed, extreme temperature conditions can shift forest ecosystems from being a net carbon sink to being a net carbon source according to Handmer et al., (2012).

One of the key sectors affected by increase in temperature is the water sector.

Warming leads to increase of evaporation which reduces the availability of water.

Table 4 3: Temperature trends statistics (1982-2010)

Indices	Slope	STD_of_Slope	P_Value
TXx (ºC)	0.024	0.012	0.048
TXn (ºC)	-0.004	0.017	0.825
TNx (ºC)	0.034	0.016	0.047
TNn (ºC)	0.084	0.024	0.001
Tx10p (days)	-0.115	0.054	0.043
Tx90p (days)	0.124	0.106	0.254
Tn10p (days)	-0.446	0.061	0
Tn90p (days)	0.483	0.1	0
WSDI (days)	0.062	0.127	0.631
CSDI (days)	-0.063	0.071	0.384

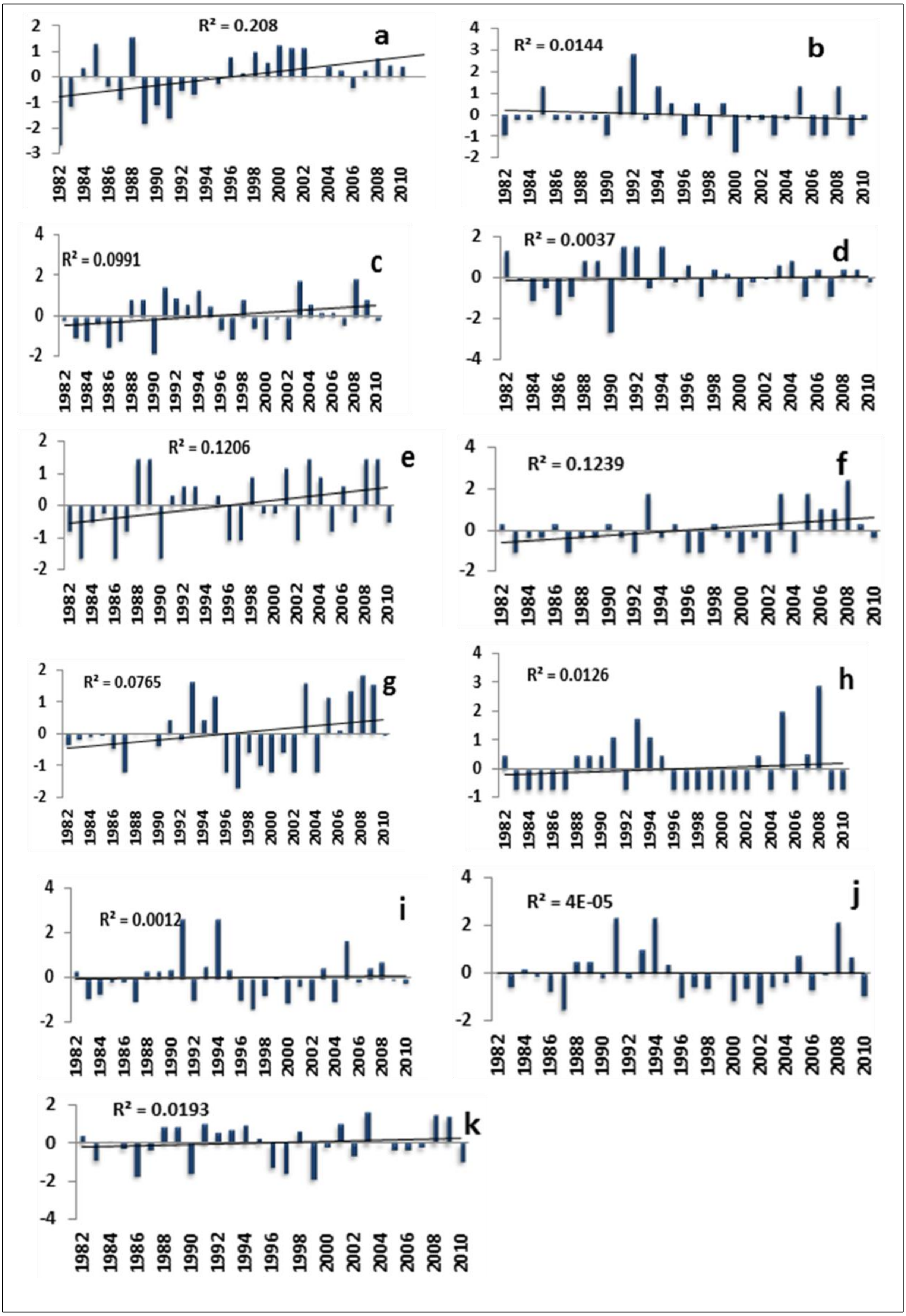


Figure 4.11: Precipitation indices in Faga for 1982-2010: CDD, CWD, PRCPTOT, R10 mm, R20 mm, R50 mm, R95p, R99p, RX1day, RX5day, SDII, from 19822010. R is the linear trend coefficient. (a) Consecutive dry days (CDD). (b) Consecutive wet days (CWD). (c) Annual total wet-day precipitation (PRCPTOT). (d) Number of heavy precipitation days (R10 mm). (e) Number of very heavy precipitation days (R20 mm). (f) Number of very heavy precipitation days R50mm. (g) Very wet days (R95p).(h) Extremely wet days (R99p). (i) Maximum 1-day precipitation (Rx1day). (j) Maximum 5-day precipitation (Rx5day). (k) Simple daily intensity index (SDII).

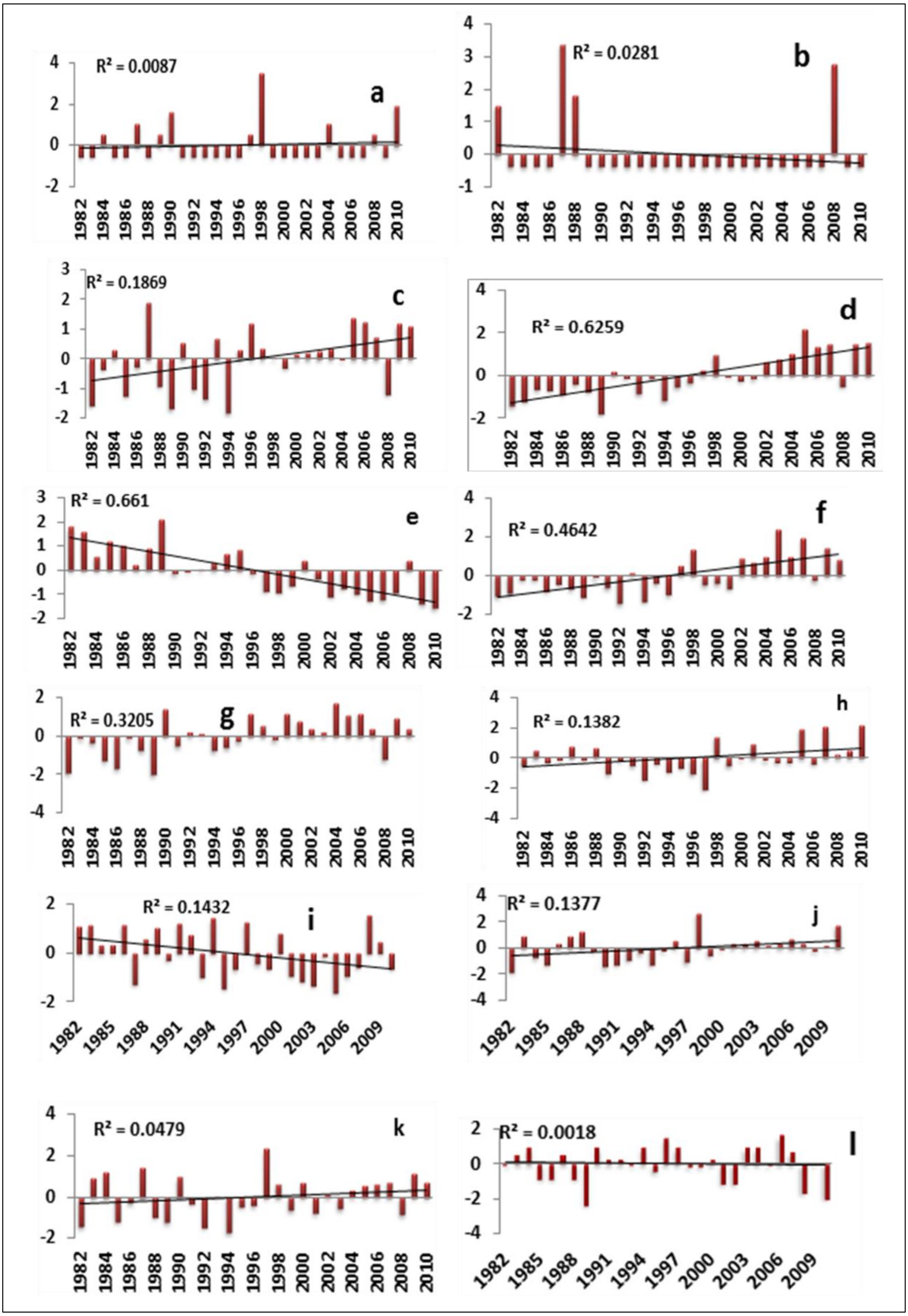


Figure 4.12: Temperature indices for the period 1982-2010: TN10p, TX10p, TNN, TXN, TN90p, TX90p, TNX, TXX CSDI and WSDI. R is the linear trend line. (a) Warm spell duration indicator (WSDI). (b) Cold spell duration indicator (CSDI). (c) Mean monthly maximum value of daily maximum temp (d) Mean monthly minimum value of daily minimum temp. (e) Cool nights (TN10p). (f) Warm days (TN90p). (g) Monthly minimum of Tmin (TNN). (h) Monthly maximum of Tmin (TNX). (i) Cool days (TX10p). (j) Monthly maximum of Tmax (TXX). (k) Warm nights (TX90p). (l) Monthly minimum of Tmax (TXN).

4.6. Impact of rainfall variability on the Faga River flow AdvOT863180fb

To assess how sensitive the Faga River flow is to rainfall variability over the study period, rainfall and flow time series were plotted simultaneously in the same graph. Indeed, annual time scale of rainfall and flow as well as seasonal time scale plots were used to perform interannual and seasonal variation of rainfall on the river flow analysis respectively.

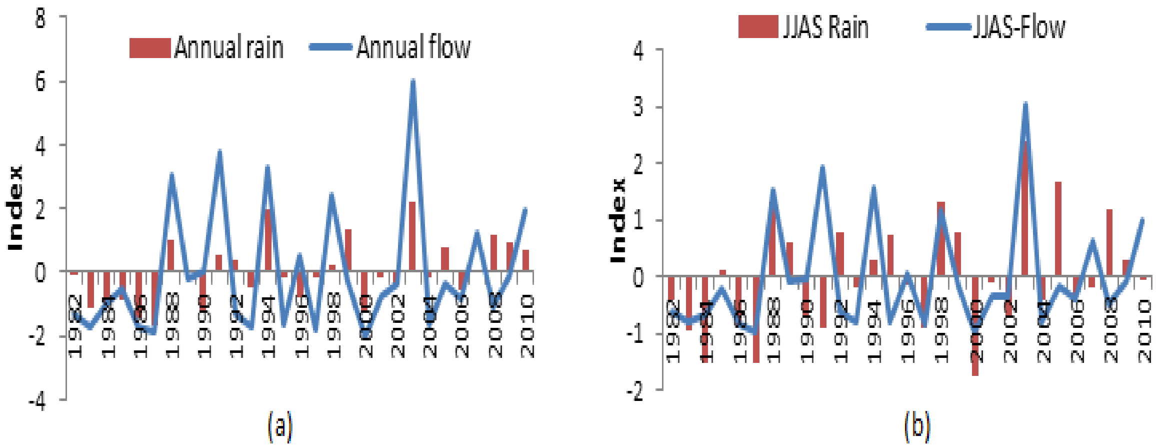


Figure 4.13: Flow sensitivity to rainfall; (a): annual sensitivity (b): seasonal sensitivity

The total amount of rainfall and flow through 1982-2010 shows a co-variation for the annual as well as the seasonal time scale as shown in Figure4.16. The period 2003-2010 is marked by deficit flow while the excess rainfall occurs along the remaining period. Through that period the years flow deficits mutch rainfall deficit years and flow excess also mutch rainfall excess years as well. .. This situation clearly showed that in general the Faga River flow is closely linked to rainfall occurrence. However the mean annual runoff coefficient showed an upward trend over the study. Indeed, the runoff coefficient calculated as the ratio of runoff to rainfall for the study period (1982-2010) is about 31% against 18% for the period 1973 to 1982. This result is in accordance with previous studies showing the increase in runoff coefficient within the whole Sahelian region of Burkina-Faso following the observed increase runoff coefficient over the West African region since 1970 (Mahé et al., 2003; Descroix et al., 2009;Karambiri et al., 2011) for instance. The increase trend of runoff coefficient over the Faga basin could be explained by the fact that the net effect of dams on river runoff was not included in this analysis. The following chapter will the net effect of dams considered in the hydrological modelling process for the Faga river flow regime assessment.

4.7. Partial Conclusion

The seasonal and the interannual variation of hydroclimatic variables reveal increase in mean temperature through the study period in conformity with the USGS and USAID, (2012) that suggest that temperature in Burkina-Faso increased by 0.60C since 1975. Rainfall over the basin seems to be increasing during the study period by 6.6mm and 3.79 mm for the annual and the seasonal time scale. These results are in accordance with the observed rainfall recovery in the 1990s following the rapid decline in rainfall between 1950 and the mid-1980s.

Results from extremes analysis in the basin support the general trend showing an increase of the number of warm days and decrease in cold days. An upward trend is observed in the number of consecutive dry days while the number of consecutive wet days is decreasing. Hydroclimatic variables change over the basin reverberates on the River flow which follows the rainfall pattern.

Climate variability and its impact assessment result on river hydrology aline up with previous studies focus on climate variability assessment findings. Indeed, Li et al, (2009) found that “climate variability influenced surface hydrology more significantly in the Heihe catchment” located in China.

The river flow may also be influenced not only by change in rainfall pattern but also by the great number of reservoirs the basin holds.

The following chapter deals with the effect of small dams on the Faga River flow through the study period.

CHAPTER 5: HYDROLOGICAL IMPACT OF SMALL DAMS ON THE FAGA RIVER FLOW REGIME

5.1. Introduction

The Faga River Basin located in Burkina-Faso witnesses climate variability as the others countries in the Sub-Saharan Africa. This variability may cause changes in rivers' hydrology That could be intensified with the numerous water storage infrastructures built in the river catchments to secure water for riparian populations.

The aim of this chapter is to assess the hydrological alteration of the Faga River caused by small dams in a context where very limited hydrological data are available. Specifically it is to not only assess the seasonal and the interannual flow regime variability but also to analyse the frequency of flood phenomenon over the Faga River located in the North-eastern part of Burkina-Faso between 1982 and 2010. Indeed runoff constitutes one of the main parameters of a stream network which may alter stream physical environment and modify the surrounding uses according to Puckridge et al, (1998). This streamflow variability assessment is fundamental for it will help to understand and forecast the hydrological effect of existing small dams on the Faga River and the above change in temperature and rainfall effect as well. It will also be useful for decision makers in handling the consequences of the large number of small dams along the Faga River.

It also provides assessment of the socio-economic impact of these changes on the riparian population in downstream Faga Basin. Trend analysis was done by comparing the average flow of the baseline and the current periods using the following ration estimation:

$$\theta = \frac{CAMf - BAMf}{BAMf} \times 100 \qquad (5.1)$$

With: = Rate of change

BAMf = Baseline annual mean flow

CAMf = Current annual mean flow

5.2. The Faga river flow changes as dams' effect

5.2.1 Interannual flow changes

After calibration and validation WaSiM was used to simulate 1950-1958 flow which was considered as the baseline flow. The interannual variation of the Faga River flow was assessed by comparing the annual mean flow of the simulated baseline (1950-1958) to the annual mean flow of the current (observed) flow (1980-2010). The mean annual flow was estimated

at 67.34m^3/s for the baseline period while the current flow annual mean is estimated at 43.12m^3/s leading to a decrease at about 54.10%.
However the Mann Kendall and Sen's slope estimation show that the Faga River and followed by an upward trend over the baseline and the current period as presented in Table 5.1. Indeed flow increased by around 2.001m3/s from 1950 to 1958 while the 1980-2010 period only increased by 0.24m^3/s.

Table 5.1: Mann-Kendall and Sen's' statistics of interannual and seasonal river flow

Scenarios	**Z statistics**	**Sen's Slope (m^3/s)**
Baseline		
Interannual flow	1.15	2.001
Seasonal Flow	2.18	2.30
Current		
Interannual flow	4. 6	0.24
Seasonal Flow	5.4	2.72

Table 5.2: Mean seasonal and interannual flow changes

Flow time scale	**Baseline (AR: m^3/s)**	**Current (AR: m^3/s)**	**Flow change (%)**
Interannual	67.34	43.12	- 35.97
Seasonal	62.12	53.34	- 40.96

AR= Annual runoff

5.2.2. Seasonal flow changes

Figure 5.1 presents the monthly flow for the baseline and the current periods.
A decrease of about 14.18% was observed in the Faga River monthly flow from baseline to the present day. Indeed, the mean monthly flow was estimated at 18.39 and 21.43m^3/s respectively for the current flow and the baseline flow periods. The mean seasonal flows for the two periods were compared for trend assessment and the rate of change was estimate using the above equation 5.1. The same downward trend was also observed for the seasonal flow

over the two periods. Table 5.2 shows that the River flow decreased by 40.96% from the baseline to the current time scale.

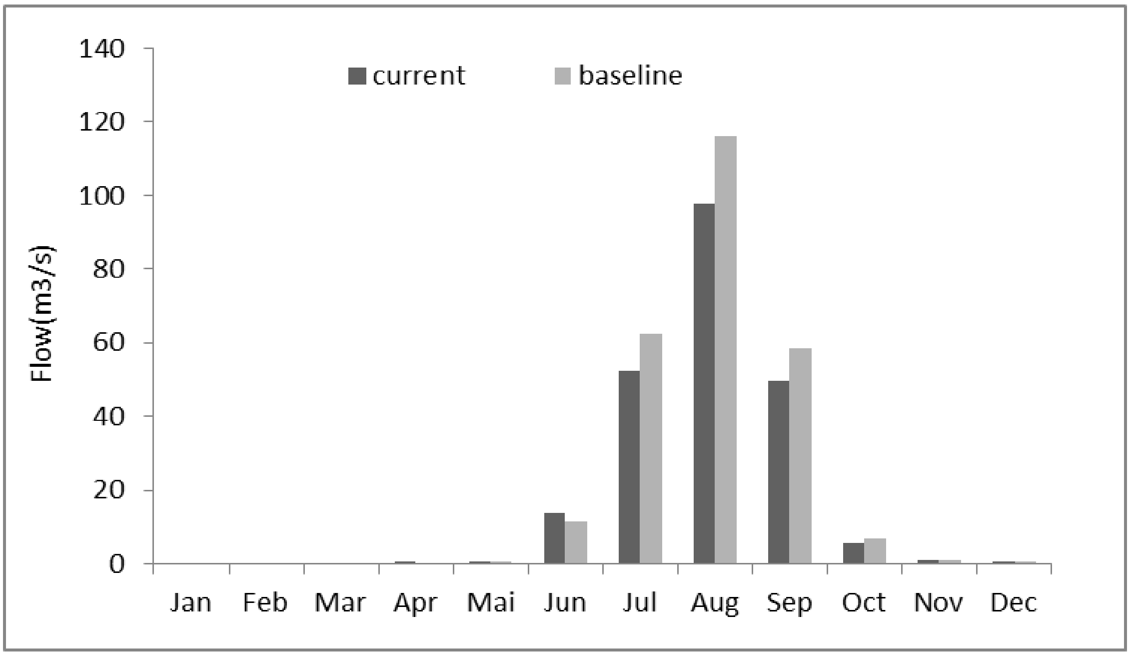


Figure 5.1: Current and baseline Monthly flow

JJAS flow increased by 2.30m^3/s over the baseline period. For the 1982-2010 period flow showed an increase of 2.72m^3/s..

Interannual as well as seasonal flow decreased through each period and between the two periods with different rates.

5.2.3. Impact of dams on water balance components

In our study, the dry season is not too adequate for the hydrological parameters analysis since the Faga River is an ephemeral one. Results showed for the baseline scenario that the observed increase in the Faga river flow in the rainy season result from the increase of flow regime components. Along the year, the baseflow constitutes the major contributor of the total runoff (Figure5.2). Indeed, the baseflow constitutes around 65.25% of the amount of the total runoff while the interflow constitutes 24.224% and the surface flow 10.53% of the amount of the total runoff (Figure5.3).

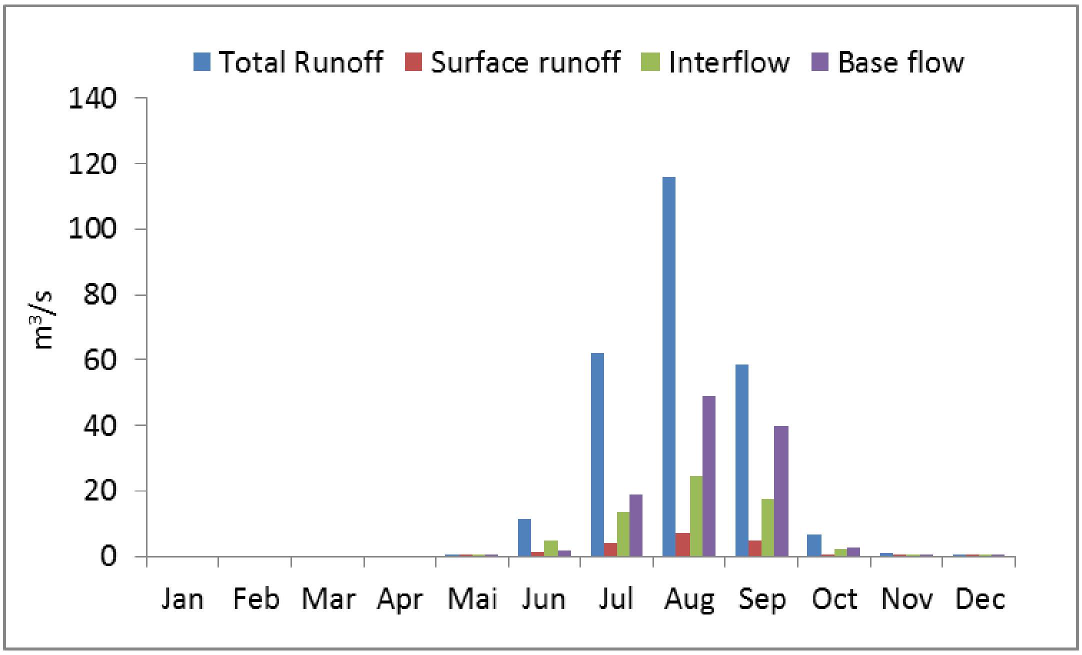


Figure 5.2 : Baseline monthly flow components

Tough the dams' scenario simulation showed a downward trend of the Faga river flow, the portions of the river flow components have approximatively the similar magnitude than the baseline with 62.15% of the base flow contribution to the total runoff and 26.06% for the interflow. The surface flow contributes at around 11.48% of the total runoff for the dams' scenario.

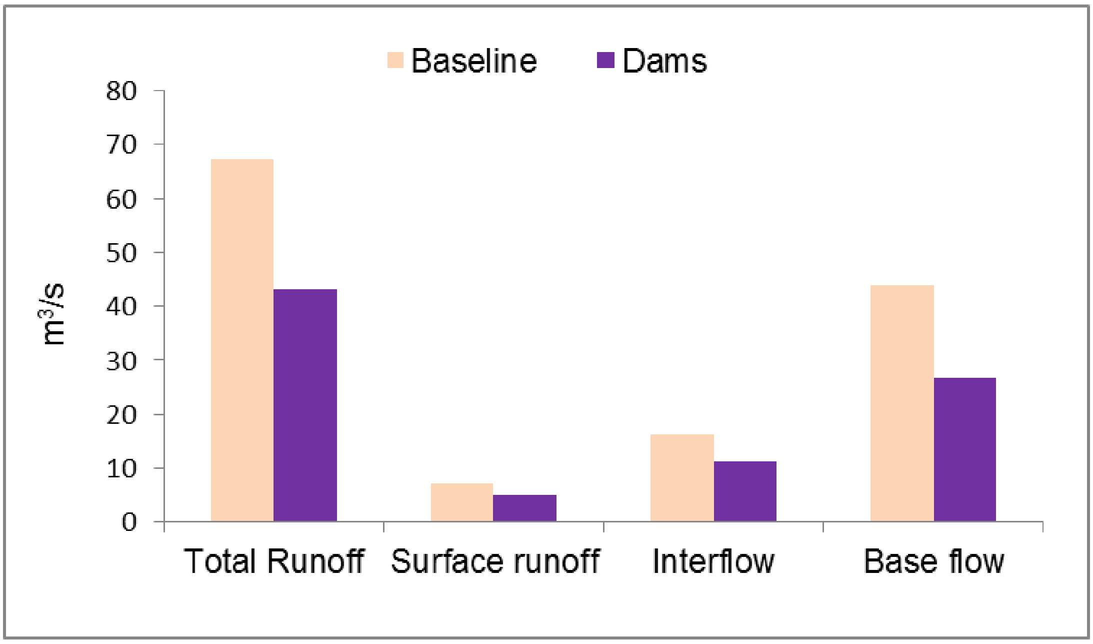


Figure 5.3 : River flow components variation for baseline and dams' scenario

From the baseline to the dams' scenario, the river flow decrease following the decrease of the flow components due to the existing dams along the river in the simular range (Figure

5.3). The total runoff decreased by 35.97% from the baseline to the dams' scenario while the surface flow decreased by 31.08%. The baseflow and the interflow fell by about 39% and 30.18% respectively.

A general upward trend in evaporation was observed over the basin. Inded, from the baseline to dams' impact estimation, the evapotranspiration increased by around 30.15% (from 2012.49mm to 2619.35mm). This increase could be explained by the increase of small dams number during the period 1982-2010. Since dams are opened storage infrastructures, this makes the stored water exposed to a high evaporation. Furthuremore, the observed increase in air temperature in the basin constitutes a potential source of increase of evaporation.

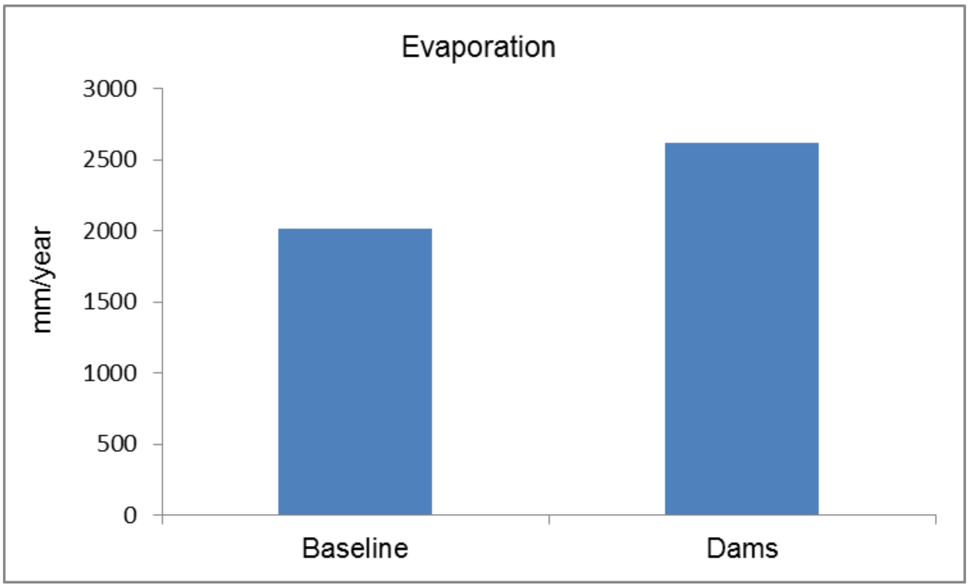


Figure 5.4 : Evaporation fluctuation for baseline and dams' scenario

5.2.4. Flood frequency analysis

The average annual peak flow in the Faga River was estimated at 114.82m^3/s and 135.46m^3/s through the current and the baseline period respectively. The flow change was estimated at 15.24%.

Only flow peak exceeding the average annual were considered for flood analysis in this study. The EasyFit software was used to perform the fitting test. Table5.3 presents the results of the fitting tests performed with four (4) distribution models namely: Generalized Extreme Value (GEV), Pearson5(3p (3p), Frechet (3p), and Log-Pearson 3. The distributions are ranked following their P-value. The closer the P-value is to one (1) the better the distribution fits the data set.

In this study the Generalized Extreme Value (GEV) was found to best fit the two data sets with a P-value of 0.97, followed by the Frechet (3p), the Log-Pearson 3 and Pearson5(3p).

The GEV was used to calculate the probability of exceedence and the return period of each flood event as presented in Table 4 below. It is expressed as follows:

$P = \frac{m-1}{n} a$ and $T = \frac{1}{P} = \frac{n}{m-1}$ (5.2)

Where:

is the rank of the maximum flow ranging from 1 (here the largest flow)

"n" is the number of years of record.

is the probability of exceedence and is the return period

Table 5.3: Fitted probability distributions statistics

Distributions	Statistics	P-values_basline	Rank	P-values_Current	Rank
Generalized. Extreme Value	k=0.38994 σ=38.964 μ=75.781	0.97516	1	0.95528	1
Frechet (3p)	α=2.0428 β=72.648	0.96859	3	0.8867	2
Log-Pearson 3	α=7.1213 β=0.22966 γ=2.9671	0.96941	2	0.6953	4
Pearson 5 (3p)	α=2.1346 β=125.59 γ=19.737	0.96103	4	0.86627	3

NB: *(α, k) = shape parameters*
(σ, β) = continuous scale parameters
(μ, γ) = continuous location parameters

Table 5.4: results of annual maximum fitting to gev probability distribution

Baseline Estimated_ peak flow (m3/s)	Probability (%)	Return period (Years)	Current Estimated_ peak flow (m3/s)	Change (%)
205.86	20	5	173.49	-15.72
259.76	10	10	207.84	-19.99
307.56	4	25	243.62	-20.79
330.25	2	50	265.09	- 19.73
355.37	1	100	279.40	- 21.38
484.06	0.05	200	300.87	- 37.84

Return periods ranging from 5 to 200 years with the estimated flood peak for each return period for current and baseline period are presented in Table 5.4.

From the baseline to the current period, the predicted 5-year peak flow decreased by 15.72% shifting from 205.86 to 173.49. The peak flow of the other projected return periods followed the same downward trend. The 10-year peak flow declined by 19.99% and the 25-year decreased by 20.79%. Likewise, the 50-year, the 100-year and the 200-year reduced by 19.73%, 21.38% and 37.84% respectively.

Peak flow was potentially reduced from the Baseline period to the present days as response to the small dams' effect on the Faga River flow.This is in accordance with many other studies assessing dams and reservoirs effects on Rivers. Indeed Maingi and Marsh, (2002) found that the main effect of the Masinga Dam building is the decrease of maximum flow peaks and increase of the low flow. Lauri et al, (2012) also found that "reservoirs cause a clear increase in monthly average dry season discharges and a decrease in wet season". The finding also lines up with previous studies assessing reservoirs and dams' effect on rivers' flow regime. Indeed, Batalla, (2004) showed that dam contributes in the reduction of the frequency and magnitude of extreme flow throughout the Ebro River in Spain. According to Zwarts et al. (2005) there is "a reduction in peak flood over the Niger River due to the Selingue dams' storage".

5.3. Environmental and socio-economic effect of the Faga River changes

The decrease in flood peaks could be interesting on the one hand for downstream riparian population for it will reduce flood related disasters. On the other hand this decrease may lead to diminution of floodplains which are exploited for agricultural purpose. Ecosystem and incomes of downstream communities relying on natural peak discharge may be affected by flow and flood reduction.

The survey data analysis showed that crop yield reduction constitutes the greater issue for downstream communities followed by the loss of livelihood and the dams' Banks reduction. Indeed, 95%, 90% and 85% of the interviewees related these issues to changes in the Faga River flow regime respectively. Sediment deposit increase was noted by 70% of the interviewees and the floodplains reduction by 65%. The reduction in the number of days flooded was observed by 30% of the interviewees. In addition 18% observed that water sources have been reduced. Furthermore, from the 500 interviewees about 175 people, claim to have sacred places where they periodically make sacrifices and rituals. However, around 28.6% (about 50 interviewees) of them reported to have lost these places following dams construction, development of banks and irrigated planes. These people represent about 10% of the total interviewees presented in Figure 5.2.

For the interviwees, decrease in water resource quantity is due to the decrease of rainfall and the decrease of dams capacities caused by increase of sediment deposit. Indeed silt is drained by the rain into the dams due to soil ersosion. Plastics and other hard waste are also drained into the dams. The reduction of the banks of dams as result of irrigation into the banks constitutes a source of sediment accumulation into dams and water pollution as well. Following the accumulation of silt, plastics and solid waste, dams tend to loss their capacity. This lead to a rapid filling up of dams and sometimes occurrence of flood.

Reduction of floodplains is found as direct effect of decrease rainfall but also plains degradation caused by the silting up. Farmers attempt to overcome this issue by building barriers all around the floodplains to decrease the amount of silt flowing into the plains as well as other solid waste. With regard to the increasing runoff observed over the basin, population already undertook vegetation regeneration process in order to slow down the surface runoff. Population is also organized in cooperatives or associations working on banks and other natural vegetation and biodiversity protection and conservation.

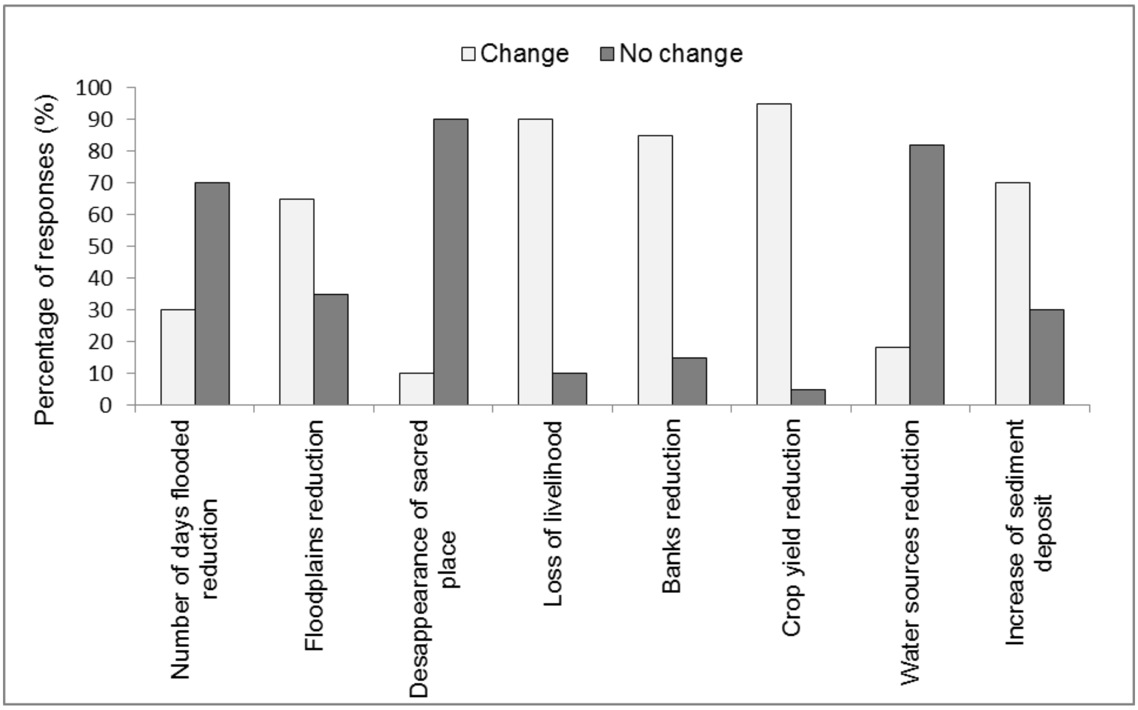


Figure 5.5: Downstream riparians report on Faga River flow regime changes challenges

Loss of livelihood could be directly attributed to the above issues that cause reduction of rainfed crop yiled. This probably explain the boom of irrigated crop beacause everyone finds it as a source of livelihood during the lean seasons. In regard to these results, it is clear that changes in the Faga River flow regime due to small dams have brought some serious challenges to downstream communities. Therefore, there is the need to find mitigation and/or adaptation measures to these adverse dam impacts.

5.4. Partial conclusion

Results of the present study showed a decrease of Faga river flow by around 54.10% from the baseline to the current period. This suggest that ensemble of small dams along the Faga River caused an important alteration of the flow regime. The interannual as well as the seasonal Faga River flow showed a substantial downward trend throughout the study period as consequences of the multiple dams. The study also demonstrates that flood peaks over the Faga River decreased substantially following dams'construction. The results of our study indicate the magnitude, rate of change and frequency of the Faga river flow fluctuations. As a result of the changes in the flow regime of the river, downstream communities are faced with livelihood support and other socio-cultural and economic challenges.

These results are in accordance with many other studies assessing dams and reservoirs effects on Rivers. Indeed Maingi and Marsh, (2002) found that the main effect of the Masinga Dam building is the decrease of maximum flow peaks and increase of the low flow. Lauri et al, (2012) also found that "reservoirs cause a clear increase in monthly average dry season discharges and a decrease in wet season." These changes are attributed to dams' primary function that is flow regulation.

In addition the downward trend of flood peaks through the study period found in this study lines up with previous studies assessing reservoirs and dams' effect on rivers' flow regime. Indeed, Batalla, (2004) showed that dam contributes in the reduction of the frequency and magnitude of extreme flow throughout the Ebro River in Spain. According to Zwarts et al., (2005) there is "a reduction in peak flood over the Niger River due to the Selingue dams' storage". Results also demonstrate that dams may inversely reduce river's peak flow and increase low flow. This could be made by water impounding and releasing in and from the dams. The hydrological regime found in this study could be attributed to population growth, deforestation, droughts, mining expansion etc.

Moreover, Changes in the Faga rivers flow as well as the observed environmental and socio-economical changes could have been more pronounced when combining climate and dams scenario's to land use/land cover change scenario that is not considered in the present study. The following chapter deals with the projected changes the Faga River flow may face due to the combined effects of small dams and climate change.

CHAPTER 6: PROJECTED CHANGES ON THE FAGA RIVER FLOW FROM EFFECTS OF SMALL DAMS AND/ORCHANGE IN CLIMATE

6.1. Introduction

Climate variability and water storage infrastructures as found above alter the Faga River flow regime. This alteration is source of environmental and socio-economic challenges for the riparian communities in downstream. With the increase of the population there will be the need to find additional sources of water to satisfy supply water need with probable more effect on the river hydrology. In this framework the rising concern is how the Faga River will behave in the short and long term. However sound and detailed research related to the combined impacts of small dams as well as climate change is missing in the Faga Basin. The aim of this chapter is to assess how the Faga River flow is projected to change under different climate scenarios on one hand and how this flow will respond under the cumulative impact of small dams and climate change scenario.

6.2. Change in rainfall

Climate models output demonstrate that rainfall will mainly increase over 2040-2070 in the Faga River Basin as shown in Figure 6.1. Indeed, simulations from Can-ESM2, EC-Earth and MPI-ESM-LR Regional climate models under RCP 4.5 and RCP 8.5 showed a contrasted result. Rainfall is projected to decrease by about 9% in the basin according to the simulation with the MPI-ESM-LR using the RCP 4.5 emission scenario. However, using the RCP 8.5 the model showed increased rainfall.

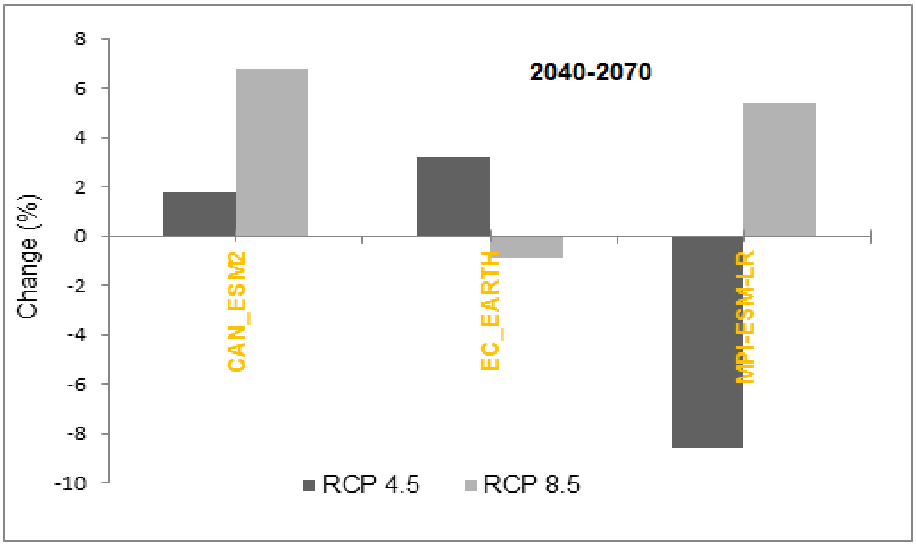


Figure 6.1: Projected change of rainfall in the Faga Basin

Table 6.1. Projected rainfall variation over the Faga River

Parameter	Baseline	MPI		EC-Earth		Can-ESM2	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Rainfall (mm/y)	684.5	decrease 622.9	increase 723.24	increase 690.5	decrease 662.66	increase 696.75	increase 730.97

The EC-Earth model run projected a downward trend of 0.89% of rainfall under the RCP 8.5 emission scenario while an upward trend of 3.19% was observed under the RCP 4.5 scenario. However Can-ESM2 simulations project that rainfall will increase in the basin by around 1.79% and 6.75% under RCP 4.5 and RCP 8.5 scenarios respectively as presented in Table 6.1.

6.3. Change in temperature

Results presented in Figure 6.2 show that temperature over 2040-2070 in the Faga basin is expected to increase by almost 4.57% and 2.478% with RCP 4.5 and RCP 8.5 respectively for EC_EARTH model simulations.

Can-ESM2 model and MPI-ESM-LR showed the same trend of temperature. An increase of about 0.48% and 3.28% are expected respectively for CAN_ESM2 and MPI-ESM-LR models run under RCP 8.5 scenario. Simulations under RCP4.5 scenario showed a decrease temperature of around 0.34% and 2.79% respectively for CAN_ESM2 and MPI-ESM-LR model.

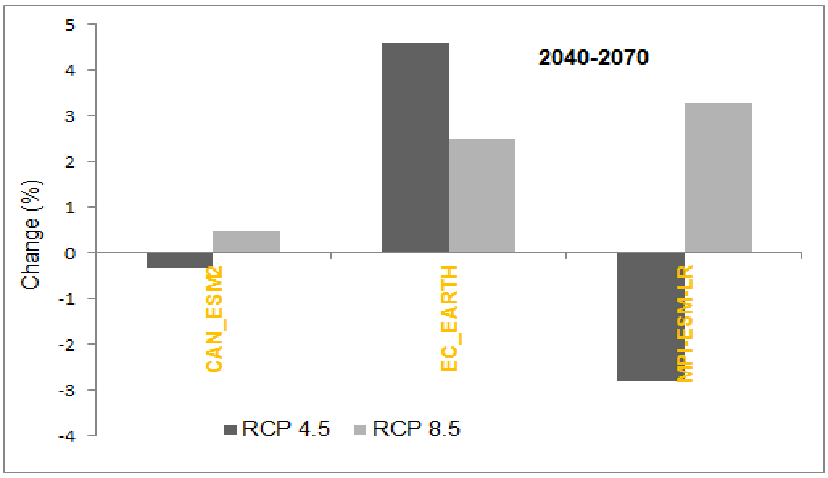


Figure 6.2: Projected change of rainfall in the Faga Basin

6.4. Effect of climate change on the Faga River flow

6.4.1. Interannual flow change

Results in Table 6.3 show that only one model simulation project an increase of the interannual flow of the Faga River for 2040-2070 when the others project a decrease. Indeed the EC-EARTH model simulations under RCP 4.5 and RCP 8.5 showed that the interannual flow will increase by about 4.9 and 8.1 respectively.

Can_ESM2 model simulation under RCP 4.5 showed a decrease of about 10.6% and 16.3% for RCP 8.5. Flow is expected to decrease by 13.4% and 15.8% for MPI_ESM run under RCP 4.5 and RCP 8.5 scenario.

Table 6.2: Annual and seasonal flow change under RCP4.5 and RCP8.5 scenarios compared to baseline flow

	Climate Scenarios						
	Base-line	**MPI**		**EC-Earth**		**Can-ESM2**	
Parameters		*RCP4.5*	*RCP8.5*	*RCP4.5*	*RCP8.5*	*RCP4.5*	*RCP8.5*
Annual flow	67.34	58.32	56.70	70.64	72.79	60.50	56.36
Seasonal flow	62.12	57.51	56.09	65.37	65.23	50.01	50.87

Table 6.3: Changes in the Faga River runoff under climate change for 2040-2070

Emission scenarios	RCMs	Climate change impact on runoff (%) (2040-2070)	
		Annual change	Seasonal change
RCP4.5	Can_ESM2	-10.6	-13.04
	EC_EARTH	+4.9	+5.23
	MPI_ESM	-13.4	-7.42
RCP8.5	Can_ESM2	-16.3	-18.11
	EC_EARTH	+8.1	+5.1
	MPI_ESM	-15.8	- 9.07

The observed increased flow with EC-Earth model run using RCP4.5 climate scenario could be attributed to the increase rainfall predicted by the model (Table 6.2). Since the Faga river flow regime follow the rainfall regime river flow automatically rises with important rainfall amount indicating that rainfall greatly influences river flow.This finding lines up with rainfall trend is in according with the study of MILLER and RUSSELL.,(1992) who predicted that runoff will increase for some rivers over the world following doubled CO_2 climate scenario. Generally, this increase follows the precipitation increase observed in the basin.

Meanwhile for model run using RCP8.5 climate scenario, the river flow declines instead of expected decrease as response to rainfall increase (Table 6.1). The present situation could be due to land use/land cover change that would be observed in the basin for the projected period. This result lines up with the study of Mahe et al, (2005) which found increase Nakanbe river flow in contrast of decreasing rainfall. Mahe, (2006) showed that runoff coefficient of the West African Sahelian streams present an upward trend with decreasing rainfall amount since 1970s and this contrasted change is attributed to the observed land degradation in the region.

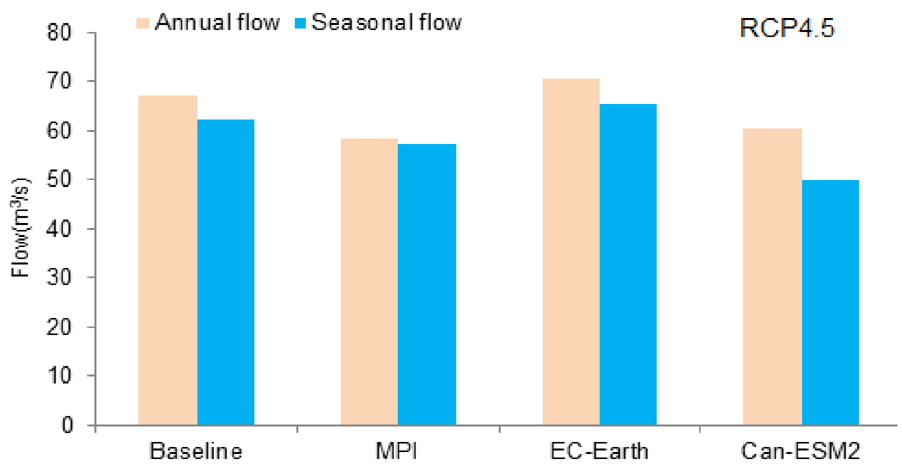


Figure 6.3: Annual and seasonal flow variation under RCP4.5 scenario

For hydrological simulation using MPI model run under RCP4.5 climate scenario, the river flow lines up with the rainfall as they all showed a decrease trend. However, the RCP8.5 climate scenario simulation showed a decrease flow while rainfall is increasing. Simulation with Can-ESM2 out using RCP 4.5 and RCP8.5 also showed a decrease rainfall with an increase rainfall. This downward trend of flow with increase rainfall could be caused by the increase temperature leading to increase evaporation losses.

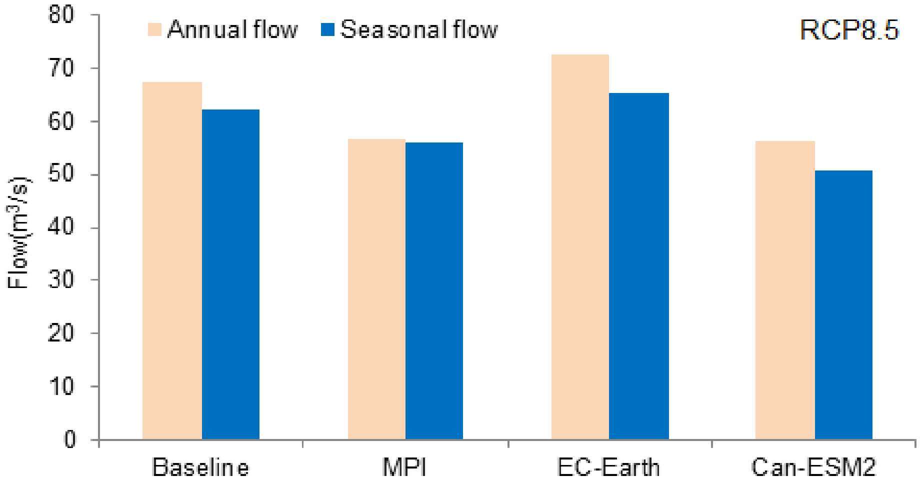


Figure 6.4: Annual and seasonal flow variation under RCP8.5 scenario

6.4.2. Seasonal flow change

Climate change impact assessment on the Faga River Flow showed that the seasonal flow will follow a downward trend over 2040-2070 for two models and an upward trend for one model. Results are summarized in table 6.1 and presented in figure 6.3 and figure 6.4.

Indeed, models run under RCP 4.5 estimated the Faga seasonal flow decrease at 13.04% for the Can_ESM2 and 7.42% for MPI_ESM while EC_EARTH showed increase of 5.23%.

Results from RCP8.5 scenarios follow the same trend as RCP 4.5 scenario.

Flow will decrease by 18.11% and 9.07% for Can_ESM2 and MPI_ESM but will decrease with EC_EARTH model by 5.1% under RCPC 8.5 scenario.

The seasonal flow for simulations using out of EC-Earth run with both RCP4.5 and RCP8.5 climate scenarios present an increase trend as the annual flow probably leading the increase rainfall as well.

When simulating the model with MPI and Can_ESM2 out run under RCP4.5 and RCP8.5 showed a decrease seasonal flow simularly with the annual flow simulation trend.

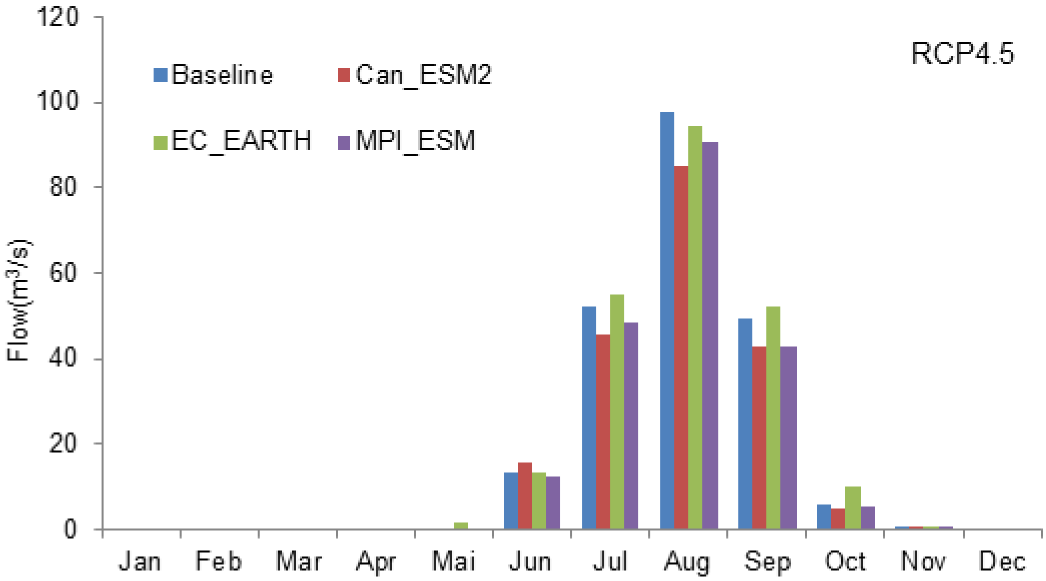


Figure 6.5: Climate change flow run under RCP 4.5 scenario (2040-2070) vs baseline (1982-2010) flow

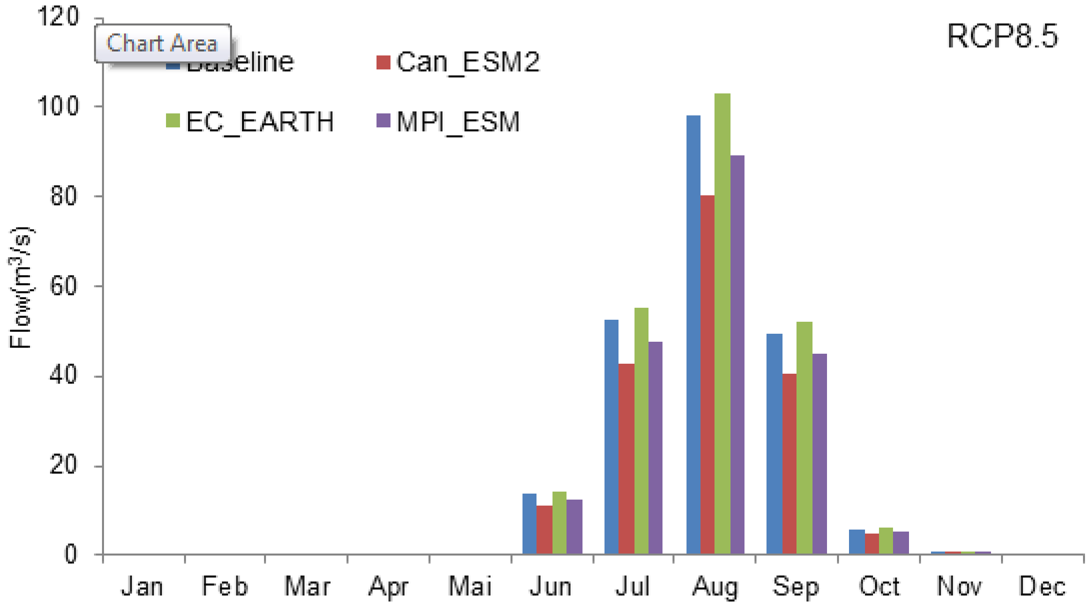


Figure 6.6: Climate change flow run under RCP 8.5 scenario (2040-2070) vs baseline (1982-2010)

6.5. Effect of dams on future Faga River flow

6.5.1. Inter-annual flow change

For the projected impact of the increase number of small dams over the stuay basin we arbitrary choosed to increase virtually the number of dams by 15% and by 25% to assess the propobable effect of growing water storage infrastructures on the hydrology of the river using the baseline (1950-1958) climate data. The simulation results showed that the inter-annual river flow will be reduced by 37.40% to 40.03% using 15% and 25% increasing dams scenarios respectively (Table6.4). In the mean-time the surface flow showed a slight increase in proportion as reservoirs number increase.

Table 6.4: Inter-annual variation of flow due to dams

Interannual flow	Baseline	15% of increase	25% of increase	Rate of changes	
	67.34	42.15	40.38	- 37.40	- 40.03

6.5.2. Seasonal flow change

The simulation results presented in Table 6.5 showed that the seasonal river flow will dercease by 39.54% when the number of dams was increased by 15%. When rising the number of dams at 25%, river seasonal flow is projected to decrease by 42.31%.

Table 6.5 Projected seasonal variation of flow for dams' impact

Seasonal flow m3/s	Baseline	15% of increase	25% of increase	Rate of changes	
	62.12	37.55	21.66	- 39.54	- 42.31

6.6. Cumulative effect of small dams and climate change on the Faga River flow

6.6.1. Interannual flow change

Projected changes of the Faga River flow for 2040-2070 period are presented in Table 6.7. Under RCP 4.5 scenario, the interannual flow of the Faga River is expected to decrease over the study period. This decrease is around 15% for Can_ESM2, 3.75% for EC_EARTH and 32.8% MPI_ESM.

Result of RCP8.5 simulations demonstrate that a decrease of about 22.1% will be observed in the Faga River flow for Can_ESM2.

EC_EARTH and MPI_ESM respectively showed a rate of 0.9% and 45.82% of decrease.

Table 6.6: Annual and seasonal flow change under RCP4.5/RCP8.5 and dams scenarios compared to baseline flow

	Climate Scenarios						
	Baseline	MPI		EC-Earth		Can-ESM2	
Parameters		*RCP4.5*	*RCP8.5*	*RCP4.5*	*RCP8.5*	*RCP4.5*	*RCP8.5*
Annual flow	67.34	45.25	36.48	64.85	66.73	57.24	52.26
Seasonal flow	62.12	54.98	50.71	58.32	58.96	41.01	49.70

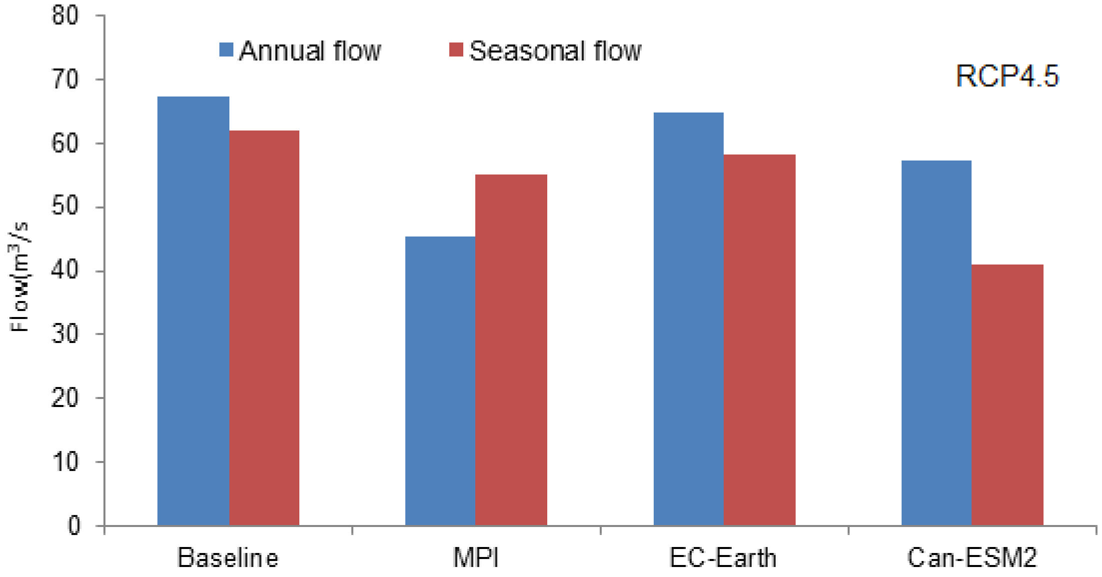


Figure 6.7: Annual and seasonal flow variation under RCP4.5 and dams' scenario

For more water storage issue due to the growing population a number of small dams may be projected to be built in the basin. For the purpose of probable effect of an inceasing number of water storage infrastructures Simulations of river flow with an increasing number of small dams showed that the inter-annual river flow presents a downward trend in proportion as the number of dams increase. Indeed, a increase of 25% of dams in relation to the actual number will reduce the flow at about 15% for Can_ESM2, 3.75% for EC_EARTH and 32.8% MPI_ESM under RCP 4.5 scenario.

The simulations using the RCP8.5 climate scenario showed that inter-annual flow will decrease by 22.1% when using Can_ESM2 climate model output. EC_EARTH climate model gave a slight decrease by 0.9% and MPI_ESM climate model showed that annual flow will drop down by about 45.82% compared to the basline inter-annual flow.

Table 6.7: Changes in of the Faga River under climate change and small (2040-2070)

Emission scenarios	RCMs	Climate change + Dams' impact (%)	
		Annual change	Seasonal change
RCP4.5	Can_ESM2	-15	-25.4
	EC_EARTH	-3.7	- 6.12
	MPI_ESM	- 32.8	- 11.5
RCP8.5	Can_ESM2	-22.1	- 20
	EC_EARTH	-0.9	-5.08
	MPI_ESM	-45.82	-18.37

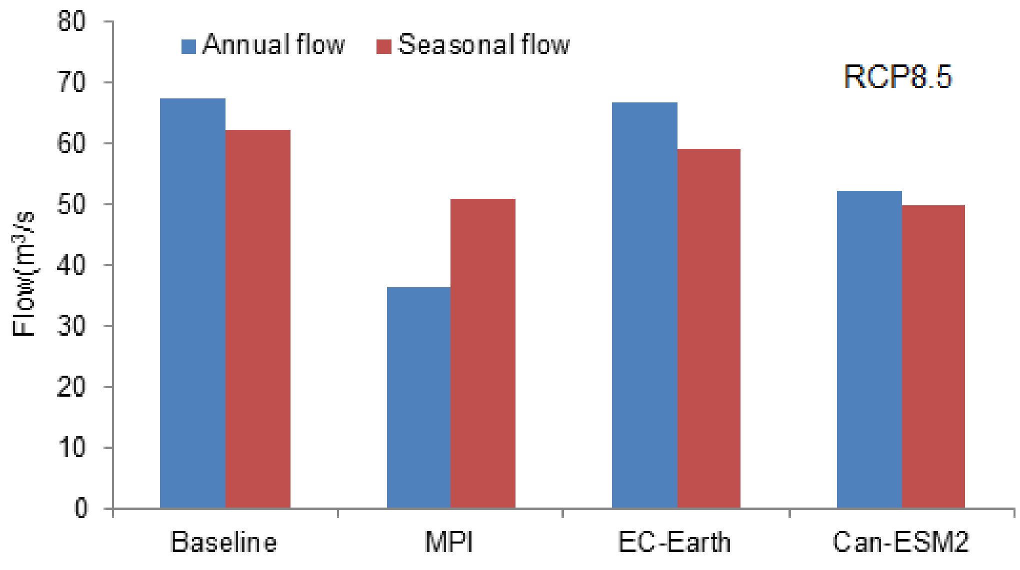


Figure 6.8: Annual and seasonal flow variation under RCP8.5 and dams scenario

6.6.2. Seasonal flow change

The cumulative effect of climate and small dams on the Faga River seasonal flow indicates that tis flow will follow a downward trend over 2040-2070. Results of simulations are presented in Figure 6.9 and Figure 6.10.

Models run under RCP 4.5 and small dams' scenario indicated that seasonal flow will decrease by approximately 25.4%, for Can_ESM2; 6.12% for EC_EARTH and 11.5% for MPI_ESM model. In the same order, simulations under RCP8.5 showed a decrease of 20%; 8.5% and 18.37.

The average monthly flow using RCP4.5 climate scenario was estimated at about 41.01m^3/s and 58.32m^3/s for Can-ESM2 and EC-Earth models respectively and 54.98m^3/s for MPI model. The average seasonal flow also showed a decrease trend for all climate model and RCP8.5 scenarios (Table6.6; Figure 6.7 and Figure 6.8) comparing to the baseline. This decrease could be explained as river flow response to the hydrological induced impact of reservoirs as the primary function of reservoirs in to reduced peak flow and consequently drop down flood frequencies. This result sustains the study finding in section above 5.2.2.

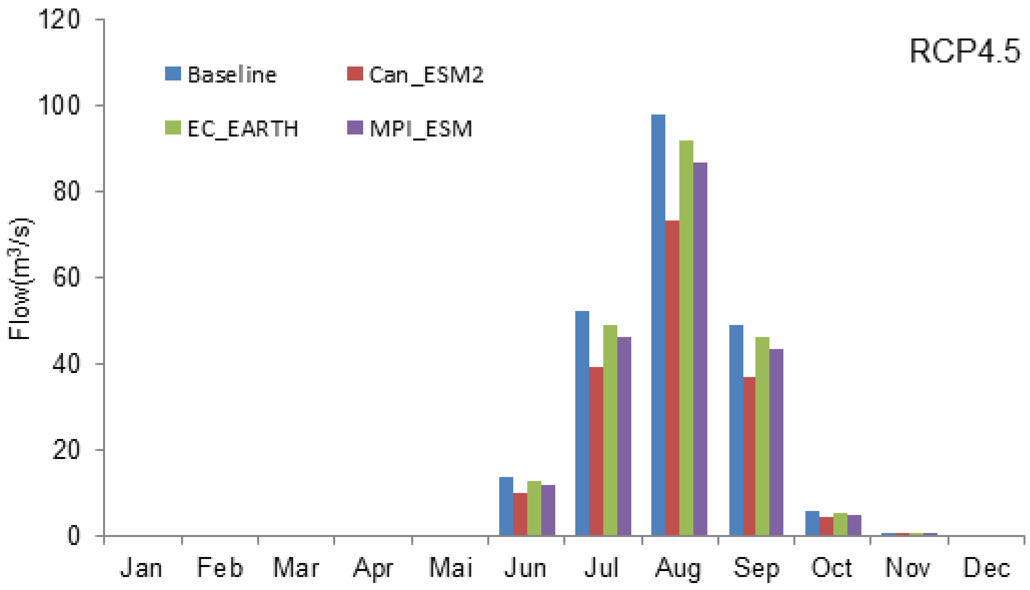


Figure 6.9: Dams and climate change flow run under RCP4.5 scenario (2040-2070) vs baseline (1982-2010) flow

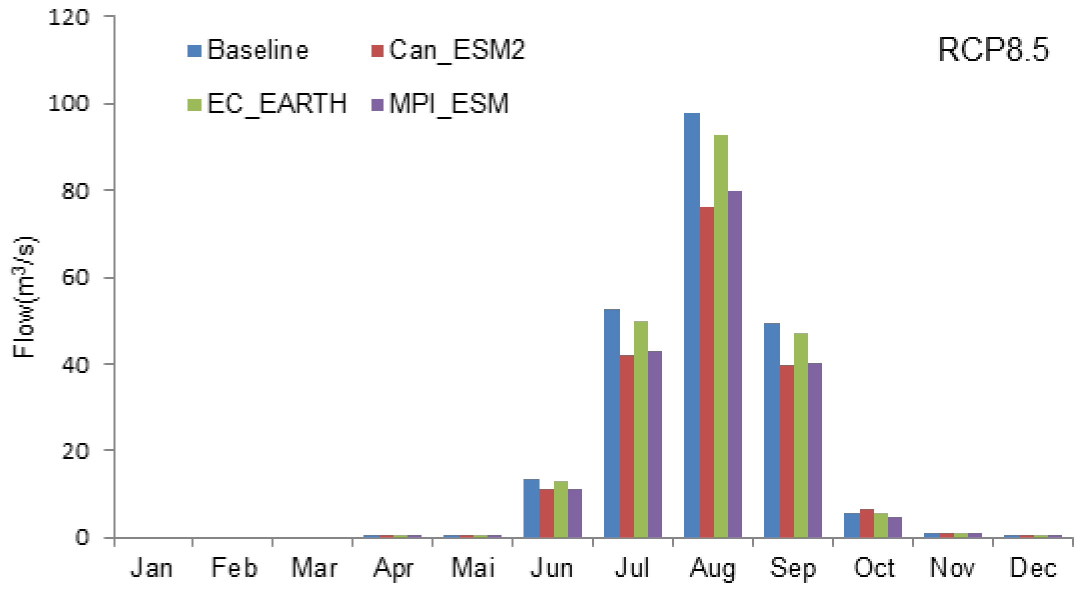


Figure 6.10: Dams and climate change flow run under RCP8.5 scenario (2040-2070) vs baseline (1982-2010) flow

The WaSiM model simulations results showed a varying flow fluctuations for inter-annual and the seasonal Faga River flow as well, following the climate model output used for the simulation. Indeed, climate change will lead to a decrease of inter-annual Faga River flow as well as the seasonal flow for two climate models (MPI and Can-ESM2) run with RCP4.5 and RCP8.5 for the period 2040-2070. In the meanwhile an increase trend will observed for EC_Earth climate model using both RCP4.5 and RCP8.5 climate scenarios.

The Faga River is an ephemeral river and dries up from end of October to beginning of the rainy season. Dams filling up in the seasonal time period could be the driver of this change in seasonal flow attesting therefore the function of peak flow reduction of dams.

When comparing separately impact of climate and and dams' impact on the Faga River hydrology, one can see that changes due to single climate change is less intensive than dams' induce changes (Table6.6 and Table6.7 for instance). These result demonstrate that change in the Faga River hydrology is mainly driven by numerious open water storage infrastructures.

6.6. Future changes of the water balance components

6.7.1. Changes due to projected climate

For the water balances componenets simulations using RCP4.5 emission scenario, the rainfall showed a decrease trend for MPI and EC-Earth models' output wheras an increase trend is observed for the Can-ESM2 model. In WaSiM runs of RCP8.5 emission scenario, rainfall only decrease for EC-Earth model while an increase trend is showed for both MPI and Can-ESM2 (Table 6.8). Simulation results showed a general increase of evaporation for the all climate models and for all emission scenarios used in the study. Indeed, the evaporation increase range from 5.60% to 12.69% using the RCP4.5 scenario and from 9.07% to 16.75% for the RCP8.5 (table6.9). A downward trend was observed for all the models as well as all the scenarios for Base flow, interflowand surface flow. For instance the ranges of base flow and surface flow change are from -15.20% to -7.16% for RCP4.5 and from -12.55% to -3.94% for RCP8.5 respectivelly (table 6.9).

Evaporation is found to be increasing in all simulations with varying magnitude due to the general increase trend of temperature in the basin. This sustains the fact that the decrease river flow could lead to increase evaporation mentioned in a above sections.

Table 6.8: Variation in water balance components due to climate change

Water balance components for climate impact scenarios	Baseline	MPI		EC-Earth		Can-ESM2	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Rainfall (mm/y)	684.5	622.90	723.24	690.5	662.66	696.75	730.97
Base flow(m3/s)	43.94	37.26	36.12	40.79	39.42	38.35	35.90
Interflow	16.31	14.12	13.69	15.46	14.94	14.53	13.61
Surface flow	7.09	6.43	6.24	7.04	6.81	6.62	6.20
Total runoff	67.34	58.49	56.70	64.04	61.89	60.20	56.36
Evaporation	2012.49	2267.93	2335.72	2125.16	2195.21	2245.75	2349.58

Table 6.9: Projected climate induced changes rates of water balance components compared to the baseline (%)

Simulations	Rainfall	Base flow	Interflow	Surface flow	Total run-off	Evaporation
RCP4.5						
MPI	-9.00	-15.20	-13.42	-9.31	-13.14	12.69
EC-Earth	0.89	-7.16	5.21	-0.70	-4.90	5.60
Can-ESM2	1.79	-12.72	-10.91	-6.62	-10.60	11.59
RCP8.5						
MPI	5.66	-17.79	-16.06	-11.98	-15.80	16.06
EC-Earth	-3.19	-10.28	8.39	-3.94	-8.09	9.07
Can-ESM2	6.78	-18.30	-16.56	-12.55	-16.29	16.75

6.7.2. Changes due to projected small dams

Simulation results of section above was used to analyse change in water balance component. Results brougth out a sligt increase of interflow by 9.14% and 12.62% respectively for 15% and 25% of increase in dams' number(Table 6.10). The surface flow is expected to rise up by 13.57% and around 20.78% for 15 to 25% increase reservoirs scenarios. The evaporation showed a simular increasing trend from 21.05% to 24.48% of the intial amount respectively with increase of 15% and 25% of small dams' number.

When compared to the baseline increase of 15-25% of dams' number caused respectively an decreased in interflow amount by 9.14 to 12.62% and the surface flow amount increased by 13.57 to 20.78%. The baseflow amount also observed a decrease of 21.95 -25.31% following the raising of dams (Table 6.10).

Table 6.10: Variation of water balance components under increasing small dams

Flow components for dams' scenarios	Baseline	15% of increase	25% of increase	Rate of changes	
Rainfall (mm/y)	684.5	-	-	15% of increase	25% of increase
Base flow(m3/s)	43.94	34.29	32.82	-21.95	-25.31
Interflow	16.31	14.82	14.25	-9.14	-12.62
Surface flow	7.09	8.05	8.56	13.57	20.78
Total runoff	67.34	42.15	40.38	-37.40 %	-40.03
Evaporation	2012.49	2436.18	2505.15	21.05	24.48

6.7.3. Changes due to combined climate and dams effect

Climate models outputs were computed with small dams in the WaSiM model to examine the combined effect of climate and dams on the Faga River basin hydrology. The hydrological model runs are presented in Table 6.11.

For the WaSiM model simulations using reservoirs sub-model and RCP4.5 climate scenario, baseflow presented a decrease trend for all the climate models ranging from. 5.99 to 34.39 % (Table 6.12). The total flow also will decrease by 3.70 - 32.80% while the evaporation will rise up from 13.63 to 38.80%. Interflow and surface flow will decreas with MPI and Can_ESM2 models while they showed an increase with EC-Earth model. The range of change for interflow runs is from -30.23 to 0.67% and the surface flow range between -29.76

to 0.56%. Simulations RCP8.5 climate sceanrio showed the similar trend and changes magnitudes with RCP4.5 scenaio runs for all the water balance components (Table 6.12).

Table 6.11 Changes in water balance components due to climate change and dams

Simulations	Rainfall (mm/y)	Base flow(m3/s)	Interflow	Surface flow	Total run-off	Evaporation
						RCP4.5
MPI	9.00	-34.39	-30.23	-29.76	-32.80	38.80
EC-Earth	0.89	-5.99	0.67	0.56	-3.70	13.63.
Can-ESM2	1.79	-17.02	-11.77	-11.14	-15.00	14.50
						RCP8.5
MPI	-5.66	-47.11	-43.78	-43.44	-45.83	39.21
EC-Earth	3.19	-3.25	2.88	3.53	-0.91	10.84
Can-ESM2	-6.78	-23.94	-19.13	-18.62	-22.10	17.13

Change in water balance components for climate change sceanrios and dams scenario generally follow the total runoff. However, increasing dams' number lead to increase of surface flow and this may imoact on peak flow. The growing number of dams may increase irrigation in the basin and thereby causes the increase of surface runoff due to water withdrawal for crop.

The evaporation is also increasing following the increase of dams because open water bodies present high evaporaion rate particularly for the areas with high ambient temperature as the Faga River Basin.

Table 6.12: Variations in future water balance components due to combined climate and dams

Flow components for combined climate & dams impact scenarios	Baseline	MPI		EC-Earth		Can-ESM2	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Rainfall	684.5	622.90	723.24	690.5	706.33	696.75	730.97
Base flow	43.94	28.83	23.24	41.31	42.51	36.46	33.42
Interflow	16.31	11.38	9.17	16.42	16.78	14.39	13.19
Surface flow	7.09	4.98	4.01	7.13	7.34	6.30	5.77
Total runoff	67.34	45.25	36.48	64.85	66.73	57.24	52.46
Evaporation	2012.49	2793.34	2934.61	2286.8	2230.60	2314.36	2457.25

6.8. Partial conclusion

This chapter highlighted the relative effects of climate change and water storage infrastructures on the Faga River Flow regime. It also includes effect of the cumulative impact that water storage infrastructures may have on the river. Future hydrological changes were also assessed.

The WaSiM model simulations results demonstrated that the Faga River flow varies according to the climate model and the RCP climate scenarios used for the simulations. Indeed, the river interannual flow is expected to increase by 4.9% and 8.1% for instance with EC-Earth climte model run with RCP4.5 and RCP8.5 climate scenario respectively. In the mean time simulation using MPI climate model run with both RCP4.5 and RCP8.5 predited a decrease flow for interannual and seasonal time period over 2040-2070.

The findings also suggest that the interannual and the seasonal flow of the Faga River will be highly affected by the increase of the number of small dams as presented in Table 6.4 and Table 6.5. Results also showed that cumulated effect of both climate change and small dams will intensify the Faga river flow expected decrease as well as the increase according the climate model and scenario used.

Results also showed that water balance components from the simulations generally follow the total runoff fluctuation for both climate change sceanrios and dams scenario. However, surface flow is expected to increase in the scenarios with increase number of dams probably due to the growing water withdrawal lead to stored water availability.

Moreover, our result is in accordance with Matthew et al, (2000) who suggested that “the most common attribute of flow regulation is a decrease in the magnitude of flood peaks and an increase in low flows”.

Projection results showed various changes of the Faga river flow for the individual as well as the combined climate and small dams’ effect. These results could be attributed to uncertainty in climate and hydrological models and input data as well.

CHAPTER 7: GENERAL CONCLUSION AND PERSPECTIVES

7.1. Conclusions

Our study underlined the impact of climate variability and climate change as well as small dams on the Faga River located in the North_eastern part of Burkina-Faso. Flood frequency as consequence of flow variability was also assessed. Consequences relative to change in river flow on downstream communities was assessed as well. Moreover it forecasted future changes that the hydrology of the river could have under changing climate conditions using three climate models run under RCP4.5 and RCP8.5 scenarios. Results of the study showed that mean annual temperature increased through 1980-2010 in accordance with the USGS and USAID, (2012). Analysis of extremes trend indicated that the basin got warmer from 1980 to 2010 with increase in consecutive dry days while the total rainfall amount increased. The increase rainfall in the basin aline with studies performed over West Africa, which suggest a rainfall recovery over the region since the 1990s. The results also indicated that the Faga River Flow regime which lines up with rainfall variability is substantially altered by the large amount of small dams along the river, with decrease of river flow amount and the frequency of flood occurrence. Change in the river regime is source of great socio-economic challenges face by downstream riparian communities.

Temperature in the Faga River is projected to decrease with MPI and Can_ESM2 run with RCP4.5 climate scenarios but will increase with RCP8.5 scenario for both models. However, EC-Earth model projected a decrease trend for both RCP4.5 and RCP8.5 scenarios (Figure 6.2)

Model run using RCP4.5 and RCP8.5 climate scenarios for climate impact assessment on the Faga River hydrology showed an increase trend of the inter-annual and seasonal river flow for EC_Earth climate model while MPI and Can_ESM2 climate models gave a decrease flow by around 4.9% for the period 2040-2070 comparing to the baseline (1950-1958) for both inter-annual and seasonal flow (Table6.2).

Rainfall might increase by about 0.89% with simulation EC_Earth run under RCP4.5 but decrease with the RCP8.5. Can_ESM2 climate model run with RCP4.5 and RCP8.5 climate scenario showed an increase rainfall for both climate scenarios by around 1.79% and 6.75% respectively. A decrease rainfall was observed using MPI climate model run with RCP 4.5 scenario while showing an increase trend for RCP8.5.

Single dams' impact increase the river flow by 37.40 % and 40.03% when the number of dams are increased by 15% and 25% respectively.

Combined dams and climate change decrease the river flow at about 15% for Can_ESM2, 3.75% for EC_EARTH and 32.8% MPI_ESM under RCP 4.5 scenario

The observed increase temperature for some model runs lead to increase water evaporation in the basin and therefore inducing soil water retention causing adecrease soil humidity. Yet reduction in soil humidity will have repercution on rainfed agriculture and irrigated plain crop yield as well.

This study showed varying rainfall-runoff relationship depending on the climate model and/ or the climate scenario used and with or without the incorpoaration of reservoirs in simulation process as well. This finding is in accordance with studies undertaken in West Africa. Conway et al.(2009), found a non linear dynamics in river flow response to rainfall occurrence.

The diversity in rainfall-runoff relationship may be the existence of uncertainities in climate and hydrological models. It may also be induced by input climate data and/or hydrological data as well. These dynamics may be attributed to Land use/ land cover change over the study period. Indeed, Mahe, (2006) indicate increase runoff lead to soil water content diminution when natural land cover is degradating.

The fluctuation of water balance components from simulations globaly alines with river flow fluctuation except for the surface runoff that will increased while increase number of dams will lead to a decrease flow. This may be incorporated to possible water withdrawal for irrigation purpose which could grow with the availability of water through dams' number increase.

The comparison of single climate change impact and combined climate and dams impact on the Faga River flow responses to small dams may be worsen by future climate change.

The flow regime is likely to worsen as result of the cumulative climate change and water storage infrastructures along the Faga River.

The study findings also demonstrate a varying rainfall-runoff relationship over the Faga Basin which was attributed to high evaporation and/ or change in land structure. However this result could be incorporated to uncertainities related to input climate and hydrological data and models as well.

Therefore, the findings of the present study serve as output that may be the starting point for future hydrological studies in the Faga Basin and would be useful for the design and implementation of mitigation and/or adaption measures for both socio-economic activities of the riparian communities and the river flow-dependent ecosystems at the basin scale.

Furthermore, this study could be the basis of an action plan for strategic environmental evaluation with regard to dams.

In this study, we assessed the main Faga river flow and flow components under dams and climate change scenario neglecting land use and land cover changes and this may constitute a limit for the study. However, these results could have been affected by combining dams and climate effects to land use/land cover effects.

7.2. Perspectives

Even though the study was able to achieve the stated objectives, Our perspectives for further studies are:

- ✓ To conduct a comparative study of the combined dams and climate and Land use/ Land cover effect as well with findings of the present study;
- ✓ To investigate how these numerous reservoirs may impact ground water recharge in the study basin and,
- ✓ Following the projected increase of population, we would like to undertake water resources quantification and future availability in Burkina-Faso.

7.3. Suggestions

The numerous small dams built over the Faga River Basin are beneficial for the riparian communites as they provide supply water to population, regulate flood frequences and constitute a source of livelihood. Indeed, riparian communities claim that dams contributed mostly to the improvement of their living conditions through irrigation development. However they are facing to climate related and anthropogenic issues as well. Therefore we enumerated some perpective measures that could more or less release local communities.

For adaptation measure to decrease evaporation small holes of about 20 cm of deph may be dug by each seedbed in order to retain water for soil humidity conservation. This could help farmers reducing crop yield losses.

Bulding underground dams could be an alternative mitigation measure to decrease evaporation as impact of change in climate.

As the decrease in runoff adaptation in the rainfed agricultural area, farmers could sow perpendicularly to the flowing water in order to receive more water and increase the soil water content.

An other issue faced by riparian people is the reservoirs silting up that decrease the quatity of the retained water. To overcome this issue, riparian commuties could be sensitized and motivated to mulch the surroundings of dams with straw plants called "*Pita*" in local langage as they use to for their irrigated areas. This could not only attenuate dams silting but also stop or reduce the importation of solid waste into reservoirs.

We also recommend the institution of digger fishes breeding in all or most of the reservoirs in the basin because such a fish use to dig holes in dams and reservoirs' bottoms. This could help in dams' curettage and limit sediment deposit in the water storage infrastructures.

Flood early warning system should be implemented in the Faga River Basin to prevent or mitigate floods related consequencies.

With regard to the development of market gardening along the Faga River, water quality assessment should be done in the basin as well as the availability of water for present and future uses by the government. In addition, farmers are producing important quantities of various vegetables through irrigation but because of the lack of adequate road systems, they meet with important losses particularly in the rainy season. We then recommend the opening up of the basin by roads construction and rehabilitation to limit the losses communities are meeting and therefore contributing to food insecurity reduction in the country.

The Faga basin is part of the data scarce basins while it abounds in great potentialities.

The ministry in charge of water resources should make allowance for runoff data recording as well as water withdrawals over the basin by undertaking serious monitoring of the existing runoff gauges.

This study used one hydrological model and three climate models run under RCP 4.5 and RCP8.5. A multi-model method for impact assessment is needed in order to gather large range of hydroclimatic information for further climate impact mitigation and/or adaptation at the basin's scale.

The control of low flows and their variability represent a critical objective to ensure water resource development and management within a river basin. Therefore, future studies should seek for further river flow in general and particularly low flows changes and variability in land use/land cover changing scenario as well.

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ANNEX

Annex 1 : Publish paper 1

International Journal of Current Engineering and Technology E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

 Available at http://inpressco.com/category/ijcet

Research Article

Analysis of change in climate extremes over 1982-2010 in the Faga Sub-basin, Burkina-Faso

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Accepted 23 March 2017, Available online 28 March 2017, **Vol.7, No.2 (April 2017)**

Abstract

Global climate change impacts rainfall and temperature extremes and there is an important need to study the behaviour of extreme values. According to IPCC (2007), confidence has increased that some extremes will become more frequent, more widespread and/or more intense during the 21st century. The aim of this paper is to analyse the trend in rainfall and temperature extreme values in the Faga River Basin (15700 Km^2 in the North-Eastern Burkina-Faso from 1982 through 2010. A total of eleven rainfall indices and ten temperature extremes from the recommended core indices of the World Meteorological Organization Commission for Climatology research project on Climate Variability and Predictability (WMO-CCl /CLIVAR) Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI) were computed using the R-based software (RClimDex). From 1982 through 2010, we observed a decrease in the number of consecutive wet days and the maximum 5-days precipitation amount while the remaining indices rainfall indices including the simple intensity index and the number of consecutive dry days. The temperature extremes indicate a warming weather with increase in the monthly maximum and minimum value of daily temperature, the warm spell indicator whereas the cold spell duration indicator and the Monthly maximum value of daily minimum temperature decrease.

Keywords: *Climate change, extremes, warming, Burkina-Faso, Faga River Basin, rainfall, temperature.*

1. Introduction

Many essential sectors of live on which economy depends including agriculture, water, transportation and energy are highly vulnerable to climate extremes values.

The sustainability of economic development and living conditions depends on our ability to manage the risks associated with extreme events (Albert M.G. Klein Tank, 2009). The motivation for analyzing extremes is
often to find an optimum balance between adopting high safety standards that are very costly on the one hand, and preventing major damage to equipment and structures from extreme events that are likely to occur during the useful life of such infrastructure on the other hand (WMO, 1983).According to (Zhang *et al* 2000), (Manton *et al* 2001), (Peterson *et al* 2002), (Aguilar *et al* 2005), (Griffiths *et al* 2005), (Zhang *et al* 2005b), (Haylock *et al* 2006), (Klein Tank *et al* 2006), (Alexander *et al*2006), (Skansi *et al* 2013), cited in (Keggenhoff *et al* 2014), various regional studies pertaining to temperature and rainfall extreme indices have been conducted which provide strong evidence that global warming is related to significant changes in temperature and precipitation extremes since the 1990s.

Africa is the most exposed to change in climate extremes as it is strongly depends on agriculture and infrastructures. As a Sahelian country, Burkina Faso's has a rainfed agriculture system, which employs about 86% of the active population and is strongly depends on the amount of precipitation received over the rainy season

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and how this amount is distributed. Like the other agricultural countries, the economy of Burkina-Faso heavily depends on the agriculture. However, change in extreme climate conditions (warmer or wetter) could impact on crop productivity leading to food security issue. Other risks may be the increase of diseases; death due to increased heat stress; increase water stress, etc.

Rainfall extremes may be risky to all the socio-economical domains. Indeed the deficit rainfall in the 1970s and 1980s caused enormous losses over the Sahelian Africa. For instance, during the 1984 drought the poorer rural household found their income decreased at about more than 50% in some regions of Burkina-Faso as stated in (UNEP/GRID – Arendal, 2002:12). While eleven (11) death, over 25000 affected persons and an important number of damaged infrastructures were numbered on the 1st September 2009 where an amount of 261 mm of rainfall according to Karambiri et al. (2011) was recorded in Ouagadougou. Hence there is an important need to study how climate extremes are changing at local scale in order to reinforce agriculture and water related adaptive capacities.

The purpose of the present study is to contribute to more appreciate and to understand how rainfall and temperature extremes over the Faga watershed located in the North-eastern part of Burkina-Faso varied from 1982 through 2010.

2. Study area

The field area of interest in this study is the Faga basin which is tributary of the Niger transboundary watershed situated in the North-eastern part of the country.

With a length of 270 km, the Faga River at Liptougou station located between the longitudes 1°31' Wand 00° 17' E and the latitudes 14°23'N and 12°43'N drains a watershed of 15,700 km2. It is characterized by a soudano-sahelian climate with an average rainfall between 600-1000mm per year.

The West African Monson mainly drives alternative rainy season (about 4 months) and a long dry season (about 08 months).

The potential evapotranspiration was estimated at 3795 mm Traoré (1991).

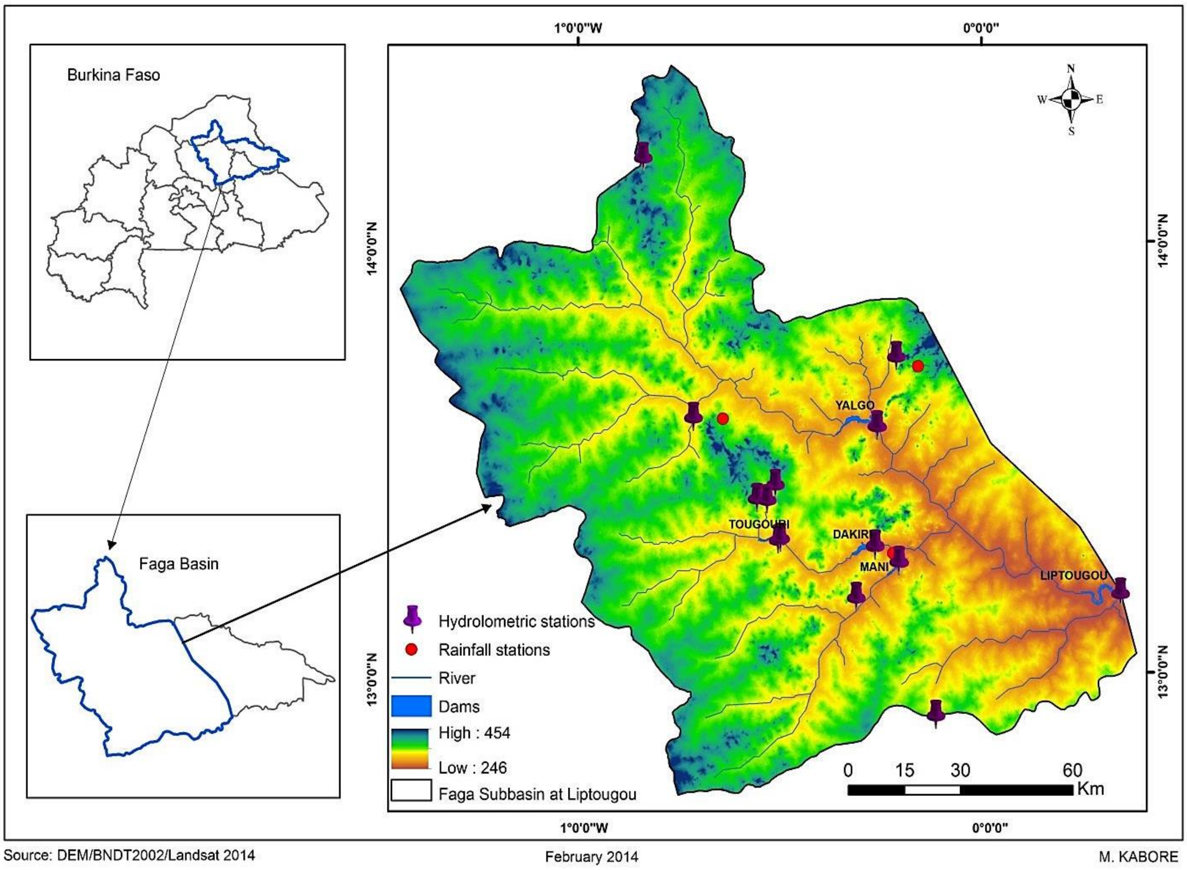

Figure 1: Faga River basin at Liptougou station

The mean monthly temperature of the Faga basin varies between 25 (°C) and 33 (°C).

The mean monthly precipitation is estimated at around 220 mm at Fada and 230 mm at Bogande.

Following the INSD (2006), population census the population of the Faga Basin is estimated at 2,107,981 inhabitants based on the giving population by province. Following the rate of population fast rising estimated at 2.8 UNDP, (2007) the population will may double by 2050.

This leads to a strong pressure on water resource that is accented particularly by the recent mining (2 Industrial and many artisanal) and market gardening development in the basin.

The vegetation is characterized by a savanna with trees or shrub in the north-sudanian agro-ecological zone while the sub-sahelian one is constituted by steppes with combretum and annual grass. According to (Fontès and Guinko 1995), the steppes are usually shrubby, dominated by thorn-bushes of the genera Acacia and Balanites.

The Basin land is mostly agricultural land like the whole country land. In general, the annual increase of the agricultural land is estimated at 3.6% for Burkina-Faso due to the increasing population.

3. Data and methods

Rainfall, minimum and maximum temperature of daily time step for the period 1982-2010 provided by the National Meteorological Services (NMS) for three stations were used for the purpose of this study.

We particularly used the ensemble mean of each parameter sets in order to detect the change in climate extremes over the study area.

To this, we used three stations data set of rainfall, maximum and minimum temperature to the ensemble mean estimation. The RHtestV3 software which is incorporated into RClimDex 1.1 was used to control the quality of the rainfall and the temperature time series and to test their homogeneity.

We examined the variability within the analysis of the climate extremes calculated from the RClimDex software (1.1). It computes all 27 core indices recommended by the World Meteorological Organization Commission for Climatology research project on Climate Variability and Predictability (WMO-CCl /CLIVAR) Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI) as well as some other temperature and precipitation indices with user defined thresholds (X. Zhang and F. Yang, 2004).

Interannual variability of annual rainfall within the study area is analyzed using the coefficient of variation in percentage in order to provide an indication of annual fluctuations.

The percentage coefficient of variation is expressed as followed:

$$C_v\% = \frac{\sigma}{\mu} * 100$$

Where:

$C_v\%$ = Coefficient of variation in percentage
σ = Standard deviation
μ = Mean
The magnitude of change is given by Sen's slope computed by the software.

Table 1 List of rainfall and temperature Indices

Indices	Indicator name	Definitions	Units
TXx	Max Tmax	Monthly maximum value of daily maximum temperature	ºC
TNx	Max Tmin	Monthly maximum value of daily minimum temperature	ºC
TXn	Min Tmax	Monthly minimum value of daily maximum temperature	ºC
TNn	Min Tmin	Monthly minimum value of daily minimum temperature	ºC
TN10p	Cool nights	Percentage of days when TN<10th percentile	Days
TX10p	Cool days	Percentage of days when TX<10th percentile	Days
TN90p	Warm nights	Percentage of days when TN>90th percentile	Days
TX90p	Warm days	Percentage of days when TX>90th percentile	Days
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX>90th percentile	Days
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN<10th percentile	Days
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	Mm
Rx5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	Mm
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCP>=1.0mm) in the year	Mm/day
R10	Number of heavy precipitation days	Annual count of days when PRCP>=10mm	Days
R20	Number of very heavy precipitation days	Annual count of days when PRCP>=20mm	Days
R50	Number of days above 50 mm	Annual count of days when PRCP>=50 mm, 50 is user defined threshold	Days
CDD	Consecutive dry days	Maximum number of consecutive days with RR<1mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR>=1mm	Days
R95p	Very wet days	Annual total PRCP when RR>95th percentile	Mm
R99p	Extremely wet days	Annual total PRCP when RR>99th percentile	mm
PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR>=1mm)	mm

4. Results and discussion

4.1. Change in rainfall extremes

From 1982 through 2010, a downward trend was detected in figure 2b) which presents the number of consecutive wet days (CWD). The maximum 5-days rainfall (RX5day) also shows a downward trend figure 2 (j) though the linear trend line due to the fact that decrease goes from very low positive index to the negative one.

Table 2 Rainfall trends statistics (1982-2010)

Indices	Slope	STD_of_Slope	P_Value
RX1day (mm)	0.069	0.378	0.857
RX5day (mm)	-0.022	0.646	0.973
SDII (mm/day)	0.035	0.048	0.471
R10mm (days)	0.033	0.104	0.752
R20mm (days)	0.148	0.077	0.065
R50mm (days)	0.059	0.03	0.061
CDD (days)	2.089	0.785	0.013
CWD (days)	-0.019	0.03	0.535
R95p (mm)	3.065	2.05	0.146
R99p (mm)	0.781	1.333	0.563
PRCPTOT (mm)	5.206	3.021	0.096

All the other extremes showed an upward trend as one can see in the table 2 below where the trends statistics for each extreme which are graphically showed in the figure 2 are presented.

Indeed, the consecutive wet days (CWD) and the maximum 5-days rainfall (RX5) day slightly decreased by 1.9% day per year and 2.2%mm per day along the study period.

The maximum 1-day (RX1day) and the simple daily intensity index (SDII) which is the quotient of the annual rainfall by the total number of wet days in the year (figure 2 i and k) showed a slight increase respectively by 0.069mm and 0.035 mm. (Bontogho *et al*. 2015) also found an increase trend in the same index for the Massili basin in Central Burkina-Faso.

The number of "heavy precipitation events increased over most areas during the second half of the twentieth century, leading to a larger proportion of total rainfall in a year from heavy falls" according to the (IPCC, 2007). This has also been notified in this study. Indeed, results showed that heavy to very heavy rainfall days which are days with rainfall more than 10mm (R10mm), 20mm (R20mm), and 50mm (R50mm) also presented an upward trend. An increase of 0.035mm was observed for the R10mm, 0.148mm for the R20mm and the R50mm rose up by 0.0 59mm per year.

The trend of the consecutive dry days (CDD) which determine the dry spell length showed an increase trend. Indeed, the number of consecutive days without rain during the rainy season rose from 1982 to 2010 by 2.089 days per year. This increase is in accordance with the work of (Karambiri *et al*. 2011) indicating an increase trend in dryness in the Nakanbe basin.

The fraction of annual precipitation due to very wet days (R95p) and extremely wet days (R99p) increased from 1982-2010 by 3.065mm and 0.781mm successively. The trend is also observed for the total wet days precipitation (PRCPTOT) which rose up at the rate 5.20mm. These results lined with the (IPCC, 2007) report on change in extremes which assess that "the index R95pTOT representing the fraction of annual precipitation amount due to very wet days shows positive trends for the majority of stations".

The slight increase in rainfall observed in the basin is in agreement with the observed recovery of rainfall over the Sahelian region since 1990s as stated in (Lodoun *et al*. 2013), (Wang and Gillies, 2011). The USGS and USAID, (2012) also reported that rainfall in Burkina-Faso recovered in the 1990s after a rapidly decline between 1950 and the mid-1980.

4.2. Change in temperature extremes

Trends analysis in temperature extreme highlighted in the table 3 and figure 2 testifies that the cold days number of warm nights (TX10p) a negative trend by 0.11 days while the number of warm days (TX90p) rose by 0.12 days. The number of cold nights (TN10p) decreased by 0.44 day whereas the number of warm nights (TN90p) showed significantly upward trend estimated at 0.48 day. A non-significant very low decrease is indicated for the cold spell duration indicator (CSDI) with a rate of 0.06 day. The warm spell indicator (WSDI) showed a slight increase with 0.06 day of rate.

As far as the monthly maximum and minimum value of daily temperature are concerned, an upward trend with low magnitude is observed for the maximum value of daily temperature (TXx) with 0.02 ºC of rate.

The same trend was detected for the monthly minimum value of daily maximum temperature (TNx), the monthly minimum value of daily minimum temperature (TNn) respectively by 0.03ºC and 0.08ºC. However, the Monthly maximum value of daily minimum temperature (TXn) showed a very insignificant downward trend with very low magnitude estimated at 0.004 ºC.

This analysis shows a clear warming weather for the Faga Basin in Burkina Faso from 1980 to 2010 with greater temperature extremes accompanied with an increase in the number of warm spell duration and a decrease of the cold spell duration. This observed increase in temperature extremes is observed general warming of the climate at the end of last century with greater warm extremes and less cold extremes(Claudia

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This positive trend in temperature has also high impact on the basin's agriculture which is as the

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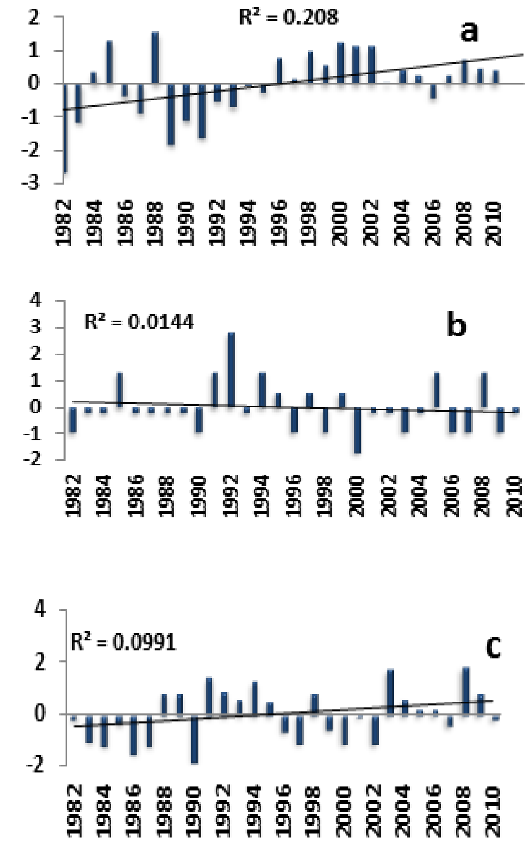
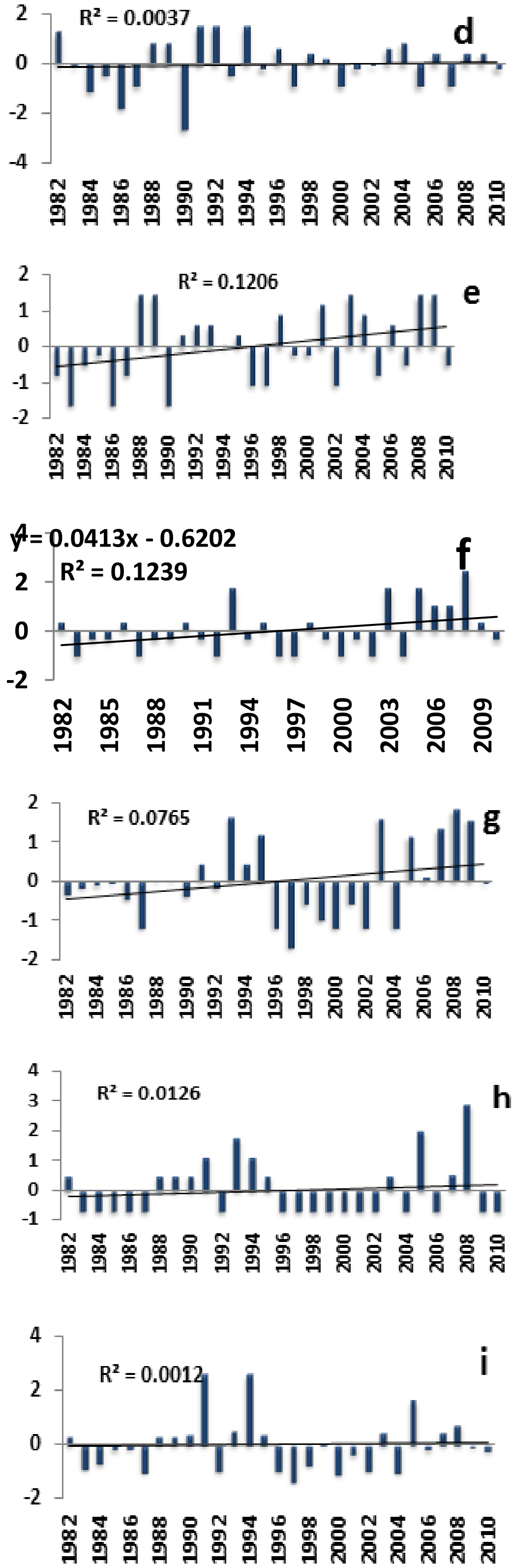
whole country qualified as rainfed agriculture. This increase in temperature may lead to an increase plant disease. Temperature extremes may negatively affects agriculture specifically when they occur during the growing period. (Benoit SARR *et al*. 2015) also found that temperature increase accelerates maturation of seedlings in nurseries of lettuce, cabbage and onion. The carbon dioxide of the net ecosystem is likely to be disturbed by the increase temperature. Indeed, extreme temperature conditions can shift forest ecosystems from being a net carbon sink to being a net carbon source (Handmer, J. *et al*. 2012).

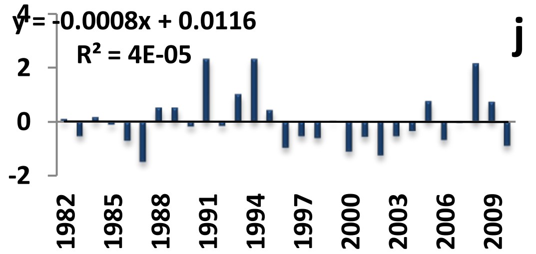
One of the key sectors affected by increase in temperature is the water. Warming leads to increase of evaporation which reduces the availability of water.

Table 3 Temperature trends statistics (1982-2010)

Indices	Slope	STD_of_Slope	P_Value
TXx (ºC)	0.024	0.012	0.048
TXn (ºC)	-0.004	0.017	0.825
TNx (ºC)	0.034	0.016	0.047
TNn (ºC)	0.084	0.024	0.001
Tx10p (days)	-0.115	0.054	0.043
Tx90p (days)	0.124	0.106	0.254
Tn10p (days)	-0.446	0.061	0
Tn90p (days)	0.483	0.1	0
WSDI (days)	0.062	0.127	0.631
CSDI (days)	-0.063	0.071	0.384







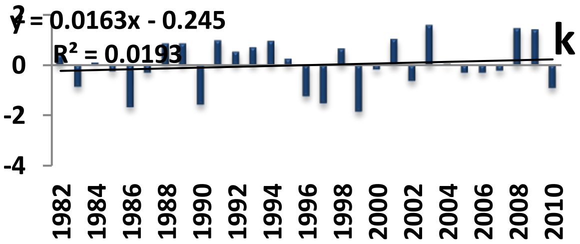
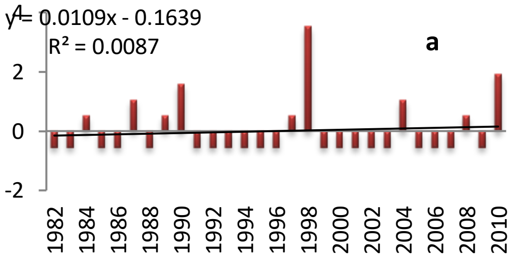
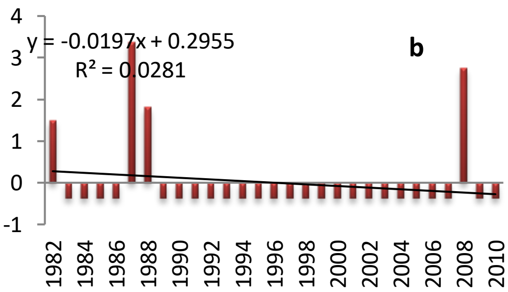
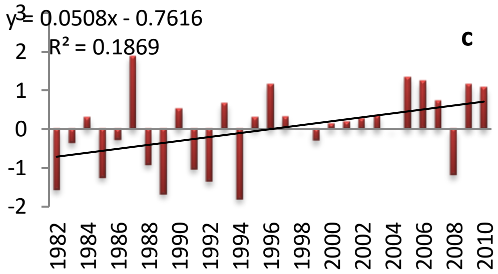
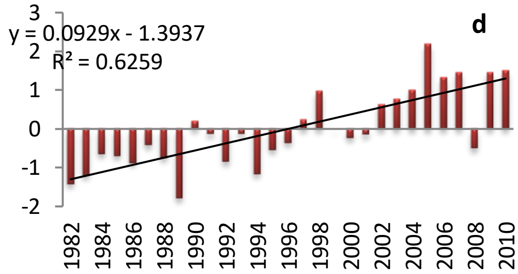


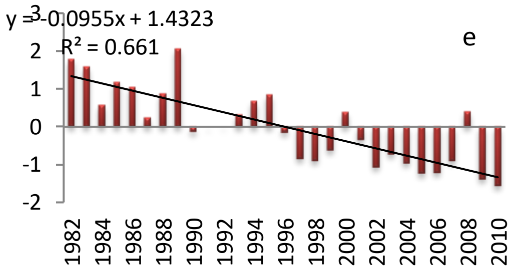
Figure 2: Precipitation indices in Faga for 1982-2010: CDD, CWD, PRCPTOT, R10 mm, R20 mm, R50 mm, R95p, R99p, RX1day, RX5day, SDII, from 1982–2010. R is the linear trend coefficient. (a) Consecutive dry days (CDD). (b) Consecutive wet days (CWD). (c) Annual total wet-day precipitation (PRCPTOT). (d) Number of heavy precipitation days (R10 mm). (e) Number of very heavy precipitation days (R20 mm). (f) Number of very heavy precipitation days R50mm. (g) Very wet days (R95p).(h) Extremely wet days (R99p). (i) Maximum 1-day precipitation (Rx1day). (j) Maximum 5-day precipitation (Rx5day). (k) Simple daily intensity index (SDII).

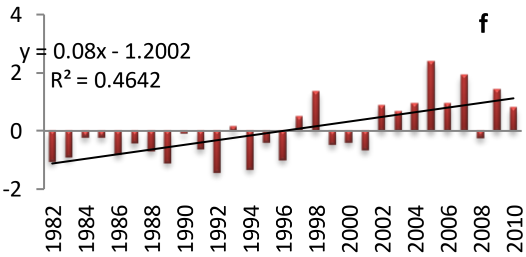


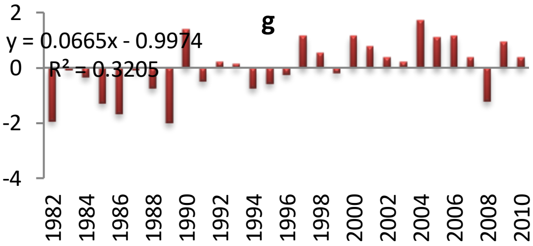


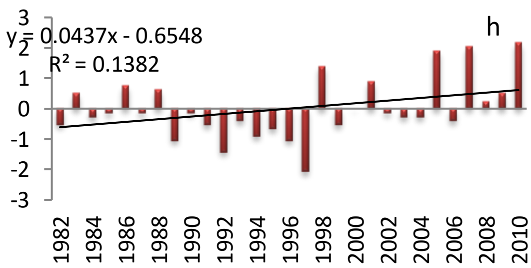












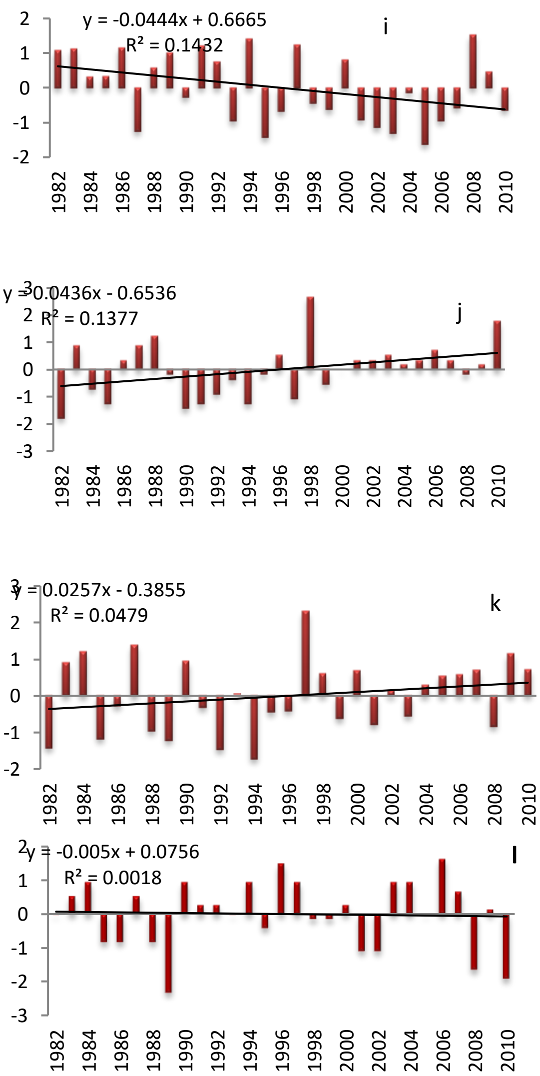


Figure 3: Temperature indices for the period1982-2010:TN10p, TX10p, TNN, TXN, TN90p, TX90p, TNX, TXX CSDI and WSDI. R is the linear trend (a) Warm spell duration indicator (WSDI), (b) Cold spell duration indicator (CSDI), (c) Mean monthly maximum value of daily maximum temp, (d) (Mean monthly maximum value of daily temp, (e) Cool nights (TN10p), (f) Warm days (TN90p), (g) Monthly minimum of Tmin (TNN), (h) Monthly minimum of Tmin (TNX), (i) Cool days (TX10p), (j) Monthly maximum of Tmax (TXXX), (k) Warm nights (TX90p), (l) Monthly minimum of Tmax (TXN)

Conclusions

Trend in climate extremes detection proves to be of a great importance for change in climate assessment and improvement of climate impact studies in climatological and hydrological area.

Studies on changes in climate extremes show a warming weather with a decrease in rainfall. The present study analyzed changes in rainfall and temperature extremes between 1980 and 2010 over the Faga river basin in Burkina Faso. Changes in temperature extremes were found in this study support the general trend with an increase in the number of warm days and nights and a decrease in cold days and nights in the study basin from 1982 to 2010. The cold spell duration indicator (CSDI) indicated a decrease trend while the warm spell indicator (WSDI) showed a slight increase.

Indices for precipitation extremes showed an increase in the number of consecutive dry days while the number of consecutive wet days presented a decreasing trend as revealed the global and regional trend. However, the present study showed an increase in the total rainfall amount. This finding is also in accordance with the studies performed over West Africa which suggest a rainfall recovery over the region since 1990s.

Change in climate extremes observed over the Faga basin should be taken into account in the adaptation measures to be implemented in order to improve the management of resources (e.g. agriculture).

It is clear that there is not enough studies on climate extremes and their trend particularly over the African region. Though, there is an important need of knowledge regarding current and future climate extremes and their impact assessment by sectors and systems. The existence of wide knowledge on climate extreme could help to overcome uncertainties related to Africa's vulnerability to extreme events. This could also be very interesting for the decision makers over Africa to understanding observed impacts for preparing measures for future extremes hazards. This study did not take into account onset and offset of rainfall in the basin. Nevertheless it may be the basis of knowledge and understanding of how climate extremes have recently changed over the Faga basin. It would be very interesting for further studies to assess future changes in climate extremes in order to help decision makers to overcoming exposure and vulnerability of the Faga basin to climate extremes events.

Acknowledgment

We are greatly grateful to the German Ministry of Education and Research (BMBF) for financing this study through the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) project. We would also like to express our gratitude to the National Meteorological Services (NMS) for its contribution within the data supply.

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Annex2 : Control file for WaSiM Run

Control file (Partial)

```
== Protected part to be changed by the module adapter ==
# == all manual changes in this section will be overwritten by the mod-
ule adapter ==

$set $startyear  = 2040
$set $endyear    = 2070

$set $outpath        =  E:\wasim1_faga\output_MPI\
$set $inpath         =  E:\wasim1_faga\Faga_Sim\
$set $time           =  1440
$set $starthour      = 24
$set $startday       = 1
$set $startmonth     = 1

$set $endhour        = 24
$set $endday         = 31
$set $endmonth       = 12
$set $readgrids      = 0

$set $grid           =  Faga
$set $stack          =  t
$set $suffix         =  grid
$set $code           =  s

# it is important to set $outpath to an empty string in order to acti-
vate $DefaultOutputDirectory
$set $outpath        =

# readgrids: 1 = read storage grids (as SI, SSNOW,SLIQ...) from hard
disk, 0=generate and initialize with 0
$set $readgrids     =  1

# read grids for dynamic phenology -> usually chilling grid should be
read in if available because otherwise thermal time method will be ap-
plied and not the sequential model
$set $DPreadgrids   =  1

# == end of protected part ==

 $set $time           = 1440

# it is important to set $outpath to an empty string in order to acti-
vate $DefaultOutputDirectory
$set $outpath        =  G:\wasim_faga\output\

# variables for parameters in unsatzon model: since several subbasins
will be parameterized with identical parameters
# it is very convenient to have them here defined as variables, so we
have only 18 parameter sets instead of 194 (for each subbasin one set)

# kd --> recession constant for single linear reservoir for direct run-
off
 $set $kd1    = 25 #45 #40 #45 #35 #25 #15 #15 #15#
 $set $kd2    = 25 #45 #40 #45 #35 #25 #15 #15 #15#
 $set $kd3    = 25 #45 #40 #45 #35 #25 #10 #15 #15#
```

```
 $set $kd4    = 25 #45 #40 #45 #35 #25 #10 #10 #15#
 $set $kd5    = 25 #45 #40 #45 #35 #25 #10 #10 #15#

# ki --> recession constant for single linear reservoir for interflow
$set $ki1    = 30 #60 #50 #60 #40 #30 #15 #30 #60 #10 #10 #60 #15 #30
$set $ki2    = 30 #60 #50 #60 #40 #30 #10 #30 #50 #10 #10 #50 #15 #30
$set $ki3    = 30 #60 #50 #60 #40 #30 #15 #30 #60 #5 #10 #60 #15 #30
$set $ki4    = 30 #60 #50 #60 #40 #30 #10 #50 #5 #5 #50 #15 #30
$set $ki5    = 30 #60 #50 #60 #40 #30 #15 #60 #5 #5 #60 #15 #30

# dr --> drainage density (interflow generation parameter)
$set $dr1    = 15 #95 #90 #80 #60 #15 #20 #1.8 #5 #10 #20 #18  #0.0 #
3.6 #1.8 #0.4 #1.8 #20 #1 #10 #1.8 #15  #  7.2  # 3.6 # 1.8
$set $dr2    = 15 #95 #90 #80 #60 #15 #20 #1.8 #5 #10 #20 #18  #0.0
#3.6 #1.8 #0.4 #1.8 #22 #1 #10 #1.8 #15 #  7.2  # 3.6 # 1.8
$set $dr3    = 15 #95 #90 #80 #60 #15 #20 #1.8 #5 #10 #20 #18  #0.0
#3.6 #1.8 #0.4 #1.8 #20 #1 #10 #1.8 #15  #  7.2  # 3.6 # 1.8
$set $dr4    = 15 #95 #90 #80 #60 #15 #20 #1.8 #5 #10 #20 #0.0 #3.6
#1.8 #0.4 #1.8 #22 #1 #1.8 #15  #  4.8  # 2.4 # 1.2
$set $dr5    = 15 #95 #90 #80 #60 #15 #20 #1.8 #5 #10 #20 #0.0 #3.6
#1.8 #0.4 #1.8 #20 #1 #10 #1.8 #15  #  7.2  # 3.6 # 1.8

# sdf --> Snow melt: Direct Runoff fraction
#$set $sdf1    = 0.05
#$set $sdf2    = 0.05
#$set $sdf3    = 0.05
#$set $sdf4    = 0.05
#$set $sdf5    = 0.05

# Variables for standard grids
# First section: grids, which differ for different subdivisions of the
basin
$set $zone_grid             =  $grid//.ezg
$set $subcatchments         =  $grid//.zon
$set $flow_time_grid        =  $grid//.fzs
$set $river_links_grid      =  $grid//.lnk
$set $regio_grid            =  $grid//.reg

#second section: grids, which doesn't depend on subdivision (only
pixel-values are of interest)
.
# Abstration rules are defined this way:
# first row: number of following columns, followed by the julian days
for which rules will be established
# the Julian day describes the LAST day, the rule is valid for, so the
year doesn't have to begin with 1
# but may begin with 31 instead to indicate, that rule one is valid for
the entire January.
# Also, the last JD doesn't have to be 366 - when no other rule follows
the actual rule, the last rule
# is valid until the end of the year
# other rows: discharge (m^3/s), followed by the abstraction valid for
this discharge (m^3/s)
# or reservoir volume in m^3, followed by the abstraction in m^3/s -->
to differentiate between discharge
# in m^3/s and reservoir content in m^3, the keyword "modus = in-
tern_with_rule" must be extended by the
# keyword "_from_reservoir", i.e. intern_with_rule_from_reservoir
```

```
[abstraction_rule_reservoir_1] # Engstlensee, AE ca. 8.25km^2, mit-
tlerer Abfluss ca. 0.2-0.4 m3/s, 10.7mio m3, TG 43
0
5           32    60    91    121   152   182   213   244   274   305   335
      366   # Julian Days; here: end of the months (rules are valid for
the period BEFORE the given JD)
0           0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
      0.0   # = leer
3.4e06            0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
      0.0   0.0   #
5.0e04            0.2   0.2   0.2   0.2   0.2   0.2   0.2   0.2   0.2   0.2
      0.2   0.2   #
9.7e06            0.5   0.5   0.5   0.5   0.5   0.5   0.5   0.5   0.5   0.5
      0.5   0.5   #
11.6e06           30    30    30    30    30    30    30    30    30    30
      30    30    # maximale HW-Entlastung
```

Annex 3: Survey questionnaire

WATER RESOURCES MANAGEMENT IN THE FAGA SUB-BASIN QUESTIONNAIRE
The responses to this questionnaire will be part of the required data that will be used within the modeling of the impact of small headwater dams on the hydrological responses of Faga river basin in the North-east Burkina-Faso under changing climate conditions.

GENERAL INFORMATIONS			
Date /__/__/-/__/__/__/-2014	N° fiche /__/__/	Province :	Village :
Interview schedulling	Start time :	End time :	Time elapse :

I. IDENTIFICATION OF THE FARMER				
Name of the owner:	Age :		Sex:	
Status :	Native /__/	Migrant /__/	(ethnic group) :	
Literacy tongue :	No one /__/	Mooré /__/	French /__/	Other /__/ (specify)
Organization	Individual /__/	Consortium /__/	Cooperative /__/	Professional /__/	Occasional /__/

II. STRUCTURAL DATA AND IRRIGATION TECHNIQUES				
	Geographical coordinates			
Dam's name	Longitude		Latitude	
Capacity	Construction date		Operating starting date	
Annual activity level: Area (Ha)				
Distance between the parcel and the dam				
Crops Type	Cereals /__/	Small Vegetables /__/	Oil plant /__/	Legumes/__/
Irrigation method used	Drip /__/	Watering /__/	Spraying /__/	Gravity /__/
Capacity of the suction pump (M^3S^{-1})				

III. WATER DEMAND					
Irrigation water consumption (M^3)	Daily		Monthly		Yearly
Household consumption (M^3)	Showers	Toilets	Washing	Apartment building	Others
Industrial water consumption (M^3)	Daily		Monthly		Yearly

IV. IRRIGATION SCHEDULING				
Irrigation start data	/ / /			
Irrigation time	Morning /__/		Afternoon /__/	Evening /__/
Irrigation Frequency	Once a day /__/	Twice a day /__/	Three times a day /__/	Every N days (Specify) /__/
Quantity of water irrigated the first day				
Irrigation Duration (Mn/Hr)				
Irrigation end date	/ / /			
Quantity of water irrigated every 15 days at the end				

V. WATER AVAILABILITY					
Access to water	**Currently**	**10 years ago**	**20 years ago**	**30 years ago**	**Remarks**

Very good					
Good					
Just enough					
Poor					
Very poor					

VI. CHANGE IN CLIMATE AND WATER RESOURCES ISSUES			
Does climate affect water re-sources	**Yes /__/**		**No /__/**
If yes what type and how? (from the last 30years to now)	**Increase**	**Decrease**	**Unchanged**
Rainfall			
Water level in the dam			
Dam's depth			
Dam's depth			
River flow			
Water stress			
Water quality			
Flood			
Drought			
Soil erosion and fertility			
Vegetation			
Exploitable surface			
Conflicts			
Other (specify)			

VII. CLIMATE CHANGE AND INTREGRATED WATER MAGEMENT
INSTITUTIONAL ISSUES

Is there a local water management institution?	**Yes**	**No**
	/__/	/__/
River basin water Agency	/__/	/__/
Local water committee (CLE)	/__/	/__/
Other structure working on climate change and water resources	/__/	/__/
ADAPTING TO CLIMATE CHANGE WATER MANGERS/OPERATORS		
1. DAMS' WATER CONSERVATION STRATEGIES		
WHICH STARGIES DO YOU USE FOR WATER CONSERVATION IN YOUR AREA?		
Dam bank protection		
Agro forestry		
Dam curetting		
Do you apply water productivity improvement methods? Yes /__/ No /__/ If yes what are they? If no why?		
2. SOIL CONSERVATION METHODS		
WHICH STARGIES DO YOU USE FOR WATER CONSERVATION IN YOUR AREA?		
Water treatment		
Soil amendment		
Irrigation		
Land reclamation		
Mulching		
Zai		

Other	

VIII. FLOW REGIME CHANGE CHALLENGES			
Parameters	**Change**	**No change**	**Neutral**
Number of flooded days reduction			
Flood plains reduction			
Disappearance of sacred places			
Loss of livelihood			
Banks reduction			
Crop yield reduction			
Water resources reduction			
Increase of sediment deposit			

Assessment of adaptation efforts

How do you appreciate the efforts made by state institutions and NGOs regarding adaptation to climate change impacts on water resources in your region?

……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
………………………………………………………

What is not done but should have been done?

……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………

What can you suggest as climate change adaptation strategy and how do you think it can be implemented?

- ………………………………………………………………………………………………………
- ………………………………………………………………………………………………………
- ………………………………………………………………………………………………………
- ………………………………………………………………………………………………………
- ……

Miscellaneous

What reservoir operating strategies can you suggest to improve water productivity in your region?

- ……
- ....
- ……

- ………………………………………………………………………………………………
……
- ………………………………………………………………………………………………
……

Annex4 Field work photo

- Photo1: Liptougou Dam in downstream Faga Basin
- Photo2: Overfall of Liptougou dam
- Photo3: Overfall of Manni dam
- Photo4: Irrigated rice field
- Photo5:Irrigated bananas filed
- Photo6: Irrigated aubergine field
- Photo7: Irrigation channel water gate at Manni
- Photo8: Field work team
- Figure 1: Normal distribution

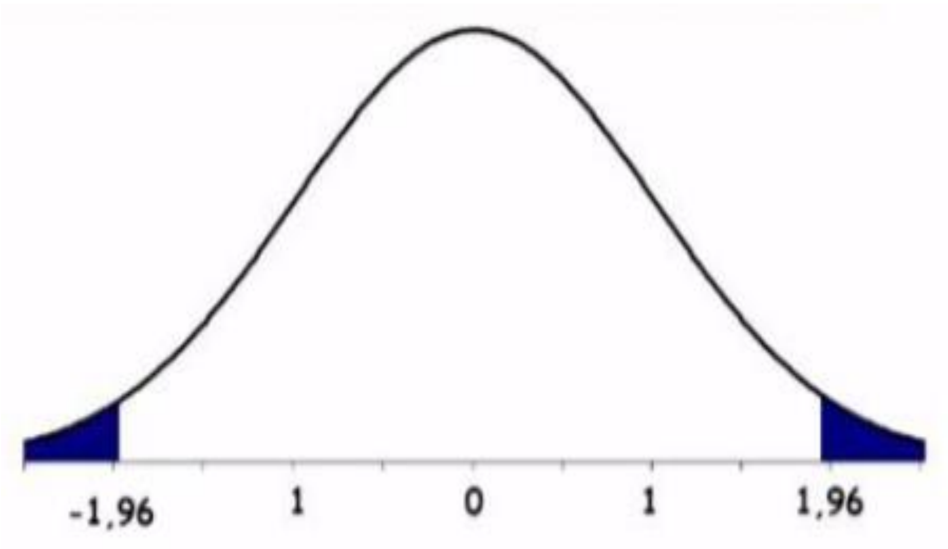

Figure 1

Mamounata KABORE received a Masters in Integrated Water Resource Management (IWRM) from the International Institute of Environment and Water (2IE) in Burkina-Faso in 2008. Before that, I got an MSc and BSc in Microbiology at the University of Ouagadougou in 2006 and 2005 respectively. From 2009 to 2010 I was a Monitoring and Evaluation Assistant at the Global Water Partnership/ West Africa for the Project "Programme for the Improvement of Water Governance in West Africa (PIWAG). From 2007 to 2012 I was a stand-in lecturer in Natural Sciences. I am now involving in the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) as a PhD candidate. My research is related to the modelling of climate change and small dams on the hydrological response of the Faga River Basin in Burkina-Faso under changing climate conditions.

Abstract:

In spite of its low emission of carbon dioxide Africa, specifically Sub-Saharan Africa is the most vulnerable to the effect of climate change and many countries have already moved toward water scarcity and Burkina-Faso is part of the water stress countries. To supply the water requirements of increasing populations and to meet economic development needs, building small reservoirs seems to be a promising option for water resources development in Burkina-Faso. However, water storage infrastructures may seriously affect, among others, the river flow regime which could worsen under climate change condition. This study aims at assessing how small dams and/or climate change could impact river basin's hydrology with the case study of the Faga River at Liptougou gauging station located in Burkina-Faso. For this purpose, hydrological parameters variation and climate extremes were assed in order to understand hydroclimatic behaviour over the basin throughout 1982-2010 using the indices of Nicholson combined to the Hanning filter and the non-parametric Mann-Kendall and Sen's slope test and RClimDex software with three climate stations and one hydrometric station data. Then we assessed the hydrological changes using the WaSiM hydrological modelled flow for the 1950-1958 as baseline for comparison and the EasyFit software. A field survey were performed to evaluate the environment and the socio-economic impact of small dams on downstream communities. We finally estimate the future changes of the river flow under increasing small dams and/or change climate scenarios over the 2040-2070. Three GCMs' runs under RCP4.5 and RCP8.5 and 15% to 25% increase of dams' number scenarios were used to run the WaSiM model. Results showed that annual precipitation increased at 18%. flow and potential evapotranspiration slightly increased of 3.48mm and 1.08mm respectively through 1982 2010 while annual mean temperature increased by 0.050C. The same trend is also observed for seasonal time scale. RClimDex run showed that the consecutive wet days (CWD) slightly decrease by 1.9% day per year and increase the monthly maximum and minimum value of daily temperature (TXx) increased by 0.02 ºC for instance. Using the WaSiM modelled flow for the 1950-1958 as baseline; results indicated that the current flow annual mean decreased at about 54.10%. Flood as 5-year peak flow decreased by 15.72% for instance. These changes caused in downstream for instance flood plaine decrease and loss of livelihood according to 65% et 90% of the total interviewee respectively.

Model simulation under RCP 4.5 showed a decrease flow of about 10.6% and 16.3% for RCP 8.5 for Can_ESM2 while EC-EARTH model simulations under RCP 4.5 and RCP 8.5 showed that the interannual flow will increase by about 4.9 and 8.1 respectively for along 2040-2070. The simulation results showed that future increase in dams' number could reduce the inter-annual river flow by about 37.40% to 40.03% using 15% and 25% increasing dams' scenarios respectively. Increase of 15-25% of dams' number caused respectively a decreased in interflow amount by 9.14 to 12.62% and the surface flow amount increased by 13.57 to 20.78%.

Combined dams and climate scenarios, under RCP 4.5 show an interannual flow decrease of 3.75% for EC_EARTH and 32.8% for MPI_ESM. A decrease of 3.70 - 32.80% is observed for the total flow and evaporation rose up from 13.63 to 38.80%.

RCP8.5 run show a surface runoff decrease of 22.1% with Can_ESM2 while MPI_ESM show a baseflow decrease of 47.11% throughout 2040-2070.

Key words: Climate change, small dam, hydrological, flow, modeling, scenario.