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MULTI-MODEL EVALUATION OF BLUE AND GREEN WATER AVAILABILITY UNDER CLIMATE CHANGE IN FOUR-NON SAHELIAN BASINS OF THE NIGER RIVER BASIN

A thesis submitted in partial fulfilment of the requirements for
the degree of Doctor of Philosophy (PhD)

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Genius is 10 per cent inspiration and 90 per cent perspiration.

Thomas Edison

If you scrutinise beyond the horizons, seas, mountains and hills, you will see the rising sun.

Jean-Claude Giannada

Those who wept as they went out carrying the seed will come back singing for joy, as they bring in the harvest.

Psalm 126, 6

Dedication

I dedicate this work to my late father who despite his illiterate status knew the prominence of instruction and struggled for me to go to school. I was a little boy when you departed. I am certain that from above you rejoice for what the Lord has done for me through this PhD thesis.

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Abstract

A proper estimation of future water availability is vital information for water planners. However, most contemporary quantitative hydrological predictions are mostly streamflow-centred which makes them fundamentally uncertain. Since, total streamflow represents only 35% of the total incoming rainfall at the global scale and even less than that in regions like West Africa, an alternative of using soil moisture and evapotranspiration is a possibility. This study explored these alternative avenues for more accurate hydrological prediction. From a theoretical perspective, water resources were treated as blue water (BW, sum of streamflow and deep aquifer recharge) and green water (GW, sum of actual evapotranspiration and soil moisture). The theoretical aspect also addressed the uncertainties associated with the use of a single hydrological model and adopted a multi-model evaluation instead.

This theoretical framework was applied to the Benin Portion of the Niger River Basin, a conglomerate of four understudied and poorly gauged basins, Coubéri, Gbassè, Yankin, and Kompongou. This area provides a number of ecosystem services whose sustenance requires better hydrological knowledge. To this purpose, four objectives were addressed in order to assess the impact of climate change on future BW and GW availability in the study area.

The first objective was to identify within a set of hydrological models the most suitable ones to better simulate streamflow and soil moisture. The performance of four hydrological models (HBV-light, UHP-HRU, SWAT and WaSiM) to simulate daily streamflow and the ability of three of these models (UHP-HRU, SWAT and WaSiM) to reproduce daily remotely-sensed soil moisture dynamic were compared. The results showed that none of the hydrological models clearly outperformed the others in the simulation of streamflow in all the basins. While WaSiM was the most suitable to simulate streamflow in the Yankin and Kompongou basins, HBV-light was the best for the Coubéri and Gbassè basins. However, regardless of the basin, UHP-HRU was the most adequate model to simulate soil moisture.

The second objective dealt with the downscaling of three regional climate models outputs (HIRHAM5, RCSM, and RCA4) under RCP4.5 and RCP8.5 for the historical period (1976-2005) and the future (2021-2050). To this end, the Statistical DownScaling Model (SDSM) was used. The results suggested that rainfall will increase (1.7 to 23.4%) for HIRHAM5 and RCSM under both RCPs but will show mixed-trends (-8.5 to 17.3%) for RCA4. Mean temperature will also increase (-0.1 to 0.48°C) for HIRHAM5 and RCSM but decrease for RCA4 (-0.37 to 0.1°C).

On the basis of the results of the two previous objectives, the third objective was to quantify the future BW only with the models found robust to simulate streamflow and future GW solely with the models found suitable to simulate soil moisture. It was found that GW will increase in all the four investigated basins while BW will only increase in the Kompongou basin.

The last objective was about the quantification of the overall uncertainty associated with the evaluation of future BW and GW. This was done by computing the inter-quartile range of the total number of model realizations for each basin. The results show that BW evaluation is associated with larger uncertainty than GW quantification. To cope with the projected decrease in BW that could adversely impact livelihoods and food security of the local population, some recommendations for the development of adequate adaptation strategies including the rational use of BW are briefly discussed.

Résumé

L'évaluation précise de la disponibilité future de la ressource en eau est une information vitale pour les acteurs du secteur de l'eau. Cependant, la plupart des prédictions hydrologiques sont fondamentalement incertaines en partie parce que centrées sur le débit d'écoulement. Le débit d'écoulement ne représentant que 35% de la pluviométrie totale à l'échelle du globe et même moins que cela dans des régions comme l'Afrique de l'Ouest, la prise en compte de l'humidité du sol et de l'evapotranspiration est une alternative. La présente étude a exploré des approches alternatives en vue d'une prédiction hydrologique moins incertaine. Du point de vue théorique, la ressource en eau a été traitée comme eau bleue (EB), somme du débit d'écoulement et de la recharge de la nappe, et eau verte (EV), somme de l'evapotranspiration réelle et de l'humidité du sol. L'aspect théorique a aussi abordé la problématique liée à l'utilisation d'un seul modèle hydrologique et a adopté une approche multi-modèles. Ce cadre théorique a été appliqué à la partie Béninoise du Bassin du fleuve Niger, un ensemble de quatre sous-bassins peu-étudiés et insuffisamment jaugés, Coubéri, Gbassè, Yankin, et Kompongou. Cette zone fournit plusieurs services éco-systémiques dont la conservation requiert une bonne connaissance hydrologique. A cette fin et en vue d'évaluer les impacts du changement climatique sur la disponibilité future en EB et en EV du secteur d'étude, quatre objectifs ont été définis.

Le premier objectif a consisté à identifier, dans un jeu de modèles hydrologiques, ceux qui sont les mieux indiqués pour la simulation du débit d'écoulement et l'humidité du sol. A cet effet, la capacité de quatre modèles (HBV-light, UHP-HRU, SWAT et WaSiM) à simuler les débits journaliers et celle de trois de ces modèles (UHP-HRU, SWAT et WaSiM) à reproduire la dynamique de l'humidité du sol par télédétection ont été comparées. Les résultats révèlent que pour la simulation des débits journaliers, aucun modèle ne surpasse les autres. WaSiM est le modèle le mieux adapté pour les basins de Yankin et Kompongou tandis que HBV-light est le mieux indiqué pour les bassins de Coubéri et Gbassè. Toutefois, la comparaison de la capacité des modèles à simuler l'humidité du sol montre qu'indépendamment du bassin, le modèle UHP-HRU surpasse les autres.

Le second objectif a été la désagrégation des produits de trois modèles climatiques régionaux (HIRHAM5, RCSM, et RCA4) suivant les scenarii d'émissions RCP4.5 et RCP8.5 pour la période historique (1976-2005) et pour le futur (2021-2050). Le modèle de désagrégation statistique SDSM a été utilisé à cette fin. Il en ressort que les précipitations connaitront une tendance à la hausse (1.7 à 23.4%) pour les modèles HIRHAM5 et RCSM sous les deux scenarii d'émissions mais une variation de -8.5% à 17.3 % pour le modèle RCA4. Les températures moyennes connaitront également une hausse (-0.1 à 0.48°C) pour les modèles HIRHAM5 et RCSM mais une décroissance (-0.37 à 0.1°C) si l'on considère le modèle RCA4.

Partant des résultats des deux premiers objectifs, le troisième objectif a consisté à quantifier la disponibilité future en EB rien qu'avec les modèles jugés convenables

pour la simulation des débits et la disponibilité future en EV uniquement avec les modèles jugés adéquats pour simuler l'humidité du sol. Il en découle que l'EV connaitra une hausse sur l'ensemble des quatre bassins tandis que l'EB ne connaitra d'augmentation que sur le bassin de Kompongou.
Le dernier objectif a été relatif à la quantification de l'incertitude liée à l'évaluation de la disponibilité future en EB et en EV. Cela a été fait en calculant la variation interquartile du nombre total de combinaisons modèles hydrologiques-scenarii climatiques. Il est constaté que l'évaluation de l'EB est entachée d'une plus grande incertitude que celle de l'EV.
Pour remédier à la baisse de l'EB qui pourrait impacter négativement le gagne-pain et la sécurité alimentaire des populations du secteur d'étude, quelques recommandations en vue de la conception de stratégies adéquates d'adaptation y compris l'utilisation rationnelle de l'EB sont brièvement présentées.

Zusammenfassung

Genaues Wissen über die Wasserverfügbarkeit in der Zukunft ist unentbehrlich für Entscheidungsträger und Planer. Allerdings sind quantitative hydrologische Vorhersagen im Wesentlichen unsicher, besonders, aber nicht ausschließlich, da Abfluss zumeist die einzige beobachtete Variable darstellt gegen die die Performanz eines Modells evaluiert wird.

Da der gesamte Abfluss nur 35% der globalen Niederschläge und in einigen Regionen wie beispielsweise Westafrika sogar weniger beträgt, stellt die Betrachtung der Bodenfeuchte und der Evatranspiration eine gute Alternative dar um Vorhersagen zu treffen. Die vorliegende Untersuchung erkundete diese Alternativen zur Verbesserung der hydrologischen Vorhersagen. Aus einer theoretischen Perspektive wurden Wasserressourcen als „blue water“ (BW, Summe der Abflüsse und Neubildung von tiefem Grundwasser) und „green water“ (GW, Summe der tatsächlichen Evapotranspiration und Bodenfeuchte) behandelt. Der theoretische Aspekt adressiert zudem die Unsicherheiten, die mit dem Einsatz eines einzigen hydrologischen Modells einhergehen, weshalb eine Multi-Modell-Bewertung stattdessen vorgenommen wurde.

Dieser theoretische Rahmen wurde im beninischen Teil des Niger Einzugsgebietes, eines Konglomerats von vier bisher wenig untersuchten und gemessenen Teileinzugsgebieten - Coubéri, Gbassè, Yankin und Kompongou - angewendet. Dieses Gebiet bietet eine Vielzahl von Ökosystemdienstleistungen, deren Instandhaltung besserer hydrologischer Erkenntnis bedarf. Hierzu wurden vier Ziele zur Untersuchung der Auswirkung des Klimawandels auf die künftige Verfügbarkeit von BW und GW im Gebiet verfolgt.

Das erste Ziel war es, das geeignetste Modell zur bestmöglichsten Simulation von Abfluss und Bodenfeuchte aus einem Set hydrologischer Modelle zu identifizieren. Die Leistung vier hydrologischer Modelle (HBV-light, UHP-HRU, SWAT und WaSiM) bezüglich der Simulation täglicher Abflussmengen sowie die Fähigkeit von drei dieser Modelle (UHP-HRU, SWAT und WaSiM) tägliche fernerkundete Bodenfeuchtedynamiken zu reproduzieren wurden verglichen. Die Ergebnisse haben gezeigt, dass keines dieser hydrologischen Modelle besser als die anderen bei der Simulation von Abflüssen in allen Einzugsgebieten ist. Während WaSiM das geeignetste war, Abflüsse in Yankin und Kompongou zu simulieren, erwies sich HBV-light als das Beste für Coubéri und Gbassè. Allerdings war UHP-HRU unabhängig des Einzugsgebietes das am besten geeignete Modell zur Simulation der Bodenfeuchte.

Das zweite Ziel behandelte das Downscaling dreier Outputs regionaler Klimamodelle (HIRHAM5, RCSM und RCA4) unter RCP4.5 und RCP8.5 für den Zeitraum von 1976 bis 2005 und von 2021 bis 2050. Hierzu kam das statistische DownScaling Modell (SDSM) zum Einsatz. Die Ergebnisse zeigen, dass für HIRHAM5 und RCSM unter beiden RCPs Niederschläge steigen werden (1.7 bis 23.4%). Allerdings ist der Trend uneinheitlich für RCA4 (-8.5 bis 17.3%). Die Durchschnitttemperatur wird unter

HIRHAM5 und RCSM von (-0.1 bis 0.48°C) steigen aber unter RCA4 sinken (-0.37 bis 0.1°C).

Auf Grundlage der Ergebnisse beider vorausgegangenen Ziele kam es beim dritten Ziel dazu, zukünftige BW Ressourcen allein mit den robusten Modellen – in Bezug auf die Simulation von Abflüssen - zu quantifizieren. Ebenfalls wurden zukünftige GW Ressourcen nur mit den Modellen quantifiziert, die sich auch als geeignet für die Simulation von Bodenfeuchte erwiesen. Es hat sich herausgestellt, dass sich das GW in allen vier untersuchten Becken erhöhen wird während das BW nur im Kompongou Becken steigen wird.

Das letzte Ziel bezog sich auf die Quantifizierung der gesamten Unsicherheiten, die mit der Bewertung zukünftiger BW und GW Ressourcen verbunden sind. Getan wurde dies, indem der Interquartilbereich (Differenz zwischen dem 75. und dem 25. Perzentil) der gesamten Anzahl von Modellläufen für jedes Untersuchungsgebiet berechnet wurde. Die Ergebnisse zeigen, dass die BW Evaluation mit höherer Unsicherheit verbunden ist, als die GW Quantifizierung.

Um den projizierten Rückgang der BW Ressourcen zu bewältigen, welcher sich negativ auf die Existenzsicherung und Ernährungssicherheit der lokalen Bevölkerung auswirken könnte, wurden einige Empfehlungen für die Entwicklung geeigneter Anpassungsstrategien einschließlich der rationellen Nutzung von BW Ressourcen kurz diskutiert.

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Abbreviations

AMMA-CATCH:	African Monsoon Multidisciplinary Analysis-Coupling Tropical Atmosphere and Hydrological Cycle
ANN:	Artificial Neural Network
ASTER GDEM:	Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model
AMSL:	Above Mean Sea Level
BPNRB:	Benin Portion of the Niger River Basin
BW:	Blue Water
CENATEL :	Centre National de Télédétection et de Suivi Ecologique du Bénin
CIV:	Modèle hydrologique de capacité d’infiltration variable
CN:	Curve Number
CPCS:	Commission de Pédologie et de Cartographie des Sols (Commission of Pedology and Soil Mapping)
DEM:	Digital Elevation Model
DGEau :	Direction Générale de l’Eau
DMN:	Direction Météorologique Nationale
ESA CCI:	European Space Agency Climate Change Initiative
ECHAM5:	European Center/Hamburg Atmospheric Model 5
FAO:	Food and Agriculture Organization
FEFLOW:	Finite Element Subsurface Flow & Transport Simulation System.
GCM:	Global Circulation Model
GDP:	Gross Domestic Product
GLOWA:	Globaler Wandel des Wasser kreislaufes (Global Change and the Hydrological Cycle)
GW:	Green Water
HBV-light:	Hydrologiska Byråns Vattenavdelning-Light
HRU:	Hydrological Response Unit
HSPF:	Hydrological Simulation Program-Fortran

IMPETUS:	Integratives Management Projekt zum effizienten und tragfähigen Umgang mit Süßwasser in Westafrika (An integrated approach to the efficient management of scarce water resources in Western Africa)
INRAB :	Institut National des Recherches agricoles du Bénin
INSAE:	Institut National de la Statistique et de l'Analyse Economique
IPCC:	Intergovernmental Panel on Climate Change
IRD :	Institut de Recherche pour le Développement
LAI:	Leaf Area Index
LHME:	Laboratoire d'Hydraulique et de Maitrise de l'Eau
LSS:	Laboratoire de Sciences du Sol
MAE:	Mean Absolute Error
MOLUSCE:	Modules for Land Use Change Evaluation
ORSTOM:	Office pour la Recherche Scientifique et Technique d'Outre Mer (Office for Overseas Scientific and Technical Research; now IRD)
PNE:	Partenariat National de l'Eau
RC:	Research Clusters
RCM:	Regional Climate Model
RCP:	Representative Concentration Pathways
REMO:	Regionalmodell (Regional Model)
RIVERTWIN:	Regional Model for Integrated Water Management in Twinned River Basins
SCS:	Soil Conservation Service
SDSM:	Statistical DownScaling Model
SWAT:	Soil Water Assessment Tool
SUFI-2:	Sequential Uncertainty Fitting version 2
UNEP:	United Nations Environment Programme
UHP-HRU:	Universal Hydrological Program – Hydrological Response Unit
USDA:	United States Department of Agriculture.
WaSiM:	Water Balance Simulation Model
WP:	Work Packages

1 General introduction

Water is one of our most critical resources – even more important than oil. Water sustains agriculture and, thus, our food chain... It could be said our economy runs on water.

Morrison *et al.*, 2009

Water is an indispensable resource to every facet of life making hydrological modelling a crucial tool for the development of human society. This role of hydrological modelling is rendered even more prominent given the current population growth and global warming which lead to more pressure on water resources. A number of theoretical and practical hydrological questions are raised. The theoretical questions comprise the excessive weight given to streamflow in most of the quantitative hydrological predictions and the problem of making these predictions in basins that are poorly gauged which raises the issue of uncertainty. Consequently, multi-model evaluation is introduced as a path both for assisting in a robust selection of hydrological models and uncertainty quantification. The last part of the chapter highlights some key water-related issues of the Niger River basin which appeal for a more accurate hydrological modelling.

1.1 Framework of the study

The current research was undertaken under the auspices of the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL). Climate and land use changes are part of the major challenges of our century (Morrison *et al.*, 2009, Speth *et al.*, 2010, UNEP, 2012) with West Africa being one of the most vulnerable regions (Boko *et al.*, 2007). The WASCAL initiative was set up to contribute to the enhancement of the resilience of sub-Saharan countries to changing climate and land use. Previous projects such as the African Monsoon Multidisciplinary Analysis (AMMA), the Global change of the water cycle-Integrative management project for an efficient and sustainable use of freshwater resources in West Africa (GLOWA-IMPETUS), and the GLOWA-Volta had the same noble vision. The uniqueness of WASCAL is on building up a network of West African scientists from English and French speaking countries; thus overcoming the language barrier and bringing together the experience of individual countries for the development of solutions of common cross-cutting climate problems.

WASCAL has six research clusters (RCs) which are climate and weather, landscape dynamics, agricultural systems, markets and livelihoods, risks management and integrated assessment. The RCs are further subdivided into a total of 21 Work

Packages (WP) among which is the WP 2.4 which deals with water resources under climate and land use change. This WP is made operational via the Graduate Research Program on Climate Change and Water Resources (GRP CC-WR) hosted by the University of Abomey-Calavi (Benin Republic), in collaboration with the Hydrologic Research Group of the University of Bonn (Germany), and constitutes the basis for the present study. For more details regarding the core research programs of WASCAL, please refer to Denich *et al.* (2010).

1.2 Background

1.2.1 Water: the blue gold

Water is a prerequisite for human life. Historically, the ancient greatest civilisations (e.g. Greek, Egyptian, Babylonian, Assyrian) were built close to water points (Musy & Higy, 2011). Similarly, the development of the modern society is water-dependent (Morrison *et al.*, 2009). In Zimbabwe, a strong correlation between gross domestic product (GDP) and rainfall variability was reported for the period 1979 to 1983 (Saghir, personal communication, December 2003). The 2006 report of the UN-WATER underscored a similar correlation between GDP and rainfall for the period 1979-2000 for Kenya. Unfortunately, sometimes, water is a source of conflict between socio-economic groups within the same state just as it was a cause of clashes between ancient civilizations in the past (Chang, 2002). An example of such conflicts is given in the book of (Chang, 2002) where “A dam on the Nueces River Basin in south Texas was planned in the 1960s but was delayed for almost 20 years due to disputes over water rights between upstream and downstream water users, along with the conceptual struggle between conservationists and developers.“

In their struggle for a better society, developing countries in general, and the West African ones in particular, face various water challenges. Among these challenges are the supply of drinking water, adequate sanitation, water for self-sufficient agriculture, trans-boundary basin water management, hydropower for energy security, land degradation and water pollution, growing water demand, water under climate change and capacity building (UN-WATER/AFRICA, 2000). Of all the challenges, emphasis should be on water for food security since rainfed agriculture is the principal economic activity and occupies more than 90 % of farmed land (Wani *et al.*, 2009, Cooper *et al.*, 2008). Thus, the goal of UN-WATER/AFRICA by 2025, “An Africa where there is an equitable and sustainable use and management of water resources for poverty alleviation, socio-economic development, regional cooperation and the environment” is topical.

Based on this background, a number of projects have been undertaken. One can, among others, cite: The IMPETUS[1] (Integrated Management Project for an Efficient

[1] IMPETUS project ran from 2000 to 2012

and Sustainable Use of freshwater resources in West Africa), the AMMA/CATCH[2] (African Monsoon Multidisciplinary Analysis/Coupling Tropical Atmosphere and Hydrological Cycle) and the RIVERTWIN[3] (Regional Model for Integrated Water Management in Twinned River Basins) projects.
The IMPETUS-project sought to comprehend the relationships between the hydrology, hydrogeology and pedology of the Ouémé (Benin) and the Upper Drâa (Morocco) basins under climate, land use and socioeconomic changes. The drivers of the hydrological cycle were identified and analysed; future scenarios of the hydrological cycle were modelled and adaptive management options were developed for policy makers (e.g. Bossa, 2012, Speth *et al.*, 2010).

The famines of 1972, 1973 and 1984 in the Sahel caused by the 30 years (1970s - 1990s) of drought over West Africa were one of the key motivations of the AMMA/CATCH-project (Lebel *et al.*, 2009). Three distinct mesoscale sites (in terms of their climate, geography, hydrology and land use) were selected namely Gourma in Mali, the Niamey Square Degree in Niger and the Upper Ouémé Valley in Benin. A multidisciplinary and multi-scale approach was developed in order to account for the interaction between atmospheric dynamics, hydrological cycle and land cover change. Combining field observations, processes studies and modelling climate variability on water resources, the project improved the knowledge of the intra-seasonal variability of West African monsoon and its impacts on the water cycle. Furthermore, the project documented the concept of the "Sahelian paradox". Despite the reduction in rainfall (due to the drought), the mean annual discharge of several Sahelian rivers increased (e.g. Albergel, 1987, Mahé *et al.*, 2005). The groundwater table of some aquifers of the Sahelian region (e.g. in Niamey) also increased (Descroix *et al.*, 2009). The increase in streamflow and groundwater table in the context of the decrease in rainfall was termed the "Sahelian Paradox" (Amogu *et al.*, 2010, Descroix *et al.*, 2009). It was shown that reduction in land cover caused increase in runoff coefficient which in turn favoured filling of ponds and therefore groundwater recharge.

Against the background of the European Union Global Water Initiative, the RIVERTWIN-project was designed for developing an integrated regional model for the strategic planning of water resources management in twinned river basins, river basins being considered as the basic unit for all planning and management actions. Like for the IMPETUS-project, the ultimate goal was to help decision makers in developing adaptive strategies to long term variability of water resources under economic, technological, global climate and land use changes. An economic valuation of water stocks and flows was done and a multifaceted database (soil, socioeconomic, water resources including water demand by sector) was established. In particular, water demand in agriculture including irrigation was estimated and water management scenarios defined. A GIS-based model considering water

[2] AMMA/CATCH has two phases : 2002-2010 (phase I) and 2010-2020 (phase II)
[3] RIVERTWIN project ran from 2003 to 2007

availability and quality on the one hand, and water demand and water use on the other, was implemented for the Ouémé Basin (Barthel *et al.*, 2009, Kaule & Raumer, 2008).

1.2.2 Climate change: the threat

Stern (2010) identified climate change and poverty as the two major challenges of our time. Land use change also acts together with climate change to intensify the hydrological cycle both at global and regional scales (L Descroix *et al.*, 2009, Huntington, 2006). To enhance human resilience to the effects of climate change, tremendous efforts have recently been made. Climate scientists have attempted to better understand the current climate behaviour and have designed numerous models to project expected future trends of climate variables under environmental and socio-economic changes.

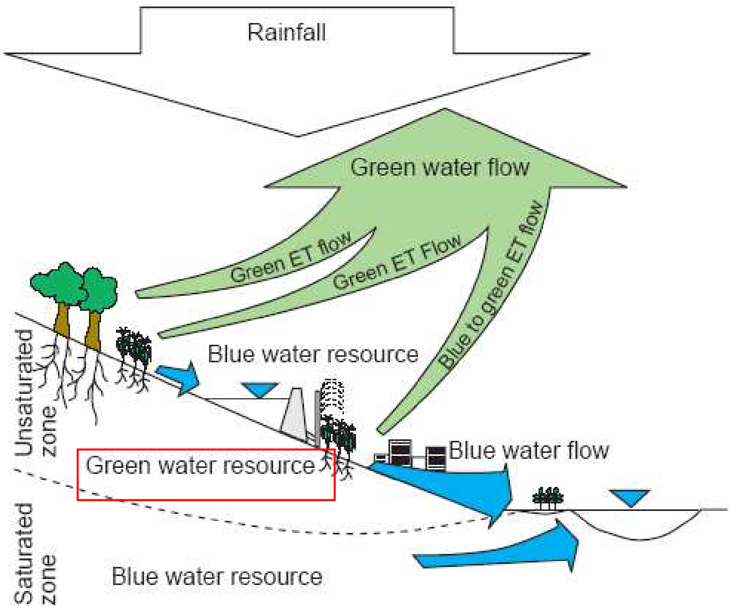
Despite the progress made, the issue of the ‘’actual’’ future trends of rainfall and, consequently, water resources over the region is still a challenge for climate scientists and hydrologists. The IPCC (2007a, 2007b) reported that West Africa is one of the world’s most vulnerable zones and a region where the extent to which climate change will impact water resources is still unclear. A comparison of 10 recent climatic studies over West Africa have showed that the direction in which rainfall will vary during the current century is an open question (Druyan, 2011). Comparing the effects of climate change and population growth on groundwater in Africa, Carter and Parker (2009) found that the latter will be more severe. However, the authors recognized the uncertainty associated with the impacts of climate change both in direction and magnitude. Furthermore, in 2013 and 2014, the IPCC indicated that potential impacts of climate in the future will be even more severe than previously projected (IPCC, 2013). As for Carabine *et al.* (2014), regardless of the uncertainty, “climate change will amplify existing stress on water availability for society and the natural environment in Africa”.

1.3 Problem statement

1.3.1 The problem of streamflow as the sole reference to assess the performance of hydrological models

A common and classical procedure in quantitative hydrology is the use of streamflow alone for model calibration and validation. From this procedure, hydrological models are judged as excellent or poor and used for future prediction (e.g. Golmohammadi *et al.*, 2014, Cornelissen *et al.*, 2013, Kebede, 2013). The procedure has the advantage to be simple and therefore to support the principle of parsimony suggested by Beven (1989). Besides, this procedure facilitates teaching in hydrology (Seibert & Vis, 2012).

However, at the basin scale, water is distributed between streamflow, deep aquifer recharge, soil moisture storage and actual evapotranspiration. Consequently, the evaluation of the performance of hydrological models against streamflow alone might be inadequate (Faramarzi *et al.*, 2009). Since, total streamflow represents only 35% of the total incoming rainfall at the global scale and even less than that in regions like West Africa (Falkenmark & Rockström, 2004, 2006), an alternative consideration such as soil moisture and evapotranspiration can be explored. As a matter of fact, inspired by the works of L'vovich (1979) on soil moisture, Falkenmark & Rockström (2004, 2006) recommend that hydrologists focus more on evapotranspiration than on streamflow and suggest that water resources be treated as blue and green water (see Figure 1-1). Blue water is the visible liquid water which flows in rivers through surface/subsurface runoff and baseflow from groundwater and stored in aquifers, lakes, wetlands and dams. On the contrary, green water is the invisible water which goes back to the atmosphere mainly through the consumptive use by vegetation (forests, savannahs, croplands, grasslands, etc.). The primary source of green water is soil moisture which is transformed into transpiration known as the "productive part" of biomass production and evaporation the "non-productive part".



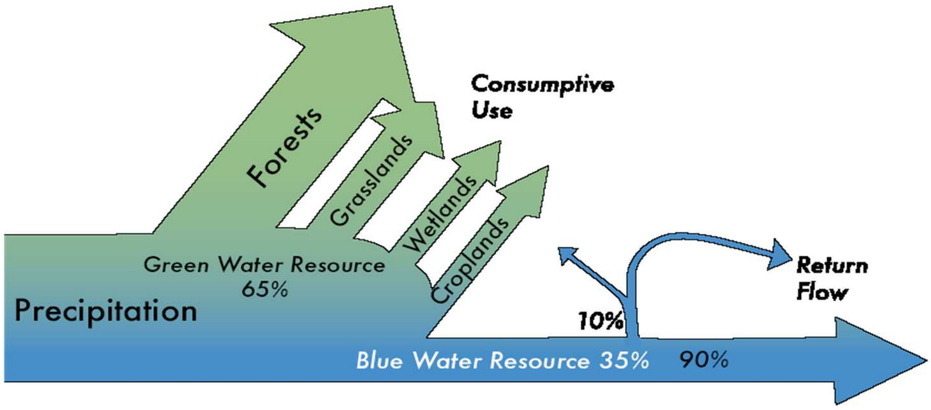


Figure 1-1: The concept of blue and green water (Falkenmark & Rockström, 2006)

Nevertheless, a major constraint to the application of the suggested methodology could be data availability especially in regions like West Africa. The point is that streamflow series have a longer history of collection and therefore more readily available than soil moisture and evapotranspiration datasets. To overcome this difficulty, remotely-sensed soil moisture and evapotranspiration archives that are growing worldwide could be a valuable solution. These data sets have reported adequate accuracy as compared to in situ measurements over the AMMA region (Lebel *et al.*, 2009) and West Africa (Gruhier *et al.*, 2008, Lee *et al.*, 2014). Abbaspour (2008) believes that combining *in situ* data (such as streamflow) and remotely-sensed data, among others, is a promising path to achieve better hydrological modelling. Forootan *et al.* (2014) for instance used the remotely-sensed gravity data of the GRACE (Gravity Recovery and Climate Experiment), rainfall of the TRMM (Tropical Rainfall Measuring Mission), and sea surface temperature (SST) data over the Atlantic, Pacific, and Indian Oceans to evaluate changes in West African monthly total water storage.

1.3.2 The uncertainty problem

Uncertainties in hydrological modelling emanate from various sources such as the model structure, assumptions and parameters, the forcing data and the modeller (Anderson & Bates, 2001, Beven, 2001, Brown & Heuvelink, 2005, Pappenberger & Beven, 2006).

The uncertainties emanating from hydrological models are split into epistemic uncertainty and aleatory uncertainty. While epistemic uncertainties are due to an incomplete knowledge regarding the system, the parameters, and the processes, aleatory uncertainties originate from the variability and non-uniqueness of the hydrological model parameters and properties (Hofer *et al.*, 2002, Krzykacz-hausmann, 2006, Oberkampf *et al.*, 2004). Epistemic uncertainties can be reduced if the modeller has a better knowledge of the processes occurring within the basin to achieve a better consideration of these processes in the structure of the model.

Aleatory uncertainty, however, cannot be reduced. They can only be quantified using uncertainty frameworks like the Generalized Likelihood Uncertainty Estimation, GLUE (Beven & Binley, 1992), the Particle Swarm Optimization, PSO (Eberhart & Shi, 2001, Eberhart & Kennedy, 1995), the Markov Chain Monte Carlo, MCMC (Kuczera & Parent, 1998, Vrugt *et al.*, 2003, Yang *et al.*, 2007), the Parameter Solution, ParaSol (van Griensven & Meixner, 2006), the Sequential Uncertainty Fitting, SUFI2 (Abbaspour *et al.*, 2004, 2007), and the Artificial Neural Networks, ANN (Maier & Dandy, 2000, Srivastav *et al.*, 2007).

Abbaspour (2012) termed the uncertainty due to the structure of hydrological models "conceptual model uncertainty". For Abbaspour (2012), this uncertainty arises from the assumptions of the conceptual model (e.g. simulation of surface runoff with the SCS CN approach), from the failure of the model to account for some processes occurring in the studied basin (e.g. rapid conversion of land cover), from the failure of the modeller to consider some processes occurring in the basin though incorporated in the model (e.g. water diversion, reservoirs), and from the failure to include processes neither included in the model nor known of the modeller (e.g. construction of large dams, roads, bridges).

The consideration of the uncertainty deriving from parameters estimation has led to the definition of the concept of equifinality (Beven and Binley, 1992). Equifinality describes different parameter sets which lead to the same model output. Abbaspour (2008) explained that since parameters can combine in thousands of ways to give the same output, equifinality is inherent to any hydrological modelling. Thus, a robust modelling exercise should not seek for a single set of parameters but rather seek sets of parameters leading to behavioural solutions (Krauße, 2013). Such solutions are deemed to lead to acceptable performances for calibration and validation, acceptable representation of processes and not sensitive to little variation of the parameters.

The uncertainties related to the data can be discussed in terms of the quality of the forcing data and observed variables, and the selection of the data to use for calibration, validation and prediction. Errors in the measurement of climate variables, particularly rainfall (Diederich and Simmer, 2010), land use maps (Bossa, 2012), among others, are propagated through hydrological models leading to predictive uncertainty. Similarly, the observed variables used to validate models are not error-free (Krauße and Cullmann, 2012; Bárdossy and Singh, 2008) and affect model outputs. For the particular case of streamflow, the errors emanate from the measuring devices, their rating curves and techniques. In northern Benin, for example, the rating curves of 1985 and 1997 are still used to date to derive daily discharge of the Mékrou River, and the Sota and Alibori Rivers respectively (DG-Eau, 2008) despite being obsolete (enlargement of the riverbanks, silting of the rivers). Bormann (2005) reported that the unavailability of climate and hydrological data in terms of quality and quantity renders prediction of water resources uncertain and hampers the design of suitable water resources management tools in West Africa.

Also, the actual choice of the calibration data could be a source of uncertainty and requires an "intelligent selection" (Krauße, 2013). Sorooshian and Gupta (1983) reported that it is more the information content rather than the length of the calibration data which affect model outputs. Often, hydrological modellers select the calibration and validation periods within more or less the same climatic conditions (Bossa, 2012, Cornelissen *et al.*, 2013, Golmohammadi *et al.*, 2014, Hiepe, 2008, Sintondji *et al.*, 2013). This selection poses a problem of transferability given (i) that the sets of parameters found as behavioural during the calibration and validation are used for the prediction over a long period in the future and (ii) the stochastic and non-stationary nature of climate variables (Biao *et al.*, 2015, 2016). Another problem related to the choice of the calibration and validation data is the length of the selected data. In that sense, the current practice seems to be arbitrary (dependent on the data available) with calibration and validation periods ranging from few years as in Giertz *et al. (*2006b) to several decades as in Jiang *et al.*(2007) and Schuol *et al.*(2007). A less uncertainty-prone selection of data could be achieved by selecting the calibration and validation periods within distinct climatic conditions as suggested by Badou *et al.* (2016). Such a selection ensures that the non-stationary and stochastic nature of climate variables is taken into account.

The last but not the least source of uncertainty is the "modeller uncertainty". Various authors (Abbaspour, 2012, Diekkrüger *et al.*, 1995, Holländer *et al.*, 2014) reported that uncertainty might come from the user experience. Whatever the domain, experience is an invaluable resource and hydrological modelling is not an exception. Diekkrüger *et al.*(1995) noted that "the experience of a scientist applying a model is as important as the differences between various model approaches".

As discussed in this section, hydrological modelling is intrinsically uncertainty. The quantification of uncertainties should therefore be part of any hydrological modelling exercise since it shows how trustworthy the outputs are (Juston *et al.*, 2012, Kapangaziwiri *et al.*, 2012). Since hydrological modelling provides key information to water planners and decision makers, uncertainty quantification is of the utmost importance for a region like West Africa which is one of the most vulnerable to climate change hazards (IPCC, 2007b) and possesses very low adaptation capacity. One way of doing so is presented in the following section.

1.3.3 The problem of single and multi-modelling approaches

Hydrological modelling is a powerful tool for developing and supporting adaptation strategies for a sustainable management of water resources. However, in a countless number of studies (e.g. Bormann, 2005, Bossa, 2012, Giertz *et al.*, 2010, Hiepe, 2008, Sintondji *et al.*, 2013), one single model is used to evaluate water availability. Foley (2010) and Jiang *et al.* (2007) criticised this approach pointing out that a single model informs on a model dependent (i.e. "biased") trend and does not assist in identifying general trend. Fortunately, there is growing awareness of the limitation of the use of a single model and hydrological modellers (e.g. Bormann *et al.*, 2009, Breuer *et al.*, 2009, Golmohammadi *et al.*, 2014, Huisman *et al.*, 2009, Jiang *et al.*, 2007, Kebede *et al.*, 2013, Viney *et al.*, 2009) tend to apply two or more models.

The use of more than one model, hereinafter termed multi-model evaluation, offers the chance to encompass a range of possible or probable outputs and thereby enhance the chance to capture the uncertainties that are inherent in a single model approach. The multi-model evaluation takes different forms. In its simplest form, two or more hydrological models are forced by the same input data (e.g. Golmohammadi *et al.*, 2014, Shi *et al.*, 2011). For the prediction of future water resources, the multi-modelling approach thus implies the use of several climate models, downscaling techniques and hydrological models (Foley, 2010).

Another advantage of the multi-model approach is that it offers the possibility of identifying, within a set of candidate models, the most suitable ones for predicting particular basin behaviour. This follows the recommendation of Wagener *et al.* (2004) that models should be used depending on their strength and suitability to simulate particular basin behaviour. Several studies have compared the performance of different hydrological models to identify the most robust. Golmohammadi *et al.*, (2014) applied three physically-based models, the European Hydrological System Model (MIKE-SHE, Refsgaard & Storm, 1995), the Agricultural Policy/Environmental Extender (APEX, Williams, 1995) and the Soil and Water Assessment Tool (SWAT, Arnold *et al.*, 1998) in the Canagagigue basin in Canada and found that the MIKE-SHE model performed the best. Singh et al. (2005) compared the ability of two semi-distributed models, the Hydrological Simulation Program-Fortran (HSPF, Donigian *et al.*, 1983) and SWAT to simulate the runoff regime of the Iroquois River basin in the United States and discovered that the SWAT model surpassed HSPF. Kebede (2013) evaluated the performance of the conceptual model HBV-light (Hydrologiska Byråns Vattenavdelning) (Seibert & Vis, 2012), and the physically-based distributed model WASIM (Water balance Simulation Model) (Schulla, 1997) in simulating daily discharge of the Soro subbasin (Baro-Akobo basin, Ethiopia) and concluded that both models led, according to Moriasi *et al.* (2007), to very good results (Nash-Sutcliffe Efficiency, NSE>0.75 and coefficient of determination, R^2>0.75) but with a little advantage to the HBV-light. Cornelissen *et al.* (2013) found that the UHP-HRU ((Universal Hydrological Program – Hydrological Response Unit) (Giertz *et al.*, 2010), a semi-distributed conceptual model outperformed sophisticated models, the WaSiM and SWAT, and a simple rainfall-runoff model, the GR4J (Perrin, 2000), in simulating the discharge of the Térou, a subbasin of the Ouémé basin in Benin Republic. Bormann and Diekkrüger (2003) reported that due to data availability, the process-based model, TOPLATS (Famiglietti and Wood 1994a, Peters-Lidard *et al.* 1997) was not suitable for the Upper Ouémé basin and that a conceptual model like UHP was better (Bormann and Diekkrüger, 2004).

From these studies on inter-comparison of hydrological models, it appears that the use of more than one model enriches the debate on which hydrological model structure to use (Beven, 1989, Boyle *et al.*, 2006, Butts *et al.*, 2004). This however raises the following question. Are lumped conceptual models because of their parsimony to be preferred over physically-based and data demanding models? As evidenced by the literature cited above, there are no simple answers to this question and one is tempted to cite the Socratic paradox, “I know that I know nothing”.

1.3.4 Selecting the study area

The Niger River Basin is the largest West African and third African basin. It covers a landmass of 2,117,000 km^2 of which 1,500,000 km^2 are active[4] (Andersen *et al.*, 2005). 39,726 km^2 large, the Benin Portion of the Niger River Basin (BPNRB) is an active part of the Niger River, and is mainly located in northern Benin (Figure 2-1). The BPNRB provides a number of ecosystems services whose sustenance requires, at least, but not exclusively, better hydrological knowledge or baseline. The area contains the W-Park which is one of the most important West African wild life parks. This park stretches from Benin to Burkina Faso and Niger with Benin having the biggest part. In addition to the park, the BPNRB contains other protected areas such as the Upper Alibori Forest, the Goungoun Forest, the Sota Forest and Trois Rivières Forest (Orékan, personal communication, Nov. 2013). As a result of a changing climate and a growing population (Vissin, 2007), some of these protected areas are threatened through deforestation either for settlement or agriculture or lumber or charcoal (see Figure 1-2; Orékan, personal communication, Nov. 2013). From an economic point of view, the BPNRB is the largest zone of production of cotton (main cash crop) and vegetables, and the main zone of cattle breeding in Benin (INSAE, 2014). This leads to competition between water users and conflict between breeders and farmers (Lougbegnon *et al.*, 2012, Plagbeto, 2016).

Despite the rich ecosystem, very few hydrological studies have been conducted in the area making the BPNRB an under-studied zone. At a large basin scale, the works of Schuol and Abbaspour (2007), Schuol et *al.* (2007) and the joint report of the NBA and World Bank (2013) are examples of studies undertaken in the Niger River basin. However, these studies were limited to the application of a single model: SWAT in the case of Schuol and Abbaspour (2007) and Schuol et *al.* (2007) and the Modèle hydrologique de la capacité d’infiltration variable (CIV) for the report of the NBA and the World Bank. Such large scale researches often hide site specificities which may be important for the local area.

At the country level, Vissin (2007) reported that hydrological studies are rarely conducted in the area. Vissin (2007) investigated the hydro-climatology of the BPNRB under climate and land use changes for the years 1955-1992. However, the work was more statistical hydrology oriented, looking at breaks in rainfall and streamflow, trends in climate and land use and correlation between the Normalized

[4] Large basins like the Niger have active and inactive parts. The active parts are the parts, actually, contributing to the flow of that basin.

Difference Vegetation Index (NDVI) and streamflow. Though an effort at hydrological modelling was attempted, it was limited to the application of two lumped rainfall-runoff models, the GR4J and GR2M. Both models fail to account for land use properties which are key drivers of the hydrological cycle in the region. Contrary to the BPNRB, the Ouémé basin is intensively studied (e.g. Agbazo *et al.*, 2016, Avahounlin *et al.*, 2013, Biao *et al.*, 2016, Bossa, 2012, Cornelissen *et al.*, 2013, Giertz *et al.*, 2010, Hiepe, 2008, Kamagate *et al.*, 2007, Sintondji *et al.*, 2013, Sintondji, 2005). Given that the Ouémé basin (49,256 km^2) and the BPNRB (39,726 km^2) are the two largest basins in Benin, work on the BPNRB could be a major contribution to bridge the gap between the Ouémé basin for which a lot is known and the BPNRB for which a lot is unknown (Badou, 2013). This would help with having a more comprehensive picture of the hydrology of Benin (beyond the Ouémé basin).

While the BPNRB might be of high scientific interest, the paucity of data may explain the few studies done in the area. Actually, for a landmass of 39,726 km^2, only four streamflow gauges are currently installed and functional (DG-Eau, 2008) and the available streamflow data for two of the four outlets are of medium to poor quality (Badou *et al.* 2016 in press) making the BPNRB a poorly gauged or ungauged basin (Sivapalan *et al.*, 2003). Thus, the scarcity of data over the area seems to have rendered it less scientifically attractive in comparison to the Ouémé basin which is better equipped and monitored (Bossa, 2012, Lawin, 2007).

In conclusion, hydrological studies investigating the effects of climate and land use changes on the water resources of the BPNRB are required. Such studies could be based on a methodology considering the problems discussed in Sections 1.3.1, 1.3.2, and 1.3.3.

Figure 1-2: Illustration of the anthropogenic pressure on protected areas in the study area. The background depicts farms and settlements in the protected forest of Sota. Picture by Djigbo F. Badou (2013)

1.4 Research questions and objectives

1.4.1 Research questions

The previous sections raised a number of research questions which, among others, include:

1. Which hydrological model types can be used for simulating blue and green water in the Benin Portion of the Niger River Basin (BPNRB)?
2. To what extent will climate change impact blue and green water availability in the future in the BPNRB?
3. How large is the uncertainty associated with the impact of climate change on blue and green water availability in the study area?

1.4.2 Objectives of the study

The main aim of this work is to assess the impact of climate change on current and future blue and green water availability in the study area. To achieve this aim the following specific objectives will guide the study:

1. To identify and/or select the most suitable hydrological model/s for the simulation of blue and green water;
2. To downscale regional climate models outputs for modelling blue and green water;
3. To quantify the impact of climate change on blue and green water availability;
4. To quantify the uncertainty associated with the evaluation of availability of blue and green water.

1.5 Clarification of concepts

This section aims at harmonising the comprehension of some of the concepts used in this study.

Adaptation: “in human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate” (IPCC, 2012).

Baseflow: “the portion of streamflow that is not attributed to storm precipitation (i.e. it flows regardless of the daily variation in rainfall)” (Davie, 2008).

Climate change: “a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. This definition differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), where climate change is defined as: a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes" (IPCC, 2012).

Conceptual Model: "a hydrological model defined in the form of mathematical equations; a simplification of a perceptual model. The conceptual model may be more or less complex, ranging from the use of simple mass balance equations for components representing storage in the catchment to coupled nonlinear partial differential equations" (Beven, 2012).

Downscaling: "a method that derives local to regional-scale (up to 100 km) information from larger-scale models or data analyses. Two main methods are distinguished: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models (RCMs), global models with variable spatial resolution, or high resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the downscaled product depends on the quality of the driving model" (IPCC, 2012).

Ecosystem: "a dynamic complex of plant, animal, and microorganism communities and the nonliving environment, interacting as a functional unit. Humans are an integral part of ecosystems" (Alcamo *et al.*, 2003).

Ecosystem services: "the benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services, such as nutrient cycling, that maintain the conditions for life on Earth" (Alcamo *et al.*, 2003).

Hydraulic conductivity: "a measure of the ability of a porous medium to transmit water. This is a flux term with units of metres per second. The hydraulic conductivity of a soil is highly dependent on water content" (Davie, 2008).

Hydrological cycle (**water cycle**): "the circulation of water between the atmosphere, land, and oceans on the earth. Water evaporates from water bodies on earth to form water vapour in the atmosphere. This may condense to form clouds and be returned to the earth's surface as rainfall, hail, snow, etc. Some of this precipitation is returned to the atmosphere directly through evaporation or transpiration by plants; some flows off the land surface as overland flow, eventually to be returned to the oceans via rivers; and some infiltrates the ground to flow underground forming groundwater storage" (Oxford Dictionary, 2005). "The notion of a cycle means that, by definition, there is no beginning or end to the process" (Musy & Higy, 2011).

Hydrology: “the science dealing with all phases of the transport of water among the atmosphere, the land surface and subsurfaces and the oceans” (Pfafflin *et al.*, 2008). It could also be defined as the “branch of science which deals with the occurrence and movement of water and ice on or under the earth’s surface” (Oxford Dictionary, 2005).

Model: “mathematical representation of the essential characteristics of a real-world system or situation, which can be used to predict future behaviour under a variety of different conditions. The process of developing a simulation model involves defining the situation or system to be analyzed, identifying the associated variables, and describing the relationships between them as accurately as possible” (B. Diekkrüger, personal communication, 7 May 2013).

Perceptual model: “a qualitative description of the processes thought to be controlling the hydrological response of an area. It is the summary of our perceptions of how the catchment responds to rainfall under different conditions or, rather, *your* perceptions of that response. A perceptual model is necessarily personal” (Beven, 2012)

Physically-based (distributed) **model:** models whose parameters “a have direct physical interpretation and their range can be established reasonably well on the basis of field and laboratory investigations. It follows that knowledge of parameter values can be directly related to catchment characteristics such as soil type and land use and such knowledge should be transferable, within reason, from area to area” (Beven & O’Connel, 1982).

Runoff: “the movement of liquid water above and below the surface of the earth prior to reaching a stream or river” (Davie, 2008).

Streamflow: “the water flowing within a stream channel (or river flow for a larger body of water). Often referred to as discharge” (Davie, 2008).

Subsurface flow: “takes place in the top, shallow layers of the soil and is characterized mainly by the lateral movement of water following the infiltration process. The essential condition for subsurafce flow is that the lateral hydraulic conductivity of the soil must be clearly greater than the vertical hydraulic conductivity” (Musy & Higy, 2011).

Uncertainty: “an expression of the degree to which a value or relationship is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. Uncertainty may originate from many sources, such as quantifiable errors in the data, ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgment of a team of experts” (IPCC, 2012).

"The uncertainty in hydrological models arises due to the absence of understanding of the complex physical processes of the hydrologic cycle within the system" (Srivastav *et al.*, 2007). See also Section 1.3.2.

1.6 Organization and structure of the thesis

Chapter 1 introduces the work, reviews the literature and concludes with the statement of the problem, the objectives of the study and the clarification of some concepts. Chapter 2 is an overview on the study area. Chapter 3 focuses on the comparison and the selection of the most robust hydrological models for the research. In chapter 4, regional climate models outputs are downscaled at point scale for modelling future blue and green water resources. The fifth chapter deals with the quantitative assessment of climate change impacts on future blue and green water resources and provides the associated uncertainty related to the approaches used. The summary and/or conclusions, outlooks and some recommendations from this study are the focus of the sixth and last chapter.

2 Overview of the study area

On the care for our common home. Our common home is like a sister, with whom we share life, and as a mother, beautiful, welcoming us with open arms.

Pope Francis, 2015

The earth isn't just a planet in the sky ... It's a masterpiece created by the One above ... It's made up of animals, birds and trees and decorated with rivers, oceans and seas. The sight of mountains big and tall and the flowing currents of a waterfall seem to refresh and relax the mind. .. Man is blessed like every other creature to be a part of this God-given nature.

Roger Joseph Lurshay, 2012

2.1 Introduction

This second chapter completes the brief description given in Section 1.3.4 and provides a broader overview of the study area. The main features of the study area in relationship with the hydrological modelling to be undertaken are presented. Hence, step by step, the location, the climate, the vegetation as well as the geology, the pedology, the hydrology, and the population of the study area are described.

2.2 Location

Ninety five percent of the landmass of the study area, the Benin Portion of the Niger River Basin (BPNRB), is located in Benin Republic and the five remaining percent in Burkina Faso and Niger (see Figure 2-1). The BNPRB as defined here is different from the one described in the study of Vissin (2007). In Vissin's PhD dissertation, the BPNRB was defined as the part of the Niger River Basin exactly located in Benin Republic i.e. obtained by clipping the administrative boundaries of Benin and the contour of the Niger River Basin regardless the notion of basin. Since basin is the spatial unit of work of hydrologists, in the present study, the notion of basin was therefore used in defining the study area. This justifies why in the east of the study area (around the commune of Ségbana) some zones of Benin are not included in the study area, while in the northwest (around the W-Park) the study area goes beyond the boundaries of Benin. The name *"BPNRB"* was assigned to the area simply because Benin possesses the largest portion.

The BPNRB is situated between 1°50' and 3°75' W longitude and 10°0' and 12°30' N latitude and has a landmass of approximately 39,726 km^2. The landscape is flat; ranging between 132 and 644 m.a.s.l with some inselbergs in the southwest of the area.

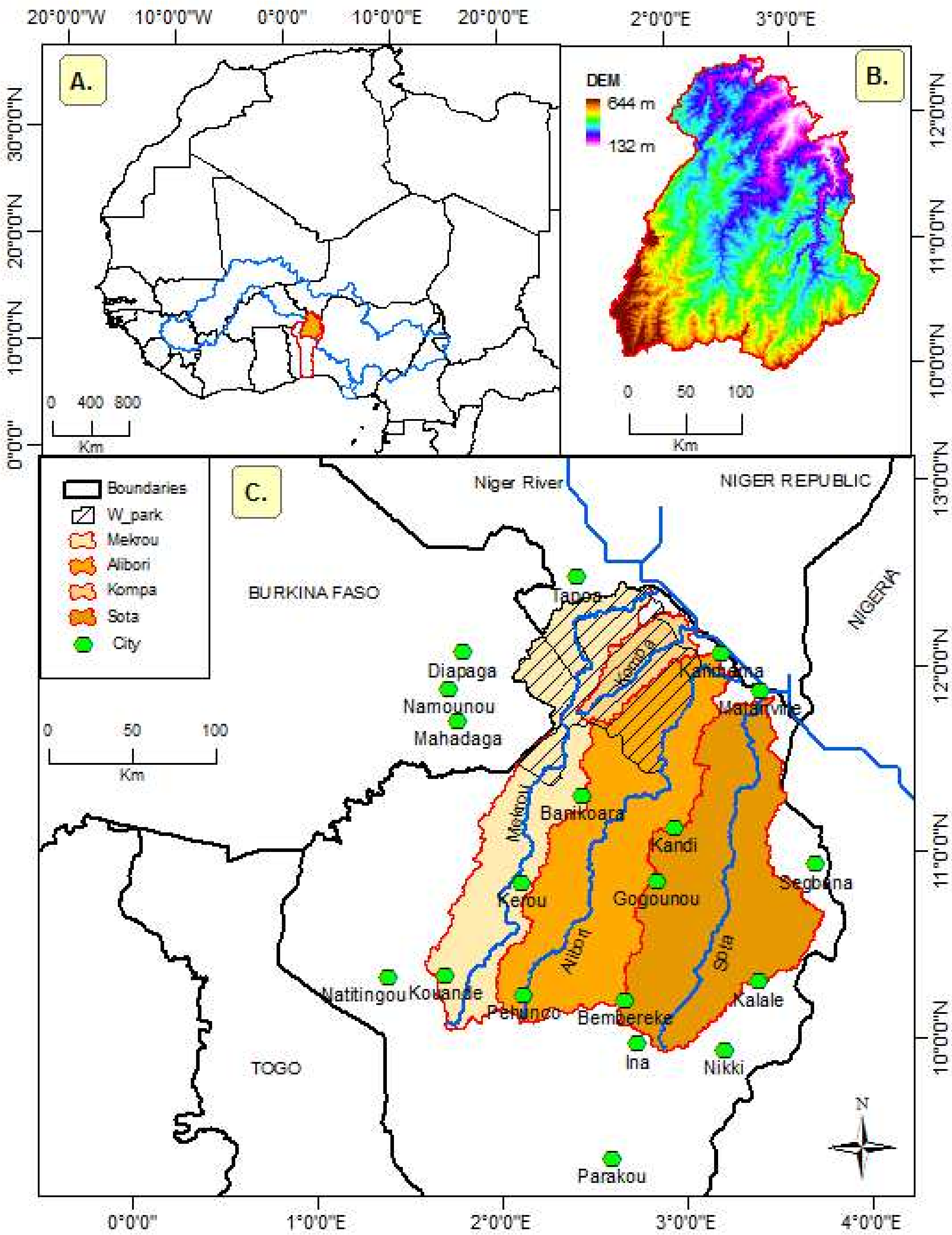


Figure 2-1: A. Location of the study area in Africa and in the Niger River basin, B. Digital Elevation Model and C. overview over the four tributaries along with the surrounding cities.

2.3 Climate

Climate is one of the principal drivers of the hydrological cycle. The mechanisms influencing the climate of West Africa and thereby the climate of the study area have been discussed in previous works (e.g. Vissin, 2007). The atmospheric circulation is controlled by the Azores high, the Saint Helena high and the Egyptian-Libyan anticyclone. Also called anticyclone, a high is a system of winds that spirals out from a centre of high pressure. The Azores anticyclone moves the maritime trade winds (steady wind that blows from east to west and below the equator.) towards West Africa. The St Helena anticyclone governs the West African monsoon. The harmattan (the dry continental trade wind) is caused by the Egypt-Lybian anticyclone. The weather and climate of the study area depend on these highs.

The climate of the BPNRB is Sudanese in the south but of the Sudano-sahelian type in the north. It is characterized by one dry season from November to March and one rainy season which starts in April and ends in October (i.e. a unimodal rainfall regime). The mean minimum and maximum temperatures of the last four decades across the area (1971-2010) were 21.5°C and 34.6°C respectively with March and April being the hottest months. Daily potential evapotranspiration varies in between 1 and 11 mm while maximum daily wind speed reaches 9.5 m s^{-1}. The mean annual rainfall for the same period is about 936 mm.

Three types of rain processes affect the area notably monsoon rains, squall lines, and isolated storms (Vissin, 2007). Monsoon rains occur mainly at night and in the morning (Moron, 1993) during the months of June to August (Afouda, 1990), are due to the northward movement of the Intertropical Convergence Zone (ITCZ), and lead to abundant and continuous rainy events. According to Agli (1995), cited by (Vissin, 2007), squall lines occur with strong wind and gusts of at least 20 knots (a unit of speed equals to 1,852 km h^{-1}), constitute the major rain type in the area (Omotosho, 1984), and take place in May-June, August and September. The isolated storms are due to local convection and accompanied with weaker winds (i.e. less than 20 knots) than in the case of squall lines, and are peculiar to the study area.

Like the whole West African region (Ali & Lebel, 2009, Amogu *et al.*, 2010, Luc Descroix *et al.*, 2015, Oyerindé *et al.*, 2014, Panthou *et al.*, 2014), the BPNRB has experienced severe drought during the 1970s and 1980s. Le Barbé et *al.* (1993) reported that 1950-1970 was a wet period but 1970-1984 a dry one. Likewise, Vissin (2007) remarked that 1955-1972 was humid while 1972-1992 was a dry period. However, in a recent study, Badou *et al.* (2016)[5] indicated that a wetter rainfall regime was noticeable in the area. Badou *et al.* (2016) showed that the shift of rainfall occurred in 1989 in the southern and northern part of the area while it took

[5] In press as: Badou, D. F., Kapangaziwiri, E., Diekkrüger, B., Hounkpè, J. & Afouda, A. A. (2016) Evaluation of recent hydro-climatic changes in four tributaries of the Niger River basin (West Africa). *Hydrological Sciences Journal*. Manuscript accepted for publication.

place around 1993 in the central part and around 2002 in some isolated stations (see Figure 2-2). In Figure 2-2, the red lines indicate the shift from the 1970s drought to a humid period and were determined with the Cross-Entropy method (Priyadarshana & Sofronov, 2014)

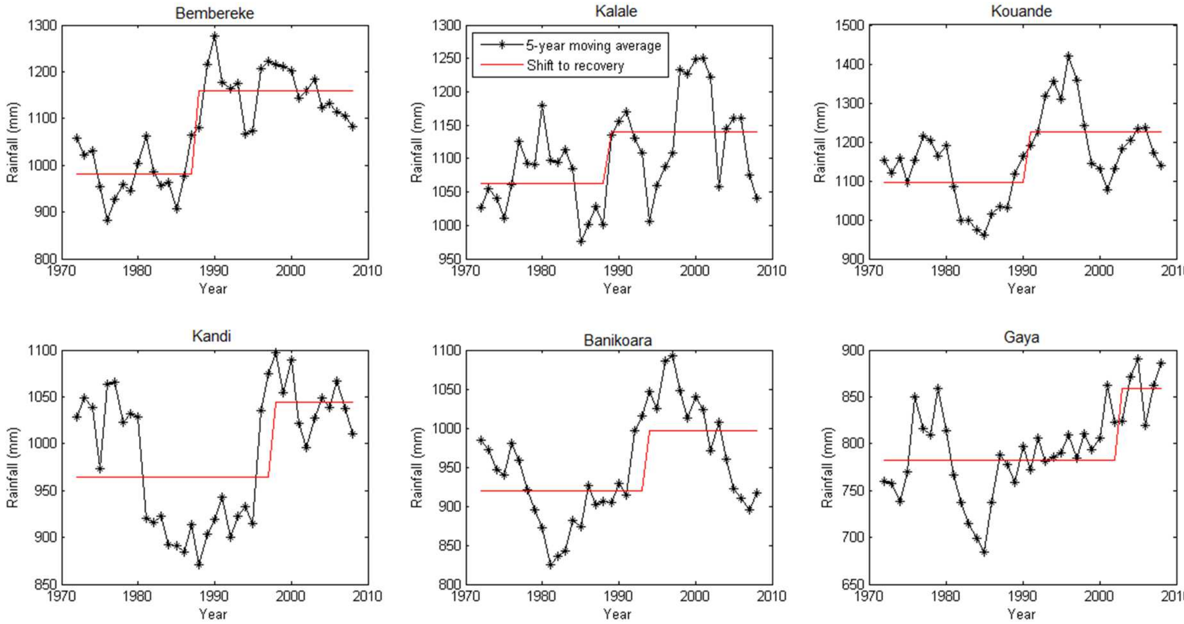


Figure 2-2: Year to year rainfall variability in the study area from 1971 to 2010. Bembèrèkè, Kalalé and Kouandé are located in the south while Kandi, Banikoara and Gaya are located in the north.

2.4 Land use and land cover

Land use/cover is the second major driver of the hydrological cycle (Descroix *et al.*, 2009, Huntington, 2006, Giertz *et al.*, 2005). At the Benin remote sensing centre, CENATEL (CEntre NAtional de TÉlédétection et de suivi écologique du Bénin), there are four land use/cover maps available for the study area. The archives have the maps of 1979, 1992, 1995 and 2006. The map of 1979 was processed using a 1979 aerial photography (1:50,000) of the Kenting Mission. The one of 1992 was established with the Spot images (10m resolution) and the Landsat images (30m resolution) of the year 1992 both at 1:100,000 (Vissin, 2007). The map of 1995 emanated from the Spot and Landsat images of the same year. Likewise, the 2006 land use/cover was obtained using the Landsat images of that very year.

The most recent, the map of 2006 (see Figure 2-3) shows that the main vegetation type is savannah (54.3%), followed by farm and fallow (24.5%), semi-deciduous forest (17.1%), dense and evergreen forest (3.5%) and plantation, settlement and water bodies (0.6%). A comparison of that map of 2006 with the map of 1995 (not shown here), revealed a 9 percent increase of farm (15.4% to 24.5%) to the detriment of the other vegetation types namely 5.7% of deciduous forest (22.8% to 17.1%), 2.1% of dense forest (2.5% to 0.4%) and 1.2% of savannah (55.5% to 54.3%). Badou *et al.* (2016) reported that this is mainly due to an increasing demand for agricultural land as evidenced by an augmentation of the cultivated cotton land from less than 50,000 ha in 1990 to more than 205,000 ha in 2013.

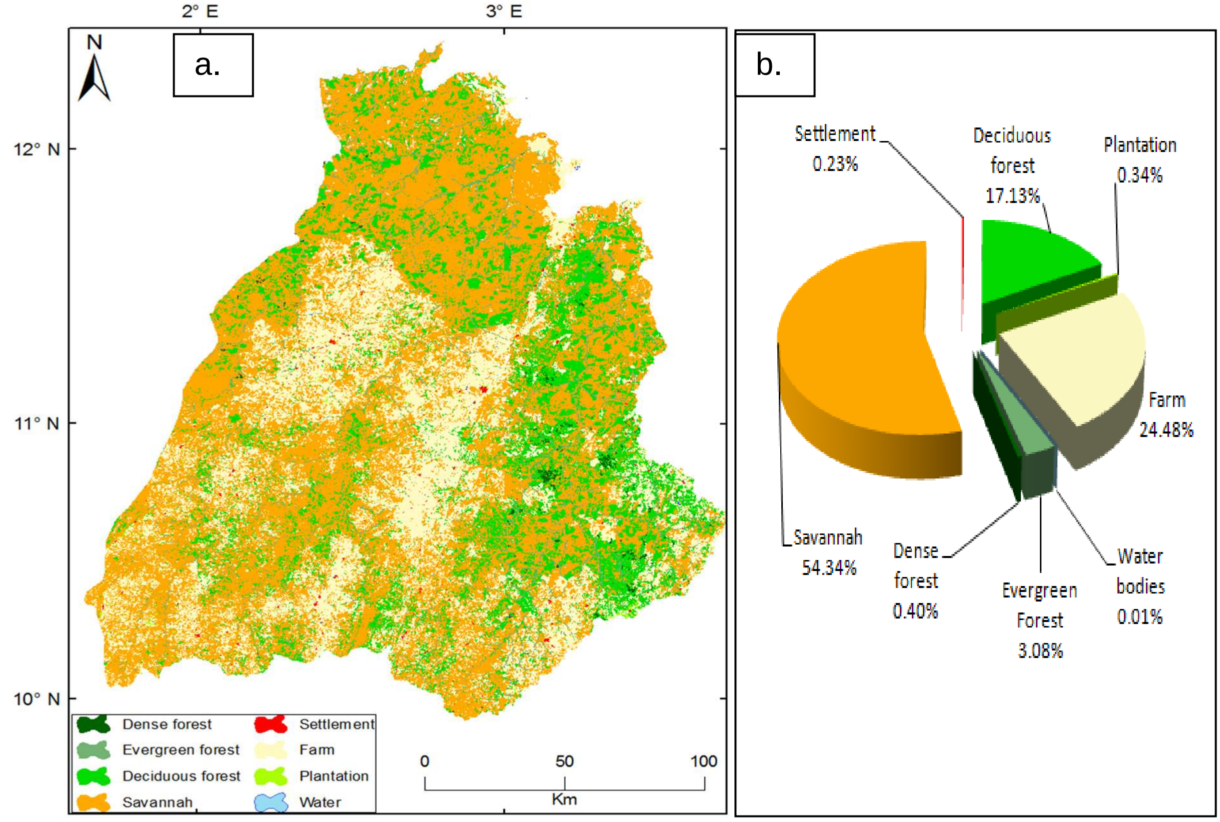


Figure 2-3: Land use map of the year 2006 (a.) and the percentage per land use/cover type (b.). The data are from the Benin Remote Sensing Center, CENATEL (Centre National de Télédetection et de Suivi Ecologique).

2.5 Geology

Benin is covered by 80 % of hard rock (Vouillamoz *et al.*, 2015) so is the study area whose geology is dominated by crystalline rocks. The basement rock covers 86% of the area with gneiss, orthogneiss and granite (Faure and Volkoff, 1998). Only 14% of the BPNRB lies on sedimentary sandstone rock. As shown in Figure 2-4, sandstone is mainly found in the northeast, in the region of Kandi.

2.6 Pedology

Soil is the result of the weathering of rocks under the influence of climate and land cover. It is also the partitioning medium of precipitation into water balance components (infiltration, surface runoff, lateral flow, soil moisture, etc.) and as such is of the uttermost importance in hydrological modelling. The only soil map which covers the study area is the one of the ORSTOM (Office pour la Recherche Scientifique et Technique d'Outre Mer). The map was established during the years

1976-1978 at the scale of 1:200,000 (Dubroeuq, 1976, Viennot, 1978)following the CPCS (Commission de Pédologie et de Cartographie des Sols) classification, a French soil classification system.

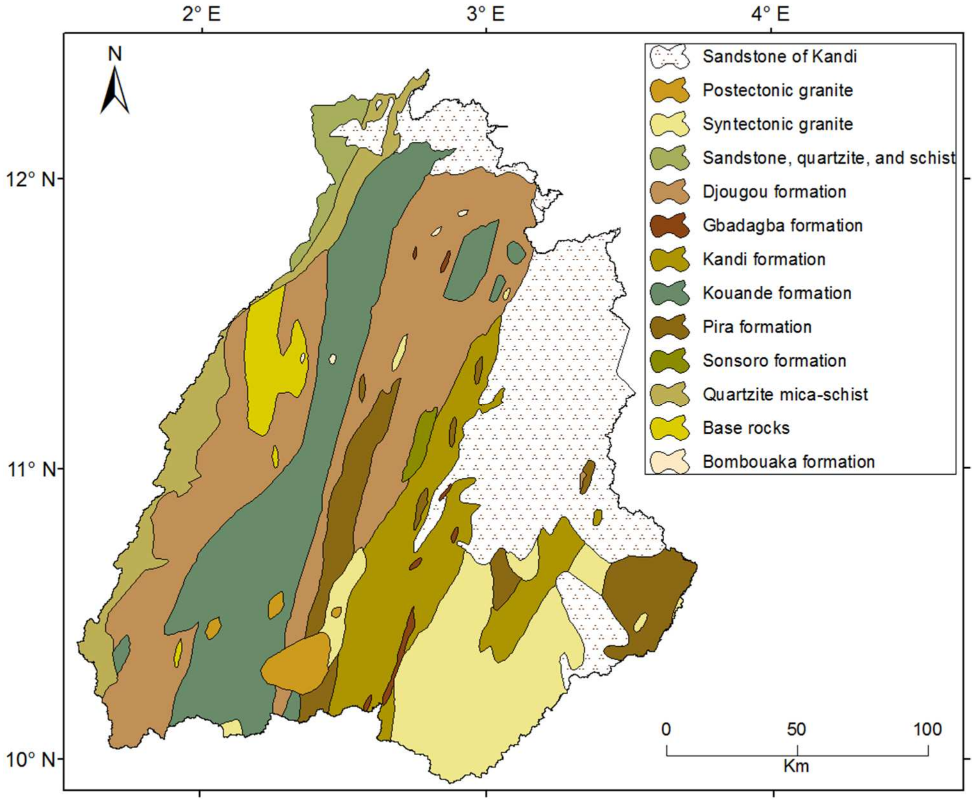


Figure 2-4: Geological units of the study area. The map is from the Beninese Office of Mines, OBEMINES (Office BEninoise des MINES).

The CPCS is a morphological and hierarchical soil classification system highlights soil characteristics, configuration and evolution. The underlying hierarchy of the system follows order class, subclass, group, subgroup, family, series, and phase. Bossa (2012) explicated that "(1) the class takes into account the evolution of the profile (presence of certain layers), the intensity of weathering, the type of humus, and some basic factors like hydromorphy (water), or solonetz (salts); (2) the sub-class is essentially defined by the soil and the climate; (3) the group is defined by morphological characteristics that reflect a specific process; (4) the sub-groups distinguish between the intensity of a group process and the action of a secondary process; and (5) the family takes into account the bedrock". The soil map of Benin is limited to the family and has the advantage to take into account the bedrock. However, Dubroeucq (1977), cited by Bossa (2012), contends that the approach fails to account for differences in topography.

Figure 2-5 shows the different soil units of the study area. The original names of in the CPCS classification system were correlated with the WRB (FAO, 2006). This was done in order to facilitate the comparison with previous studies (e.g. Bossa, 2012, Hiepe, 2008, Junge and Skowronek, 2007). The soil map displays a total of 14 soil types among which four are dominant: Albic Plinthosol (22.66 %), Haplic Lixisol (20.95%), Ferric and Albic Acrisol (20.13%), and Eutric and Chromic Luvisol (15.79%) (see Table 2-1).

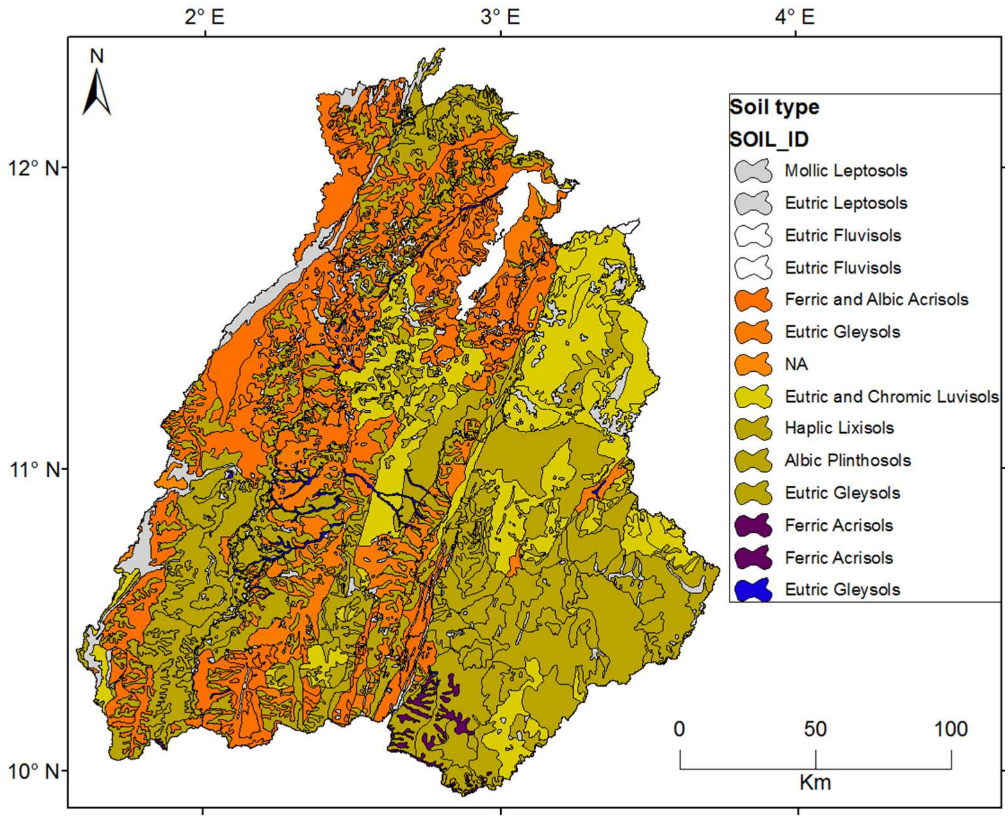


Figure 2-5: ORSTOM Soil map of the study area. NA refers to the unit « sols ferrugineux tropicaux peu lessivés jeunes » for which a corresponding reference was not found in the World Reference Base classification.

Table 2-1: Soil types of the study area and their corresponding extent in percentage. The soil types are ranked in decreasing order of extent. NA means Not Available.

French classification (CPCS)	WRB classification	Percentage (%)
Sols ferrugineux tropicaux lessivés indurés	Albic Plinthosols	22.66
Sols ferrugineux tropicaux lessivés à concrétions	Haplic Lixisols	20.95
Sols ferrugineux tropicaux peu lessivés, peu lessivés en argile, lessivés en sesquioxydes	Ferric and Albic Acrisols	20.13
Sols ferrugineux tropicaux lessivés sans concrétions	Eutric and Chromic Luvisols	15.79
Sols ferrugineux tropicaux peu lessivés hydromorphes	Eutric Gleysols	9.85
Sols minéraux bruts	Mollic Leptosols	3.55
Sols peu évolués lithiques	Eutric Leptosols	2.31

Sols ferrugineux tropicaux lessivés hydromorphes	Eutric Gleysols	1.86
Sols peu évolués hydromorphes	Eutric Fluvisols	1.53
Sols ferralitiques faiblement désaturés rajeunis ou pénévolués avec érosion et remaniement	Ferric Acrisols	0.57
Sols hydromorphes minéraux ou peu humifères à gley de profondeur	Eutric Gleysols	0.56
Sols ferrugineux tropicaux peu lessivés jeunes	NA	0.20
Sols peu évolués modaux	Eutric Fluvisols	0.01
Sols ferrallitiques moyennement désaturés typiques	Ferric Acrisols	0.01

2.7 Hydrology

The study area is made up of four tributaries of the Niger River basin. These are Mékrou (total length of 500km, and basin area of 10,552 km^2), Alibori (427 km, 13,684 km^2), Sota (254 km, 13,449 km^2) and Kompa-Gorou (100km, 2,041 km^2). As depicted in Figure 2-7, the four basins are neighbours; and lumped together forms the BPNRB. Le Barbé *et al.* (1993) gave a general description of the four rivers. The Mékrou has its source in the city of Kouandé at 640 m from the northeast of the hills of Birni on the Atacora chain. The Alibori originates on the eastern side of the Atacora's chain at 410 m in the commune of Péhunco. The Sota River flows from the Kalalé plateau at nearly 400 m. The smallest affluent of the Benin part of Niger River, Kompa-Gorou, not often cited in the literature, has its source at 300 m in the hills on the east of the "gorge de la Mékrou" (Vernet, 1994) in the W-Park. All the four rivers flow from Benin in the south to the Niger River in the north making the BPNRB a transboundary basin.

Vissin (2007) noticed that the basins of Mékrou, Alibori and Sota at the outlet at Gbassè lie on the basement rocks while the basin of Sota at the outlet at Coubéri lies on sandstone (Figure 2-7). As a consequence, the outlet of Coubéri records higher low flow than the other outlets (Figure 2-7). The reason is that a basin flowing hard rock results in more runoff than infiltration. And this, in turn, leads (all else being equal) to a quick response of the basin to precipitation with only little low flow or no flow at all during the recession period.

Figure 2-6 spots the change that has occurred in the streamflow series of the last four decades (1971-2010). The shift from a dry period (1971-1991) to a humid one (1992-2010) is noticeable for all outlets except the one of Malanville where a mixed-trend is observed. At Malanville, the shift to wetter condition can only be observed for the flows of June-October (i.e. contribution from the closest tributaries) but not for the flows of November-March (i.e. contribution from the farthest tributaries located in the western Sahel).

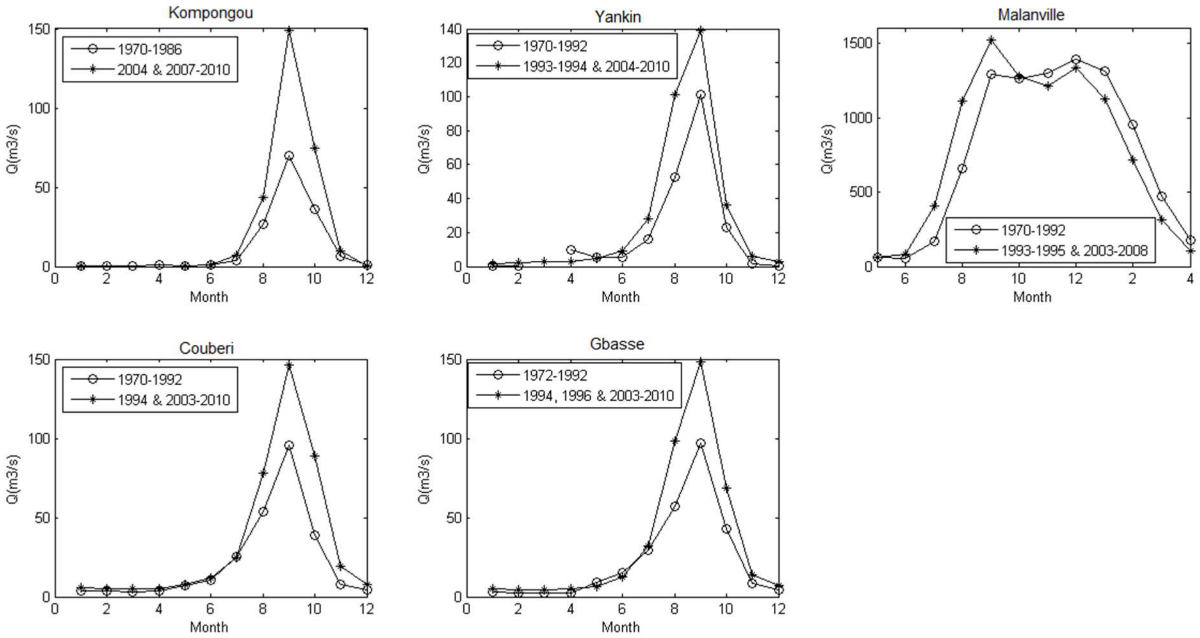


Figure 2-6: Comparison of monthly streamflow of the 2 sub-periods (1970-1992 and 1993-2010) based on the break of 1992 in rainfall data.

2.8 Population and access to water

The latest Benin census took place in 2013 and gave the number of inhabitants at 1,579,006 (INSAE, 2015) in the basin. With an inter-censual growth rate of 3.5%, the population of the BPNRB will triple and even reach more than 5,600,000 by the mid-century.

The majority of this population is rural dependent on subsistence rain-fed agriculture including cultural crops (e.g. yam, maize, sorghum, and millet) and cash crops (e.g. cotton, cashew, groundnut, and vegetable) and animal breeding. Besides, market gardening attracts growing number of farmers especially in the communes of Malanville and Karimama. This activity is primarily for the production of vegetables (e.g. onion, pepper, tomato, and okra) which also takes place during the dry season by utilising water pumped from shallow pits (surface irrigation).
Approximately 78% of the population does not have access to a standpost or a yard tap (PNE, 2009). The main sources of water supply in the BPNRB are shallow wells/pits which, according to the PNE Benin (2009) cannot be sustainable in the long term. Furthermore, some of the water bodies are venerated because they are considered to house certain divinities and genies (Vissin, 2007). As such a year of drought is seen as a curse from the gods while a well-watered year is judged as a blessing. A good knowledge of this sociological aspect is important in assisting local population to adapt to the impacts of climate change on water resources (Oyerindé *et al.*, 2014).

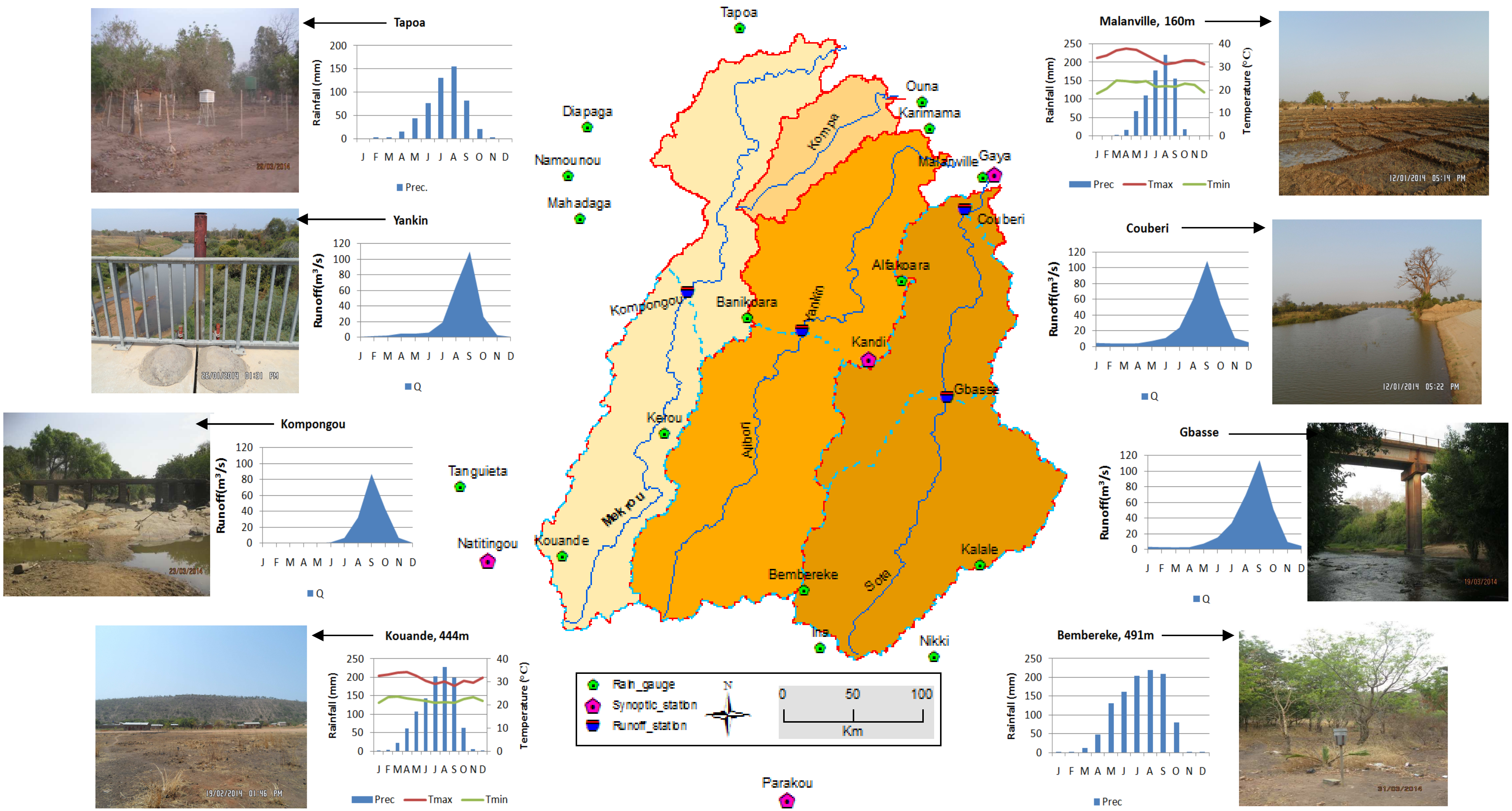


Figure 2-7: Climate and streamflow monitoring networks of the study area.

3 Selection of hydrological models

Essentially, all models are wrong but some are useful.

Box and Draper, 1987

All of these studies concluded that the models' performances are very site specific, and because no one model is superior under all conditions, a complete understanding of comparative model performance requires applications under different hydrologic conditions and watershed scales.

Golmohammadi et *al.*, 2014

3.1 Introduction

Given the plurality of hydrological models, the choice of the models to apply in any given case is a huge undertaking. The main motivation behind the present chapter is that a single model might not be robust enough to simulate all the water balance components and that hydrological models should be used depending on their demonstrated capacity to simulate particular basin behaviour. Consequently, the chapter attempts to answer to the following questions: What are the most robust hydrological models for the simulation of blue water (BW) and green water (GW) in the Benin Portion of the Niger River Basin (BPNRB)?

3.2 Methodology

Wagener *et al.* (2004) recommend that the suitability of hydrological models be investigated prior to their applications. The idea of suitability implies that models should be used depending on their capacity to simulate particular water balance components (e.g. streamflow, soil moisture, actual evapotranspiration, groundwater, and recharge). Actually, a model might be very good in simulating, for example, total runoff but fails in modelling, for instance, surface runoff or baseflow. The comparison of hydrologic models to identify the most robust for the simulation of particular basin behaviour is therefore important. Consequently, the methodology suggested in this chapter relies on a multivariate validation of hydrological models which was done in two stages.

First, hydrological models were "filtered" based on their ability to simulate daily streamflow. This step is hereinafter termed "hydrological simulation of streamflow". The same models were evaluated on their suitability to simulate daily soil moisture dynamic: This second step was entitled "simulating soil moisture". The bivariate validation (discharge and soil moisture), suggested in this study, is supported by the

reflections of Refsgaard and Henriksen (2004) on guidelines and guiding principles of modelling.
The following section describes the hydrological models involved in the study.

3.2.1 Choice of the hydrological models

Hydrological models can be split into two main categories: deterministic models and stochastic ones. “A stochastic model has at least one component of random character which is not explicit in the model input, but only implicit or *hidden*. Therefore, identical inputs will generally result in different outputs if run through the model under, externally seen, identical conditions” (Abbott and Refsgaard, 1996). On the contrary, a deterministic model is “a model where two equal sets of input always yield the same output if run through the model under identical conditions (Abbott and Refsgaard, 1996). The stochastic models category is made up of probabilistic and time series models. As for the deterministic models, the category is made up of physically-based models (white box), conceptual models (grey box) and empirical models (black box) (Loucks *et al.*, 2005). Deterministic models can further be classified with respect to their spatial discretisation as distributed, semi-distributed and lumped models.

Given the plurality of hydrological models, the choice of the ones to apply is not straightforward. In this study, five main reasons guided the choice of models:

(1) the purpose of the modelling (e.g. a model should be able to simulate daily soil moisture),
(2) the data requirements (the models should have moderate data requirements to run),
(3) the structure of the models (distinct structures of models were required (see Section 1.3.3)),
(4) the availability of assistance or expertise to handle the models, and
(5) the access to the software (due to limited budget, free software were preferred to commercial ones provided that the free ones could do the same tasks as the commercial ones).

On the basis of these criteria, four continuous streamflow simulation models were chosen. The models comprise three conceptual, semi-distributed models, the HBV-light (Hydrologiska Byråns Vattenavdelning) (Seibert and Vis, 2012), UHP-HRU (Universal Hydrological Program – Hydrological Response Unit) (Giertz *et al.*, 2010), and SWAT (Soil Water Assessment Tool) (Arnold *et al.*, 1998), and one physically-based distributed model, WaSiM (Water balance Simulation Model) (Schulla, 2012). Table 3-1 summarises the features of the models and Figure 3-1 to Figure 3-4 display their flow charts. These models are briefly described below from the simplest (the HBV-light) to the most sophisticated (WaSiM).

3.2.1.1 The HBV-light

The SMHI (Swedish Meteorological and Hydrological Institute) developed the HBV model in 1972. Since then, the model has undergone continuous development and today, the HBV exists in different versions. HBV-light is one of these versions and was first set up in 1993 at the Uppsala University, Sweden. The version used in this study is an improved version of the HBV-light and was developed at the University of Zurich, Switzerland (Seibert and Vis, 2012). The model is a conceptual, semi-distributed with the possibility to split a basin into sub-basins and to define a maximum of three vegetation zones and 20 elevation zones. The HBV-light has four modules: the snow routine, the soil moisture routine, the response routine and the routing routine (see Figure 3-1).

The snow routine

The first routine deals with precipitation. Depending on the temperature, snow is transformed into snowmelt and added to rainfall. Since, the research is located in West Africa where it does not snow, this module was not used.

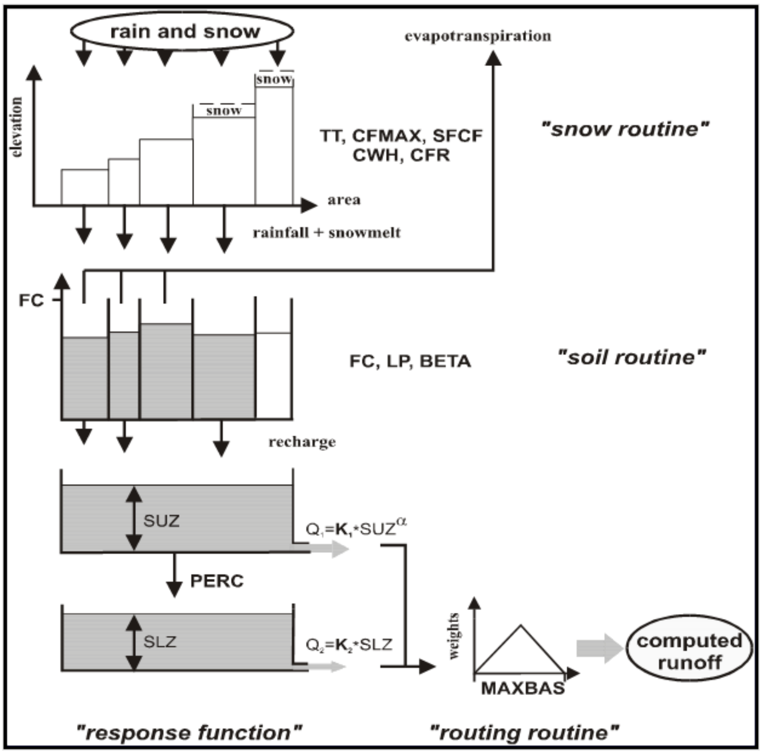


Figure 3-1: Structure of the standard version of the HBV-light model

Soil moisture routine

Within the soil moisture routine, a part of the total input rainfall evaporates and transpires (actual evapotranspiration), another percolates (recharge), and the last portion constitutes the soil moisture. The equations 3-1 and 3-2 indicate how the actual evapotranspiration is computed.

$$ET_{act} = ET_{pot} \cdot min\left(\frac{S_{soil}(t)}{P_{FC} \cdot P_{LP}}, 1\right) \quad \text{(Equation 3-1)}$$

$$\frac{F(t)}{I(t)} = \left(\frac{S_{soil}(t)}{P_{LP}}\right)^{BETA} \quad \text{(Equation 3-2)}$$

in which ET_{act} is the actual evapotranspiration [mm], ET_{pot} the potential evapotranspiration [mm], $S_{soil}(t)$ the water content of the soil at time t [mm], P_{FC} the maximum value of soil moisture storage [mm], P_{LP} the soil moisture value above which ET_{act} reaches ET_{pot} [mm], $I(t)$ the amount of water input to the soil at time t [mm d^{-1}], $F(t)$ the flux to groundwater at time t [mm d^{-1}], and $BETA$ is the dimensionless parameter determining the relative contribution to runoff from rain or snowmelt.

The response and routing routines

The response routine deals with streamflow generation. One can distinguish different configurations. In the standard model version (see Figure 3-1), soil is split into an upper groundwater zone (SUZ) and a lower groundwater zone (SLZ). In the non-standard versions the soil box is represented by one groundwater box, and two or more groundwater boxes. Regardless of the version, the groundwater (Q_{GW}) is computed using the equation 3-3. The routing routine transforms the groundwater (Q_{GW}) into simulated streamflow (Q_{sim}) by using a parameter called $MAXBAS$ (equation 3-4).

$$Q_{GW}(t) = P_{k2} \cdot S_{LZ} + P_{k1} \cdot S_{UZ} + P_{k0} \cdot \max(S_{UZ} - P_{UZL}, 0) \quad \text{(Equation 3-3)}$$

$$Q_{sim}(t) = \sum_{i=1}^{MAXBAS} c(i) \cdot Q_{GW}(t - i + 1)$$

Where $c(i) = \int_{i-1}^{i} \frac{2}{MAXBAS} - \left|u - \frac{MAXBAS}{2}\right| \cdot \frac{4}{MAXBAS^2} du$ (Equation 3-4)

where $Q_{GW}(t)$ is the flow from groundwater boxes [mm], S_{UZ} the recharge added to the upper groundwater box [mm], S_{LZ} the recharge added to the lower groundwater box [mm], P_{UZL} a threshold parameter [mm], P_{k0}, P_{k1}, P_{k2}, the storage (or recession) coefficient [d^{-1}], $Q_{sim}$the simulated streamflow [mm d^{-1}], $MAXBAS$ the parameter defining a triangular weighting function to transform Q_{GW} in Q_{sim} [-].

3.2.1.2 UHP-HRU

UHP (Universal Hydrological Programme), the parent of UHP-HRU, was first developed in 2004 by Bormann and Diekkrüger. UHP was improved to account for the spatial discretization of basins into HRU (Hydrologic Response Units), resulting in the UHP-HRU. The concept of HRU in UHP-HRU is similar to the approach of SWAT and defined in Section 3.2.1.3. The model version with the HRUs was set up by Giertz *et al* (2006). This version, however, lacked the routing module and users had to supply a file indicating the time of transition from sub-basins to gauges. This deficiency was corrected by Giertz *et al.(*2010) who added a routing routine to the model. In this work, the latest version of the model, version 2.6 (see Figure 3-2) was used. This model is a semi-distributed, conceptual model whose peculiarity is that land use (and by extension HRUs) is not constant but can vary on a year to year basis. It is a continuous daily time-step rainfall-runoff simulation model capable of simulating not only the water balance components but also the streamflow components (i.e. surface runoff, interflow and baseflow). UHP-HRU can be used to investigate the dominant hydrological processes within a basin.

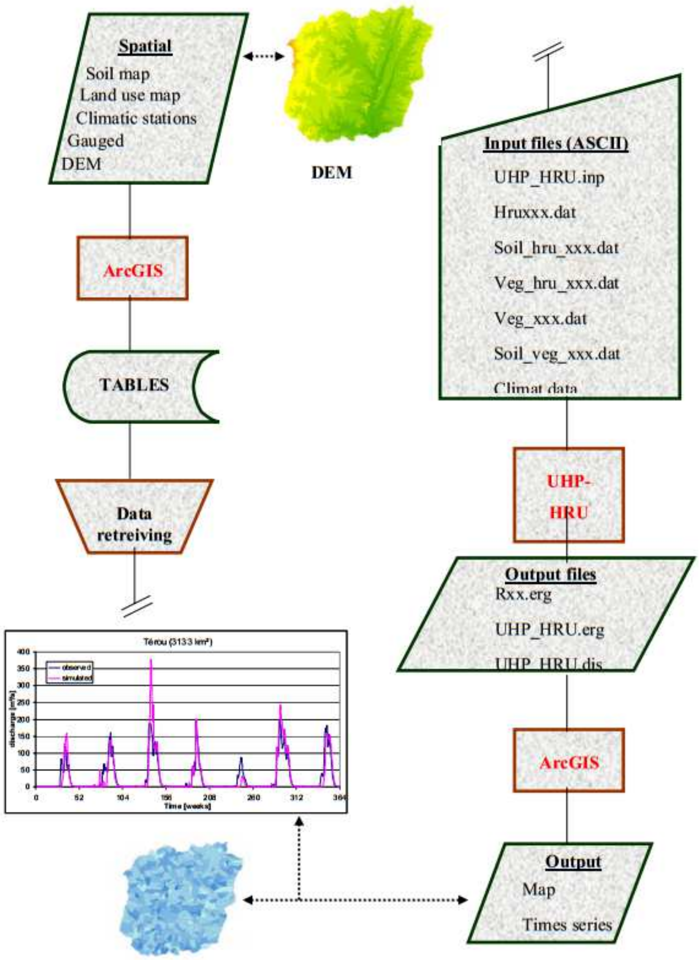


Figure 3-2: Flow chart of the UHP-HRU model

The structure of the model is such that the soil is divided into two zones viz. the root and the unsaturated zones. While the root zone is the layer where roots grow and take up water, the unsaturated zone is the layer between the root zone and groundwater zone. A portion of the rainfall which infiltrates the soil is stored in the root zone. The unsaturated zone is supplied by the water which percolates from the root zone.

The following lines describe the methods and approaches used to compute the different components of the water balance in the UHP-HRU model.

Potential and actual evapotranspiration

Potential evapotranspiration can be calculated with either Priestley-Taylor method (Priestley and Taylor, 1972) or Penman approach (Penman, 1956) or Turc's formula (Turc, 1961). The actual evapotranspiration is a linear function of the potential evapotranspiration and the soil moisture content of the root zone.

Surface runoff

In UHP-HRU, the calculation of surface runoff is based on a modified version of the USDA SCS CN (United States Department of Agriculture, Soil Conservation Service Curve Number) method (Maniak, 2005; Maidment, 1992), namely the CN II. The curve number is a parameter which reflects the capacity of the soil to run off. CN I, CN II and CN III describe the CN of dry, medium and wet soil conditions respectively with the CN I and CN III being calculated internally according to the SCS method.
CN II parameter as computed for UHP-HRU model depends upon soil and land use types. CN II values range between 30 and 100 with lower values indicating low capacity of the soil to generate runoff.

Interflow

Interflow occurs when the water which infiltrates meets a less permeable layer. In the UHP-HRU model, interflow is given by the "ratio between the actual and maximum water storage of the unsaturated zone" (Cornelissen *et al.*, 2013). This maximum water storage corresponds to the field capacity of the soil.

Baseflow

The structure of UHP-HRU is such that the groundwater zone is split into a shallow aquifer and a deep aquifer. Baseflow comes from the shallow aquifer and is computed using a linear storage approach. The deep recharge is stored in the deep aquifer and does not contribute to the flow. The recharge in the shallow aquifer is the result of the percolation from the unsaturated zone minus the sum of the deep aquifer recharge and the capillary rise.

Flow routing

The routing routine allows the inclusion of reservoirs and inland valleys in the modelling. To this end, a file named "reach" and indicating how the river streams are interconnected and how they drain one into the other must be provided by the user.

3.2.1.3 SWAT

SWAT was developed by the USDA Agricultural Research Service (ARS) with the primary objective of assessing the impacts of climate, land use and agricultural practices on water quality, water quantity and sediment yield (Arnold et al., 1998). With more than 35 years of development, SWAT is one of the most widely applied hydrological models (Gassman *et al.*, 2007). The model is a semi-distributed one whose spatial discretization is based on the concept of HRU (Hydrologic Response Unit). Within a sub-basin, an HRU lumps the areas with equal slope (or slope range), soil type and land use type. Unlike the UHP-HRU model for which the HRUs can be variable, they are fixed in the standard SWAT model. To correct this deficiency, the University of Arkansas, USA developed a tool which allows activating land use change in the model version of the year 2009, SWAT2009 (Pai and Saraswat, 2011). In this study, the standard SWAT2009 model was applied. Figure 3-3 shows the flow chart of the model while the sections below detail the methods used for the computation of the water balance components.

Potential and actual evapotranspiration

To compute the potential evapotranspiration, users have the choice between three options: the Penman-Monteith method (Allen *et al.*, 1989, Monteith, 1965), the Priestley-Taylor method (Priestley and Taylor, 1972) and the Hargreaves method (Hargreaves *et al.*, 1985). The method of Penman-Monteith given by equation 3-5 was chosen for this study:

$$\lambda E = \frac{\Delta \cdot (H_{net} - G) + \rho_{air} \cdot c_p \cdot \left| e_z^0 - e_z \right| / r_a}{\Delta + \gamma \cdot (1 + r_c / r_a)} \qquad \text{(Equation3-5)}$$

where λE is the latent heat flux density [MJ m^{-2} d^{-1}], E the depth rate of evaporation [mm d^{-1}], Δ the slope of the saturation vapour pressure-temperature curve [kPa °C^{-1}], H_{net} the net radiation [MJ m^{-2} d^{-1}], G the soil heat flux [MJ m^{-2} d^{-1}], ρ_{air} the air density [kg m^{-3}], c_p the specific heat at constant pressure [MJ kg^{-1} °C^{-1}], e_z^0 the saturation vapour pressure of the air at height z [kPa], e_z the actual water vapour pressure of the air at height z [kPa], γ the psychometric constant [kPa °C^{-1}], r_c the plant canopy resistance (inferred from the leaf area index) [s m^{-1}], and r_a the diffusion resistance of the air layer or aerodynamic resistance [s m^{-1}].

Actual evapotranspiration is the sum of the evaporation of intercepted water from the plant canopy and land surface, and the transpiration through the stomata of plants. While evaporation from the surface depends on the soil depth and the soil moisture content, transpiration is a function of plant transpiration demand and soil moisture content.

Surface runoff

As in UHP-HRU, surface runoff is calculated using the USDA SCS CN (United States Department of Agriculture, Soil Conservation Service Curve Number) approach. In this procedure, surface runoff is a function of the daily rainfall amount and the CN (curve number). CN is computed by combining hydrologic soil groups, land use, management and soil moisture conditions. Basically, they are four hydrologic soil groups, A to D, with A indicating soils having the highest infiltration rate (i.e. smallest runoff capacity) and D exactly the opposite of A. The computation of surface runoff is done via the equation 3-6.

$$Q = \frac{(R-0.2S)^2}{(R+0.8S)} \quad \text{for } R > 0.2S \quad \text{and} \quad Q = 0 \quad \text{for } R \leq 0.2S \qquad \text{(Equation 3-6)}$$

with $S = 25.4\left(\frac{1000}{CN} - 1\right)$

where R is the daily rainfall amount [mm], S a dimensionless retention parameter, and CN is the curve number.

Interflow

Interflow is termed lateral flow in SWAT and depends on many factors such as the saturated hydraulic conductivity, the slope, the drainable porosity, the water content of the saturated hillslope. For its computation, the kinematic storage approach of Sloan and Moore (1984) is used (see equation 3-7).

$$Q = 0.024.\left(\frac{2.SW_{ly,excess}.K_{sat}.slp}{\phi_d.L_{hill}}\right) \qquad \text{(Equation 3-7)}$$

where $SW_{ly,excess}$ is the drainable volume of water stored in the saturated zone of the hillslope per unit area [mm], K_{sat} is the saturated hydraulic conductivity [mm h^{-1}], slp is the increase in elevation per unit distance [-], ϕ_d is the drainable porosity of the soil [mm/mm], L_{hill} is the length of the hillslope [m], and 0.024 is the conversion factor from metres to millimetres and hours to days.

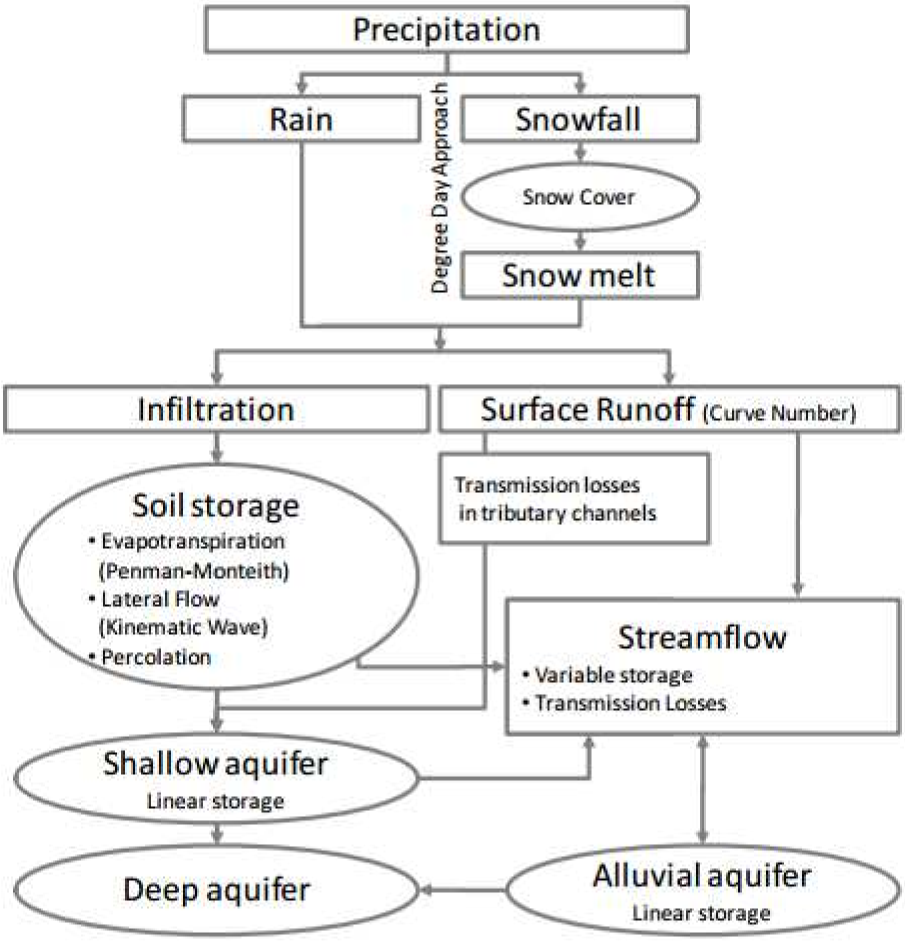


Figure 3-3: Flow chart of the SWAT model after Busche (2012)

Baseflow

In the SWAT model, the groundwater zone is split into a shallow aquifer and a deep aquifer. Baseflow comes from the shallow aquifer and is computed using a linear storage approach. The deep recharge is stored in the deep aquifer and does not contribute to the flow. The recharge in the shallow aquifer is the result of the percolation from the unsaturated zone minus the sum of the deep aquifer recharge and the capillary rise.

Flow Routing

For the flow routing, users have the choice between the variable storage routing approach of Williams (1969) and the Muskingum river routing method (Neitsch *et al.*, 2005). As in the study of Oboubie (2008) for the White Volta River basin, the Muskingum approach was used in this study.

3.2.1.4 WaSiM

WaSiM is a deterministic, physically-based and distributed model developed by (Schulla, 1997) for runoff and water balance simulation. WaSiM is classified as distributed because basins can be split into regular grids of small size (e.g. 100mx100m) and the model can be run for any time step (from few minutes to one day). The model has two main versions which are the version using the Topmodel-approach and the version using the Richards-equation. In this study, the Richards version 9.05.03 (Schulla, 2014) was used.
Figure 3-4 is a flow chart of the model as well as its sub-models and some of the key features of the model are presented below. For more details on the model, readers are kindly directed towards the user manual (Schulla, 2014).

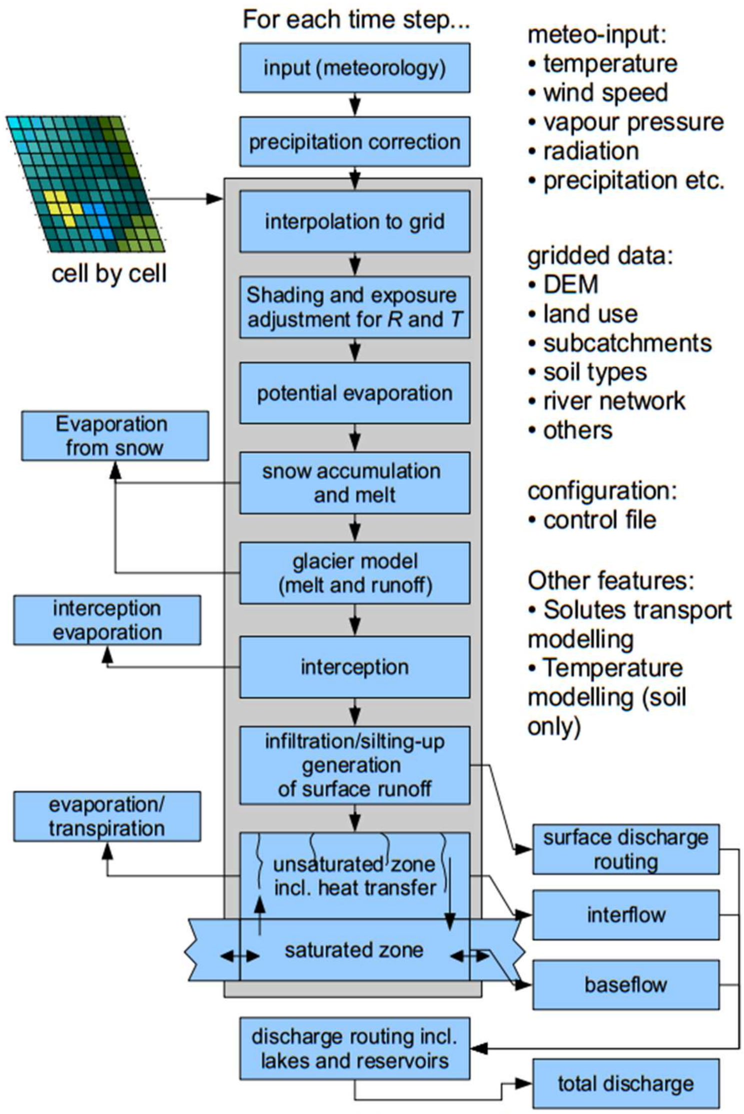


Figure 3-4: Flow chart of the WaSiM model. Blue boxes indicate the sub-models

Potential and actual evapotranspiration

As for the SWAT model, in WaSiM, potential evapotranspiration is calculated using the Penman-Monteith approach (Monteith, 1965) given in equation 3-5. The actual evapotranspiration is the sum of actual transpiration and actual evaporation. The reduction of transpiration is a function of the actual capillary pressure (i.e. suction) and land use parameters. This reduction of potential transpiration also occurs during saturation periods as a result of the soil limitation in oxygen (Feddes *et al.*, 1978). The computation of the actual evaporation (equation 3-8 below) is based on the relationship between the soil moisture content and the actual capillary pressure after van Genutchen (1980).

$$ETact_i = 0 \qquad \theta(\psi) < \theta_{wp}$$

$$ETact_i = ETpot_i \cdot \frac{\left(\theta(\psi_i) - \theta_{wp}\right)}{\left(\theta_{\psi g} - \theta_{wp}\right)} \qquad \theta_{wp} \le \theta(\psi) \le \theta_{wg}$$

(Equation 3-8)

$$ETact_i = ETpot_i \qquad \theta_{\psi_g} \le \eta.\theta_{sat}$$

$$ETact_i = ETpot_i \cdot \frac{\left(\theta_{sat} - \theta(\psi_i)\right)}{\left(\theta_{sat} - \eta.\theta_{sat}\right)} \qquad \eta.\theta_{sat} \le \theta(\psi) \le \theta_{sat}$$

where i is the index of the soil layer, $ETact$ the actual evaporation [mm], $ETpot$ the potential evaporation [mm], $\theta(\psi)$ the actual relative soil moisture content at suction ψ [-], ψ the actual suction (capillary pressure) [m], η the maximum relative water content without partly or total anaerobe conditions ($\approx$ 0.9…0.95), θ_{sat} the saturation water content of the soil [-], θ_{ψ_g} the soil moisture content at a given suction ψ_g, and θ_{wp} the soil moisture content at permanent wilting point (ψ = 1.5 MPa $\approx$150 m).

Surface runoff

Surface runoff occurs either in case of saturation excess or when rainfall intensity is higher than infiltration rate. In WaSiM, infiltration is taken as the upper boundary condition for solving the equation 3-9 below and defined as the minimum of either the fillable porosity of the uppermost numerical soil layer and the precipitation amount per time step (please see the next section for more details).

Interflow

"WaSiM version with physically-based soil module uses the Richards-equation for modelling the fluxes within the unsaturated soil zone. The flux q between two layers with indices u (upper) and l (lower) is then given by:

$$q = k_{eff} \cdot \frac{h_h(\theta_u) - h_h(\theta_l)}{0.5.(d_u + d_l)}$$ (Equation 3-9)

with $\frac{1}{k_{eff}} = \frac{d_u}{d_u + d_l} \cdot \frac{1}{k(\theta_u)} + \frac{d_l}{d_u + d_l} \cdot \frac{1}{k(\theta_l)}$,

$h_h = \psi(\theta) + h_{geo}$, and $\psi(\theta) = \frac{1}{\alpha}\left[\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{-1/m} - 1\right]^{1/n}$

where q is the flux between two discrete layers [m s^{-1}], k_{eff} the effective hydraulic conductivity [m s^{-1}], h_h the hydraulic head, dependent on the water content, ψ the suction [m] after (van Genuchten, 1976), α an empirical parameter [m^{-1}], n an empirical parameter [-], m an empirical parameter [-] with m=1-1/n, Θ actual water content [-], θ_r residual water content at $k(\theta)$ = 0 [-], θ_s saturation water content [-],the h_{geo} geodetic altitude [m] and d thickness of the layers under consideration [m]

For solving equation 3-9, the one dimensional vertical finite difference (FD) scheme is applied. Afterwards, the fluxes between the discrete soil layers are calculated followed by the calculation of interflow, drainage, and ex-filtration into or infiltration from rivers".

Baseflow

WaSiM has a 2D groundwater module which is not available in the three other models. However, when that module is not activated, as it was the case in this study, baseflow is computed following a conceptual approach (see equation 3-11) while the deep aquifer recharge is not even calculated:

$$q_b = Q_0 . k_s . e^{(h_{gw} - h_{geo,0})/k_b}$$ (Equation 3-10)

where which Q_0 is the scaling factor for baseflow [-], k_s the saturated hydraulic conductivity [m s^{-1}], h_{gw} the groundwater table [m], $h_{geo,0}$ the soil surface [m], and k_b the recession constant for baseflow [m].

Flow routing

The flow routing is based on a tree structure till the main outlet of the basin is reached (Leemhuis, 2005). At the sub-basin scale, the flows are routed separately for each tributary, and summed at the outlet. The drainage configuration allows the basic flow network to be modified to incorporate external and internal flows as well as abstractions and reservoirs.

Table 3-1: Features of the hydrological models, modified after Cornelissen *et al.* (2013)

	WaSiM	SWAT2009	UHP-HRU	HBV-light
Interception	Storage approach; function of LAI	Storage approach; function of LAI	Storage approach; function of LAI	Not considered
Potential evapotranspiration	Penman–Monteith (Monteith, 1975)	Priestley- Taylor, Penman–Monteith or Hargreaves	Priestley- Taylor, Penman or Turc	Can be computed with any method
Actuall evapotranspiration	Separate calculation of evaporation from vegetated soils considering all soil layers and from bare soil for the first soil layer; both reduced by soil moisture content of first soil layer	Calculated separately for evaporation (soil depth ,water content) and transpiration(PET, LAI)	Depends on PET and water availability in root storage zone	Estimation depends on soil moisture availability using the relation between soil moisture and field capacity
Soil module	Richards equation	Tipping bucket, soil is divided into root and unsaturated zones	Linear storage, soil is divided into root and unsaturated zone	Storage using power function, soil is made up of root zone
Infiltration	Minimum of the fillable porosity and rainfall intensity	SCS CN procedure (1972)	SCS CN procedure (1972)	Use of power function to derive net precipitation
Overland flow	Horton overland flow	SCS CN procedure (1972)	SCS CN procedure (1972)	Not considered
Percolation	Function based on soil saturation and saturated conductivity	Storage routing; travel time, up and downward flow	Storage routing; soil moisture content must exceed maximum storage capacity	Depends on relation soil moisture and field capacity; power function
Interflow	Storage approach; comparing maximum and actual rate	Kinematic storage model	Linear storage approach	Not considered
Baseflow	Linear storage approach	Linear storage approach	Linear storage approach	Linear outflow equations

Routing	Kinematic wave approach considering retention and translation	Lane's Method, Continuity equation using Manning's equation	Continuity equation using a simplified storage approach	Use of a triangular weighting function
Number of parameters	25	16	17	13
Temporal resolution used in this study	Daily	Daily	Daily	Daily
Spatial resolution	Grid based spatial discretisation	Fixed HRU	Variable HRU	Sub-basin
Input data required	DEM, Land use map and properties, soil map and properties, climate variables (rainfall, temperature, wind speed, humidity, radiation,)	DEM, Land use map and properties, soil map and properties, climate variables (rainfall, temperature, wind speed, humidity, radiation,)	DEM, Land use map and properties, soil map and properties, climate variables (rainfall, temperature, wind speed, humidity, radiation,)	Climate variables (rainfall and temperature), streamflow, potential evapotranspiration and if necessary sub-basin file

3.2.2 Data

If you torture the data long enough it will eventually confess.

Ronald Harry Coase, 1961

A major constraint to effective and sustainable development of water resources in southern Africa is the lack of reliable baseline information.

Kapangaziwiri et *al*., 2012

Applying the methodology presented in section 3.2 requires a lot of data including soil hydrological properties information (texture, bulk density, saturated hydraulic conductivity, organic matter content, water content at pF2.5, and water content at pF4.2) which were not available for the study area. To fill in this gap, a soil survey was conducted and primary data on these soil properties were generated[6]. Secondary data, however, were taken from various sources.

3.2.2.1 Hydroclimatic data

Daily observed rainfall, temperature, sunshine duration, wind speed and relative humidity were collected from the Meteorological Institutes of Benin, Burkina Faso and Niger and daily streamflow data from the DGEau, the Benin Water Directorate. The data cover the period 1971- 2010. As in Rötzer *et al.* (2014), the selected stations were located in and not farther than 50 km from the area with the exception of the synoptic station at Parakou (see Figure 2-1). The station at Parakou was chosen because there was no other closer synoptic station in the southeast of the study area.

A quality control of the raw data was undertaken to check the appropriateness of the data and detect possible gaps that might adversely affect the results. This exercise revealed huge gaps in streamflow time series especially during the 1991-2002 period (Badou *et al.*, 2016 in press). To minimize the impact of missing data on the modelling, the periods of calibration and validation were selected for consecutive years with the minimum missing data out of the period 1991-2002. The calibration and validation periods for the sub-basins are thus sown in Table 3-2 below. For the rainfall data, years having 5-10% of missing data within the rainy season (June-September) were excluded and the missing data of the non-excluded year were in-filled with the Inverse Distance Weighting (IDW) method (equation 3-11). The IDW method was applied to provide homogeneous input rainfall to the models because the SWAT and WaSiM models can internally handle gaps but HBV-light and UHP-HRU cannot do that.

[6] Presented as: Soil hydrological properties of a tropical basin: the case study of the Beninese part of the Niger River basin at the Dresden Nexus conference, Dresden, Germany, 25 to 27 March 2015.

Table 3-2: Selected periods for calibration and validation of the hydrological models.

Sub-basin	Calibration	Validation
Coubéri	1986-1992	2001-2006
Gbassè	1984-1990	2001-2006
Yankin	1982-1988	2003-2008
Kompongou	1977-1984	2005-2010

Actually, the SWAT model has a Weather Generator module to internally fill in gaps. With the WaSiM model, it is possible to use a set of spatial interpolation methods (Inverse Distance Weighting, regression, bilinear, bicubic spline, etc.) to fill gaps in climate variables. Besides, the IDW which is a deterministic spatial interpolation method was preferred to the geo-statistical Kriging method because of the sparse density of the rain gauges of the BPNRB. Li and Heap (2008) reported that the Kriging method is not appropriate when the size of the sample is less than 100 while the IDW method is applicable even with only two stations.

$$\hat{z}(u) = \sum_j \left(w_j . z(u_j)\right) \quad \text{(Equation3-11)}$$

with $w = \frac{1}{d(u,u_j)^p} . \frac{1}{C}$ and $C = \sum_j \frac{1}{d(u,u_j)^p}$ where $\sum_j w_j = 1$

where $\hat{z}(u)$ is the interpolated value at location j, w_j the weight of the observed value at the location j, $z(u_j)$ the observed value at station j, $d(u,u_j)$ the distance to station j, and p the weighting power of the inverse distance (between 1 and 3, here 2 was taken).

Very few gaps were noted in the records of the other climate variables and were filled with the arithmetic mean of the value before and after an identified gap.

3.2.2.2 Digital elevation model

WaSiM, SWAT and UHP-HRU require a DEM (Digital elevation Model) but HBV-light does not. The DEM used in this study was extracted from the ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) which has a horizontal spatial resolution of 30 m. This DEM was used for the delineation of sub-basins and the extraction of topographic parameters such as channel lengths and slopes.

3.2.2.3 Land use

Land use maps were obtained from the Benin remote sensing centre CENATEL (see Section 2.4). The maps of 2006, 1995, 1992 and 1979 were available. However, for consistency with the periods of calibration (Table 3-2), only the 1979 map was used.

Land use properties (i.e. leaf area index, albedo, root depth, interception factor, etc.) were derived from the literature: Cornelissen *et al.(*2013) for the UHP-HRU model and Cornelissen *et al.(*2013) and Kasei (2009) for the WaSiM model. SWAT model derives its own land use parameters from the map provided. HBV-light does not require a land use map.

3.2.2.4 Soil

As discussed in Section 2.6, there is an ORSTOM soil map (Dubroeuq, 1976, Viennot, 1978) that covers the study area. However, soil hydrologic properties (i.e. texture, bulk density, organic matter content, saturated hydraulic conductivity, water content at pF2.5, and water content at pF4.2) required for running UHP-HRU, SWAT and WaSiM were not available. To fill in this gap, a soil survey was conducted from November 2013 to April 2014. Isohyets and the major soil types were used to split, the study area into Pedo-Climatic Zones (PCZ). For a given soil type, a PCZ refers to the portion of that soil type in between two isohyets or between the isohyets and the boundary of the soil map. Within each PCZ, auger surveys were performed along topo-sequences and representative soil profiles were selected as in the works of Hiepe (2008) and Sintondji (2005).

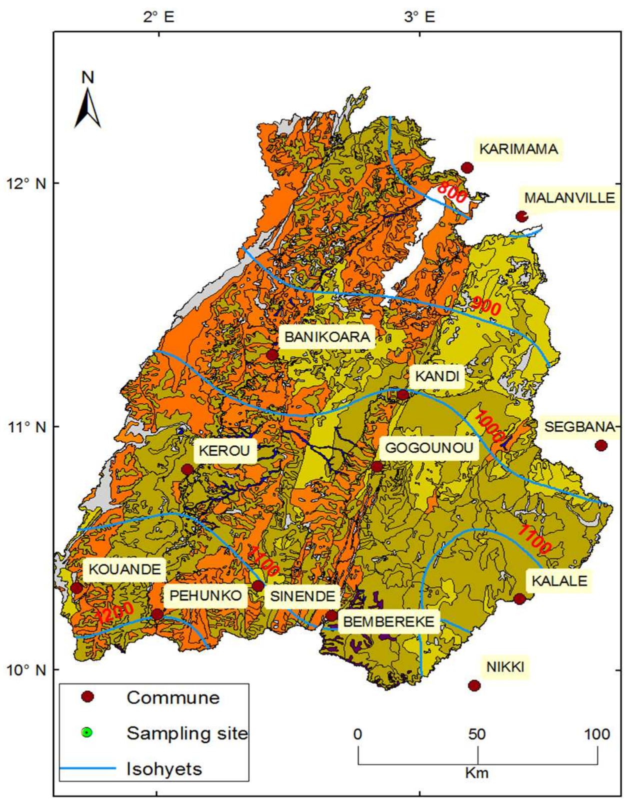


Figure 3-5: Location of the selected sampling sites during the soil survey. Colours represent the different soil types as defined in section 2.6

Since soil types are not evenly distributed and accessible across the study area, it was not possible to have the same number of sites per PCZ. This resulted in a total of 74 sites ranging from 1 to 7 sites per PCZ (see Figure 3-5). From each selected soil profile and depending on its depth, samples (2 for the topsoil and 3 for the subsoil) were taken according to FAO guidelines (FAO, 2006). A total of 304 disturbed samples and 270 undisturbed samples were sent to laboratories for analyses. While a disturbed sample of approximately 500g in weight was packed into a plastic bag, an undisturbed sample was collected in a cylinder of 98.175 cm^3. Table 3-3 summarises the methods used to derive each of the soil hydrological properties. The properties at the site scale were clustered to generate the properties at the basin scale. In Table 3-4 are summarised the statistics of the soil properties for three major soil types.

Table 3-3: Summary of the methods used to derive soil hydrological properties

Soil property	Technique used	Type of sample
Texture	Robinson pipette method(1)	Disturbed
Organic matter content	Gravimetric method(2)	Disturbed
Water content at pF2.5	Pressure plates method(3)	Disturbed
Water content at pF4.2	Pressure plates method	Disturbed
Bulk density	Drying oven method	Undisturbed
Hydraulic conductivity	Laboratory permeameter(4)	Undisturbed

(1):(Kilmer & Alexander, 1949),
(2): http://www.ecs.umass.edu/cee/reckhow/courses/572/572bk15/572BK15.html,
(3): http://www.engr.uconn.edu/environ/envphys/pdf/envMeasurements/Lab_3.pdf
(4):https://www.eijkelkamp.com/files/media/Gebruiksaanwijzingen/EN/m1-0902elab-permeameters.pdf

Table 3-4: Properties of the major soil types of the study area. n is the size, min the minimum, max the maximum, STD the standard deviation, and CV the coefficient of variation. A refers to Ferric and Albic Acrisols (sols ferrugineux tropicaux peu lessivés, peu lessivés en argile, lessivés en sesquioxydes), B to Eutric and Chromic Luvisols (sols ferrugineux tropicaux lessivés sans concrétions), C to Albic Plinthosols (sols ferrugineux tropicaux lessivés indurés), FC to field capacity, PWP to permanent wilting point, and AWC to availale water content.

Soil type	TOPSOIL						SUBSOIL					
	n	min	max	mean	STD	CV	n	min	max	mean	STD	CV
Gravel (%)												
A	15	1.42	28.73	11.11	6.78	0.59	38	0.12	72.60	21.02	17.93	0.83
B	12	1.70	20.64	8.76	6.84	0.77	29	0.18	60.87	15.97	13.46	0.88
C	13	1.26	43.69	15.32	14.58	0.97	25	0.56	54.24	14.62	11.12	0.89
Sand (%)												
A	15	42.37	82.27	63.69	12.30	0.19	38	26.48	81.55	53.55	12.89	0.24
B	12	36.13	79.02	60.47	11.40	0.20	29	21.11	72.77	55.11	11.35	0.23
C	13	24.71	76.53	54.41	17.50	0.32	25	16.60	81.22	54.10	13.52	0.28

Silt (%)											
A	15	12.80	32.50	20.37	5.78	0.28	38	9.70	30.95	18.25	5.34	0.29
B	12	12.15	47.85	24.10	10.03	0.40	29	7.50	38.80	18.24	6.77	0.36
C	13	12.80	41.80	25.20	10.24	0.41	25	4.60	35.40	18.04	4.86	0.28
Clay (%)												
A	15	4.01	41.95	14.92	8.04	0.54	38	6.29	51.25	28.01	10.46	0.38
B	12	8.75	27.25	15.20	5.00	0.31	29	6.05	49.70	26.31	9.87	0.36
C	13	6.39	51.15	19.67	11.11	0.56	25	8.30	59.85	26.86	10.87	0.39
Organic matter (%)												
A	15	0.55	3.22	1.58	1.07	0.67	38	0.21	4.62	1.34	1.04	0.79
B	12	0.40	3.69	1.46	1.26	0.84	29	0.03	3.48	1.02	0.79	0.76
C	13	0.17	6.78	1.77	1.28	0.67	25	0.12	4.64	1.41	1.07	0.70
Bulk density (g/cm3)												
A	15	1.33	1.75	1.56	0.11	0.07	38	1.19	1.85	1.56	0.12	0.08
B	12	1.36	1.80	1.61	0.12	0.07	29	1.22	1.82	1.51	0.14	0.09
C	13	1.30	1.73	1.50	0.13	0.09	25	1.32	1.86	1.54	0.10	0.06
Ksat (mm/hr)												
A	4	38.16	163.08	103.68	58.46	0.56	18	9.32	163.44	80.74	49.98	0.62
B	5	44.64	164.52	127.37	48.03	0.38	15	10.16	137.88	72.12	37.44	0.52
C	6	8.60	166.32	79.73	66.82	0.84	7	6.70	114.48	55.78	42.27	0.76
FC (% vol)												
A	15	13.09	41.19	25.00	7.86	0.33	38	11.28	46.96	27.76	8.81	0.32
B	12	11.83	48.87	25.36	10.18	0.39	29	7.53	42.11	26.33	6.98	0.28
C	13	11.51	41.39	26.83	10.94	0.44	25	7.38	48.43	26.83	9.61	0.39
PWP (% vol)												
A	15	6.94	21.83	13.32	4.19	0.33	38	5.98	24.89	14.84	4.74	0.33
B	12	6.27	25.90	13.53	5.41	0.39	29	3.99	22.32	14.16	3.75	0.28
C	13	6.10	21.94	14.37	5.88	0.44	25	3.91	26.15	14.37	5.18	0.39
AWC (cm/cm)												
A	15	0.06	0.19	0.12	0.04	0.33	38	0.05	0.22	0.13	0.04	0.32
B	12	0.06	0.23	0.12	0.05	0.39	29	0.04	0.20	0.12	0.03	0.28
C	13	0.05	0.19	0.12	0.05	0.44	25	0.03	0.23	0.12	0.04	0.39

3.2.2.5 Soil moisture

As discussed above in Sections 1.3.1 and 3.2, soil moisture was used to evaluate the performance of the hydrological models. From this perspective, remotely-sensed soil moisture data of the ESA CCI (European Space Agency Climate Change Initiative, http://www.esa-cci.org/) was utilised. The data are delivered for the 0.5-2cm uppermost soil layer, have a spatial resolution of 0.25°x 0.25° (about. 27.5km x

27.5km) and cover the period 1978 to 2013. However, only the post-2000 data were of good quality; those of the period 1978-1999 had significant gaps. This constrained the assessment of the models to the post-2000 period i.e. 2003-2010.

Table 3-5 below summarises all the data used in this chapter, their sources as well as how they were used.

Table 3-5: Summary of the data collected and used in this study.

Data	Resolution (scale) / Time period	Relevance	Sources
Climatic	04 synoptic and 12 rainfall stations / 1971-2010*	Temperature, wind speed, relative humidity, rainfall and sunshine duration.	DMN Benin, DMN Niger and DMN Burkina Faso
Topographic	30 x 30 m	Delineation of HRU, extraction of topographic parameters (channel lengths and slopes, sub-basins slopes, etc.)	ASTER GDEM
Land use	1:50,000 / 1979	HRU delineation, root depth, leaf area index, albedo, interception factor, etc.	CENATEL, Cornelissen *et al. (*2013), Kasei (2009)
Soil	1:200,000 / 1978	Texture, bulk density, hydraulic conductivity, soil moisture content, etc.	ORSTOM and soil survey
Streamflow	04 stations / 1971-2010	Assessment of the performance of hydrological models	DGEau
Soil moisture	0.25°x 0.25° / 1978-2013	Assessment of the performance of hydrological models	ESA CCI

N.B: *1. * Three of the rainfall stations have a data range of 1981-2010.*
2. ASTER GDEM stands for Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model, CENATEL for Centre National de Télédétection et de Suivi Ecologique du Bénin, DGEau for Direction Générale de l'Eau, DMN for Direction Météorologique Nationale, ESA CCI for European Space Agency Climate Change Initiative and ORSTOM for Office pour la Recherche Scientifique et Technique d'Outre Mer (Office for Overseas Scientific and Technical Research; now IRD)

The procedure implemented for the identification of the most robust hydrological models for the simulation of streamflow and soil moisture is detailed below.

3.2.3 Hydrological simulation of streamflow

3.2.3.1 Model setting up, calibration and validation

The calibration procedure varied from one model to the other. An automatic calibration was done for HBV-light using the genetic calibration algorithm (GAP) after Press *et al.*(1992) which is incorporated in the model. Though, the standard version of the model has 13 parameters, only 8 were considered for calibration (see Table 3-6) as the other five parameters were irrelevant for the study area. Table 3-6 shows the name and meaning of the parameters used during calibration for all the models.

Table 3-6: The parameters calibrated for the hydrological models used in this study.

Parameter	Description	Range	Unit
	HBV-light		
FC	Maximum of soil moisture (SM) (storage in soil box)	0-∞	mm
LP	Threshold for reduction of evaporation (SM/FC)	0-1	-
BETA	Shape coefficient	0-∞	-
K1	Recession coefficient (upper box)	0-1	d^{-1}
K2	Recession coefficient (lower box)	0-1	d^{-1}
Alpha	non-linearity coefficient	0-∞	-
PERC	Maximal flow from upper to lower box	0- ∞	mm d^{-1}
MAXBAS	Routing, length of weighting function	1-100	D
	UHP-HRU		
-	storage coefficient groundwater	0-1	d^{-1}
-	storage coefficient deep groundwater	0-1	d^{-1}
-	thickness of the unsaturated zone[1]	undefined	mm
-	maximum water holding capacity[1]	0-1	mm/mm
-	initial water content	undefined	mm/mm
-	storage coefficient unsaturated zone	0-1	d^{-1}
-	storage coefficient interflow	0-1	d^{-1}
-	root depth[2]	100-5000	mm
CNII	Curve number II[3]	35-98	-
	SWAT		
SOL_K	Saturated hydraulic conductivity[4]	0-2000	mm h^{-1}
SOL_Z	Soil depth[1]	0-3500	mm
SOL_AWC	Soil available water[4]	0-1	% vol
USLE_K	Soil erodibility factor	0-0.65	-
USLE_P	Practice factor	0-1	-
CNII	SCS runoff curve number	35-98	-
ALPHA_BF	Baseflow recession factor	0-1	d
GW_DELAY	Groundwater delay	0-500	d
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	0-5000	mm
GW_REVAP	Groundwater "revap" coefficient	0.02-0.2	-

REVAPMN	Threshold water level in the shallow aquifer for revap	0-500	mm
RCHRG_DP	Deep aquifer percolation fraction	0-1	-
SURLAG	Surface runoff lag time	0.05-24	-
ESCO	Soil evaporation compensation factor	0-1	-
EPCO	Plant uptake compensation factor	0-1	-
CH_K2	Effective hydraulic conductivity in main channel	0-500	mm h^{-1}
	WaSiM		
Ksat	Saturated hydraulic conductivity[1]	0-1	m s^{-1}
K_{rec}	Ksat recession constant with soil depth[2]	0.01-1	m s^{-1}
Kd	Direct runoff storage coefficient	1-110	-
KI	Interflow coefficient	1-110	-
Dr	Drainage density	10-100	-
K	Baseflow coefficient in the equation $qb = Q_0 * \exp(-k/z)$	0.1-2.5	m
Q0	Baseflow coefficient in the equation $qb = Q_0 * \exp(-k/z)$	0.1-2.5	mm d^{-1}
RSC	Leaf surface resistance[2]	55-110	s m^{-1}
RSE	Soil surface resistance[2]	60-300	s m^{-1}

(1): for each soil type; (2): for each land use type; (3): for each combination of soil and land use type; (4): for each soil type and for each layer

A semi-automatic calibration approach was adopted in the case of the SWAT model using the SWAT-Calibration and Uncertainty Programs (SWAT-CUP) (Abbaspour, 2012). Within SWAT-CUP, parameters sets are generated following the Latin Hypercube sampling method (McKay *et al.*, 1979) and a sensitivity analysis is performed. The Latin hypercube sampling splits the elements of a distribution of parameters into n intervals of equal probability (.i.e. n being the number of samples to generate), and then, from each interval, randomly selects one sample. With this technique none of the intervals is left out. Based on the sensitivity analysis, the user can manually fine-tune certain parameter ranges to get recommended values based on the basin being investigated.

WaSiM and UHP-HRU models were also semi-automatically calibrated. However, since these two models do not possess internal calibration modules, optimization algorithms were developed for each of them and used with Simlab 2.2 software (https://ec.europa.eu/jrc/en/samo/simlab) to generate parameter sets. Additionally, separate programmes were written in MATLAB R2014a for the sensitivity analyses of WaSiM and UHP-HRU models.

While the objective of the calibration of HBV-light was to get the best possible fit between the observed and simulated total runoff, the objective for the other models was the evaluation of both the total basin streamflow and the relative contribution of different streamflow components (i.e. surface runoff, interflow and baseflow) to the total runoff. It was thus important in these other models to identify and discuss the most dominant streamflow components.

To judge the goodness of the fit between the observed and the simulated streamflows, four performance criteria were selected. These are the Nash-Sutcliffe coefficeint of efficiency, NSE (Nash and Sutcliffe, 1970), the coefficient of determination, R^2, the Kling-Gupta efficiency, KGE (Gupta *et al.*, 2009) and the percent bias, PBIAS (Gupta *et al.*, 1999).

Nash-Sutcliffe efficiency (NSE) is a common goodness of fit criterion. Expressed by the equation 3-12, its values range between –∞ and 1 with values closest to one giving the best performances.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \right] \qquad \text{(Equation3-12)}$$

where O_i is the observed streamflow [mm d^{-1}], P_i the simulated streamflow [mm d^{-1}], $\overline{O}$ the mean the observed streamflow [mm d^{-1}], and *n* is the total number of observations.

R^2 (equation 3-13) is also a well-known criterion which describes the linear relationship between simulated and observed variables. R^2 ranges between 0 and 1 with a minimum of 0.5 required to declare the result of a simulation as satisfactory (Van Liew *et al.*, 2003, Santhi *et al.*, 2001). Though widely utilised, a common criticism against this criterion is that a model underestimating or overestimating the observations might yield a R^2 value greater than 0.5 (Bossa, 2012, Legates and McCabe., 1999).

$$R^2 = \left(\frac{\sum_{i=1}^{n} (O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n} (O - \overline{O})^2} \sqrt{\sum_{i=1}^{n} (P_i - \overline{P})^2}} \right)^2 \qquad \text{(Equation 3-13)}$$

where O_i, P_i, $\overline{O}$ and *n* are as defined in equation 3-12, and $\overline{P}$ is the is the mean of simulated streamflow [mm d^{-1}].

Equation 3-14 is used to compute the Kling-Gupta efficiency, KGE. This was developed to overcome some of the shortcomings of the NSE criterion which, among others, is the propensity to underestimate discharge peaks (Gupta *et al.*, 2009). The main advantage of the KGE metric is that it considers model calibration as a multi-objective problem and therefore takes into account the correlation, the flow variability error and the bias error during the optimization (Gupta *et al.*, 2009). KGE values vary on the interval [-∞, 1] with the ideal value being 1.

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \qquad \text{(Equation 3-14)}$$

in which r is the linear correlation coefficient between O and P (O and P are as defined in equation 3-12), α is equal to the standard deviation of P over O and β is equal to $\overline{P}$ over $\overline{O}$ ($\overline{O}$ and $\overline{P}$ are as defined in equation 3-13)

PBIAS (equation 3-15) indicates the average bias between observed and predicted streamflow. Since it is solely based on the difference between observed and simulated time series, the PBIAS is an explicit indicator of model performance. Though, the metric ranges between -∞ and +∞, the desired value is 0 with positive and negative values indicating model underestimation and overestimation respectively. One shortcoming of PBIAS is that the metric is sensitive to the climatic condition in the sense that it varies more during dry years than during wet ones (Gupta *et al.*, 1999).

$$PBIAS = \left[\frac{\sum_{i=1}^{n} (O_i - P_i) * 100}{\sum_{i=1}^{n} O_i} \right] \qquad \text{(Equation 3-15)}$$

Following the recommendations of Moriasi *et al.* (2007) and as a result of the medium to poor quality of the streamflow data (see Section 3.2.2.1), simulations were deemed satisfactory when NSE>=0.5, KGE>=0.5, R^2>=0.5 and absPBIAS<=25% where absPBIAS is the absolute value of the PBIAS metric. A simulation simultaneously meeting these criteria is thus regarded as a behavioural solution.

As discussed in Section 1.3.2 and in order to consider the issue of equifinality, a maximum of five behavioural solutions was retained per hydrological model on the basis of the lowest absPBIAS values whenever one has more than five behavioural solutions. Of the four criteria, absPBIAS (PBIAS) was preferred because it “has the ability to clearly indicate poor model performance” (Gupta *et al.*, 1999).

3.2.3.2 Ranking procedure

To facilitate the ranking of the hydrological models, inspired by the example of Yira *et al.* (2016) where the values of NSE, KGE and R^2 were summed, in this study, the values of these metrics obtained during the calibration and validation were averaged so as to get a new metric termed “NKR” after the initials of NSE, KGE and R^2. Similarly, the absPBIAS values obtained during the calibration and validation were averaged to give a new metric simply named “absPBIAS*” because of a lack of better name.

To choose the most appropriate models, a ranking procedure was undertaken as defined in the following three steps:

(1) A model should meet the criteria discussed earlier for both calibration and validation;
(2) Models fulfilling step 1 were compared on the basis of their NKR;
(3) Whenever two models have equal values of NKR, their absPBIAS* were compared.

3.2.4 Simulating soil moisture

3.2.4.1 Preliminaries and assumptions

This section analysed the ability of the hydrological models to simulate soil moisture. The HBV-light has a simple conceptual soil moisture routine (not physically meaningful) and was therefore not included in the analyses. Remotely-sensed soil moisture (used as observation) is given for the upper 0.5 to 2 cm. For a rigorous comparison, observed and simulated soil moisture should be of the same depth. While the WaSiM has a layered vertical soil moisture distribution that enables the extraction of the soil moisture of the upper 2 cm, the SWAT and the UHP-HRU have different soil moisture distributions. The SWAT model gives soil moisture for the whole soil depth, while the UHP-RU gives it for the root and unsaturated zones. Since the root zone is the uppermost of these two zones, its soil moisture was chosen for the study. Nevertheless, soil and root depths depend on soil and vegetation types. Consequently, to extract the simulated upper 2cm soil moisture, knowledge of the exact values of the soil depth (for SWAT) and the root depth (for UHP-HRU) of each soil type are mandatory. However, obtaining average values of soil depth and root depth is not straightforward because of the high spatial variability of these parameters with respect to soil and vegetation types and because soil depth and root depth parameters were calibrated. Therefore, it was assumed that the major part of the soil moisture simulated by SWAT and UHP-HRU is from the upper 1 m and the soil moisture of the upper 2 cm was estimated based on straightforward proportions. This assumption relies on the soil survey conducted in the study area (see Section 3.2.2.4) which showed that soil depths vary unevenly between 0.5 m and 1.8 m and therefore a mean depth of 1 m seems a reasonable compromise. Yet proportioning the root zone and soil depth soil moisture to the upper 2 cm and comparing them with the observed upper 2 cm soil moisture suggests that the soil moisture is constant throughout the whole root zone and soil depth. Though simple, this is rather an error-prone soil moisture extraction scheme which could be a source of uncertainty.

3.2.4.2 Validation procedure

The models were not re-calibrated with soil moisture data. Rather, the behavioural parameter sets obtained during the calibration/validation with streamflow were used. Here, soil moisture is perceived as a useful supplement to discharge for analysing spatiotemporal patterns of hydrological variables. Re-calibrating the models against soil moisture would have led to new behavioural parameter sets. Hence, for a given model one would have had a group of behavioural parameters for streamflow and another group of behavioural parameters for soil moisture. Not re-calibrating the models therefore ensures that streamflow and soil moisture are compared on the same basis. Our purpose is to check whether a model found suitable (unsuitable) to simulate streamflow is also suitable (unsuitable) to simulate soil moisture.

The assessment of the performance of the models to simulate soil moisture was only done for the validation period (2003-2010) given the gap of missing data in the remotely-sensed soil moisture for the calibration period (1979-1992). The performance of the models was based on visual inspection and the use of the coefficient of determination, R^2 and a measure of bias. Visual inspection helps “judging” whether a model simulates satisfactorily the process of interest. The bias is calculated as given in equation 3-16;

$$bias = \frac{1}{n}\sum_{i=1}^{n}(SM_{rem} - SM_{\mathrm{mod}}) \qquad \text{(Equation 3-16)}$$

where n is the number of pairwise data and SM_{rem} and SM_{mod} are the remotely-sensed and modelled soil moisture.

This bias metric thus varies between $-\infty$ and $+\infty$ with zero being the ideal score, while negative values indicate overestimation and positive values imply underestimation.

The objective of this assessment was to evaluate the ability of the models to reproduce the temporal variations rather than absolute magnitudes (actual values) of soil moisture. The reason is that the remotely-sensed soil moisture (and not actual historical observed *in situ* measurements) used here is given for the uppermost 0.5-2 cm soil layer which makes strict comparison of observed and simulated soil moisture magnitude very difficult. Thus, the R^2criterion was only used for ranking the models.

3.3 Results and discussion

3.3.1 Simulation of streamflow

3.3.1.1 Basin water balance and streamflow components

Table 3-8 shows the water balance, the partition of total runoff as well as the performance of the four models for the four basins. The results are discussed for each basin and compared to neighbouring basins (e.g. Cornelissen *et al.*, 2013, Sintondji *et al.*, 2013, Bossa, 2012, Giertz *et al.*, 2010, Kasei, 2009, Oboubie, 2008) as summarized in Table 3-7.

Table 3-7: Streamflow components of some neighbouring basins used for discussing our results.

Model	Study area	Streamflow components (% of total runoff)			Source
		Surface runoff	Interflow	Baseflow	
UHP-HRU	Térou basin (Benin)	21-26	62-65	12-14	1
	Upper Ouémé basin (Benin)	22-30	60-61	10-18	2
SWAT	Okpara basin (Benin)	39-44	1	55-60	3
	Térou basin (Benin)	43-45	0	55-57	1
	Ouémé basin (Benin)	34-54	0	46-66	4
	White Volta basin (West Africa)	32-35	0	65-67	5
WaSiM	Térou basin (Benin)	50	25-26	24-25	1
	Volta Basin (West Africa)	20-30	60-69	10-12	6

(1): Cornelissen et al., 2013; (2): Giertz et al., 2010; (3): Sintondji et al., 2013; (4): Bossa, 2012; (5): Oboubie, 2008; (6): Kasei, 2009

Coubéri

In the Coubéri basin, all the four models fulfilled the step 1 (see second panel of Table 3-8). HBV-light and WaSiM gave the best score with respect to the NKR criterion but UHP-HRU yielded the best performance when the absPBIAS* metric is considered. This shows the limit of the measures of goodness of fit. Often, when comparing different models with different objective functions, the modeller is confronted to the issue of the decision to make. In this study, a greater weight was given to NKR than absPBIAS*. Hence, in terms of performance, the models were ranked in decreasing order as follows: HBV-light, WaSiM, UHP-HRU and SWAT (see Figure 3-6).

An analysis of the streamflow components (Table 3-8) showed that, for the SWAT and WaSiM models, surface runoff is the most dominant process while for the UHP-

HRU model it is rather baseflow. The results of WaSiM are consistent with those found for the Térou basin (Cornelissen *et al.*, 2013) and the Volta basin (Kasei, 2009). However, the main streamflow process as simulated by the SWAT and UHP-HRU models are different from previous findings. In nearby basins, as shown in Table 3-7, SWAT simulates baseflow as the most dominant process while UHP-HRU simulates interflow as the principal streamflow component. Beyond the comparison with close basins, it is worth noting that distinction between the contributions of interflow and baseflow to the total runoff is not straightforward as there is no clear boundary between the two processes. This might explain the difference between the results presented here.

Gbassè

UHP-HRU and WaSiM did not meet the conditions during the validation (NSE and R^2 were less than 0.5) and were therefore discarded. However, overall, WaSiM could have even been judged better than SWAT since the two models had equal NKR value and WaSiM yielded smaller absPBIAS* (see Table 3-8). As mentioned for the Coubéri basin, this highlights the conflict between different measures of goodness of fit.

HBV-light and SWAT fulfilled step 1 and were thus judged robust with a preference for HBV-light which outperformed SWAT. However, an analysis of Figure 3-7 showed that all the models (even HBV-light) underestimated peaks discharge especially during the validation. This might be due to the fact that the calibration was done during a period of drought while the validation period was chosen within a humid period.

The consideration of the streamflow components revealed that the simulation of interflow and surface runoff as the most dominant processes by WaSiM is in agreement with the results of Kasei (2009) for the Volta basin. Unlike the WaSiM model, the partition of total runoff by the SWAT and UHP-HRU models are not consistent with the results of previous studies (see Table 3-7). While the SWAT model simulates high surface runoff and interflow but little baseflow, it was found for the Okpara basin (Sintondji et *al.*, 2013) and the Ouémé basin (Bossa, 2012) that baseflow and surface runoff are the predominant processes. While the UHP-HRU model simulates high baseflow and surface runoff, Giertz et *al.*(2010) used the same model for the Upper Ouémé basin but found that interflow was the principal streamflow component.

Table 3-8: Catchment water balance along with the corresponding performance. Etpot is the potential evapotranspiration, Etact the actual evapotranspiration

Catchment	**Coubéri**				**Gbassè**				**Yankin**				**Kompongou**			
Hydrological models	**HBV**	**UHP**	**SWAT**	**WaSiM**	**HBV**	**UHP**	**SWAT**	**WaSiM**	**HBV**	**UHP**	**SWAT**	**WaSiM**	**HBV**	**UHP**	**SWAT**	**WaSiM**
Calibration period	**1988-1992**				**1986-1990**				**1984-1988**				**1979-1984**			
Rainfall (mm)	1027	1000	1054	1027	999	979	973	999	979	923	959	980	987	927	981	986
ETpot (mm)	2125	2057	2061	2981	1782	2059	2198	2745	1778	2105	2136	2591	1644	2155	1850	2539
ETact (mm)	952	779	903	938	894	726	862	902	903	758	847	930	959	778	881	949
Measured discharge (mm)	*71*	*71*	*71*	*71*	*91*	*91*	*91*	*91*	*41*	*41*	*41*	*41*	*45*	*45*	*45*	*45*
Simulated discharge (mm)	79	81	82	95	106	96	89	106	65	71	84	60	57	57	51	57
Fraction of surface runoff (%)	-	36	56	48	-	30	56	31	-	37	96	34	-	17	92	35
Fraction of interflow (%	-	26	2	37	-	16	41	59	-	17	4	59	-	23	3	58
Fraction of baseflow (%)	-	39	42	15	-	53	3	10	-	46	0	7	-	60	5	7
Deep aq. rech.(mm)	-	136	11	-	-	158	37	-	-	93	1	-	-	93	21	-
Soil storage (mm)	-5	3	58	-6	-2	0	-16	-9	12	1	27	-11	-29	-1	29	-20
NSE	0.71	0.58	0.53	0.78	0.81	0.66	0.78	0.8	0.74	0.51	0.63	0.65	0.72	0.62	0.65	0.75
KGE	0.78	0.74	0.73	0.79	0.89	0.83	0.86	0.89	0.73	0.66	0.52	0.77	0.65	0.68	0.8	0.73
R^2	0.71	0.6	0.66	0.8	0.82	0.7	0.81	0.83	0.74	0.57	0.77	0.73	0.74	0.72	0.72	0.78
absPbias (%)	0.5	3.9	6.6	17.6	4.9	4.6	6.6	1.8	20.5	23	**41**	9.8	22.3	24.3	6.8	24.8
Validation period	**2003-2006**				**2003-2006**				**2005-2008**				**2007-2010**			
Rainfall (mm)	1059	1043	1094	1059	1102	1110	1094	1102	1063	967	1033	1064	1074	1036	1096	1075
ETpot (mm)	2231	2122	2064	3050	1709	2084	2064	2767	1659	2107	1939	2471	1558	2053	1783	2355
ETact (mm)	1001	818	1002	981	955	777	952	985	958	789	928	996	980	785	888	973
Measured discharge (mm)	*76*	*76*	*76*	*76*	*145*	*145*	*145*	*145*	*101*	*101*	*101*	*101*	*141*	*141*	*141*	*141*
Simulated discharge (mm)	84	77	68	88	138	120	104	126	91	76	81	92	89	96	92	102
Fraction of surface runoff (%)	-	28	56	41	-	21	56	29	-	27	94	28	-	14	90	43
Fraction of interflow (%	-	29	3	43	-	19	41	64	-	19	4	61	-	24	4	50
Fraction of baseflow (%)	-	43	41	16	-	60	4	7	-	53	2	11	-	62	6	6
Deep aq. rech.(mm)	-	145	12	-	-	214	53	-	-	100	2	-	-	155	33	-
Soil storage (mm)	-26	3	13	-10	9	1	-14	-10	14	3	22	-25	6	1	82	0
NSE	0.71	0.63	0.54	0.53	0.6	**0.41**	0.5	**0.48**	0.6	0.66	0.57	0.69	**0.43**	**0.42**	**0.37**	**0.42**
KGE	0.82	0.78	0.72	0.72	0.71	0.57	0.59	0.6	0.69	0.59	0.63	0.81	**0.27**	**0.41**	**0.37**	**0.43**
R^2	0.76	0.64	0.64	0.64	0.6	**0.43**	0.51	**0.49**	0.6	0.68	0.59	0.71	0.58	**0.45**	**0.41**	**0.45**
absPbias (%)	9.9	4.1	14	15.7	2.5	14.3	9.7	11	10.1	25.2	22.9	8.8	**41.9**	**34.6**	**39.1**	**31.1**
NKR[a]	0.75	0.66	0.64	0.71	0.74	0.6	0.68	0.68	0.68	0.61	0.62	0.73	0.7	0.67	0.72	0.75
absPBIAS*[a] (%)	5.2	4	10.3	16.65	3.7	9.45	8.15	6.4	15.3	24.1	**31.95**	9.3	22.3	24.3	6.8	24.8

[a]: *average of the calibration and validation except for Kompongou for which values are given for the calibration period alone (sex text for more detail).*

Figures in bold: the corresponding performance criterion is not met

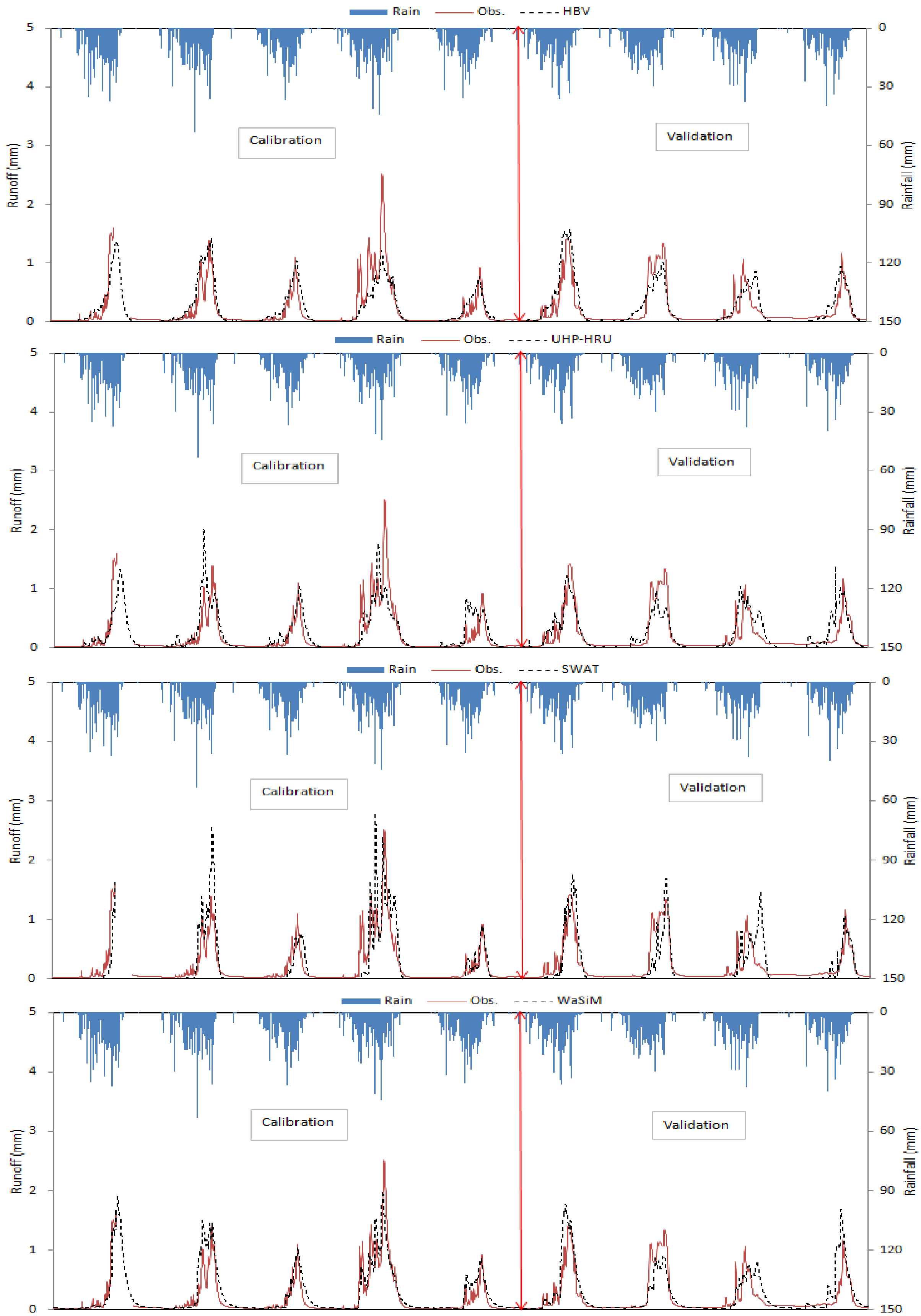


Figure 3-6: Observed and simulated daily streamflow using HBV-light, UHP-HRU, SWAT and WaSiM during the calibration period (1988-1992) and the validation period (2003-2006) for the Coubéri basin. The red arrow divides the calibration from the validation periods.

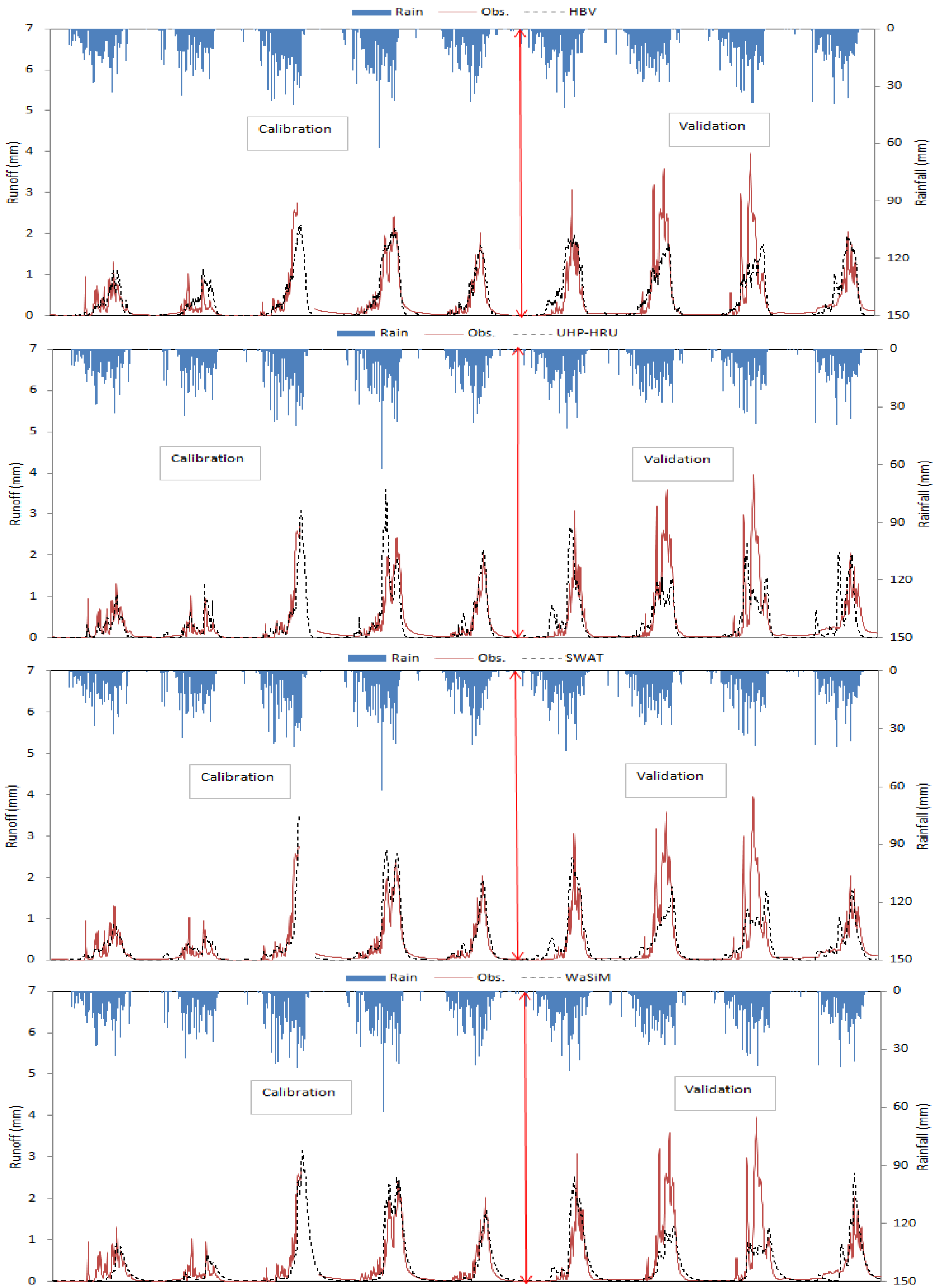


Figure 3-7: Observed and simulated daily average streamflow using HBV-light, UHP-HRU, SWAT and WaSiM during the calibration period (1986-1990) and the validation period (2003-2006) for the Gbassè basin. The red arrow divides the calibration from the validation periods.

Yankin

SWAT was excluded because its absPBIAS metric during calibration (41%) was too high. This is due to the fact that the model simulated very high surface runoff but nearly no baseflow (see fourth panel in Table 3-8). In terms of NKR and absPBIAS*, WaSiM outperformed the other models followed by HBV-light and UHP-HRU. Figure 3-8 shows that WaSiM yielded a better fit with the observed streamflow than the other models. Notwithstanding, an analysis of the streamflow components showed that, during the calibration, WaSiM simulates little baseflow (7%) when compared to earlier studies (see Table 3-7). As for UHP-HRU, it was noted an overestimation of baseflow (46%) when one considers the maximum of 18% obtained by Giertz *et al.* (2010) for the upper Ouémé basin of Benin.

Kompongou

For Kompongou, only the results of the calibration were used because none of the models met the performance criteria during the validation (see Figure 3-9). Three main reasons might explain such result. The first is the poor quality of the data. Kompongou is a station with 49% of missing streamflow data (Badou *et al.* 2016 in press). The second reason is the information content of the streamflow data. Actually, the mean streamflow of the validation period (141 mm) is three times greater than its counterpart of the calibration period (45 mm) for a difference of less than 100 mm between the mean rainfall of the calibration (986 mm) and that of the validation (1075 mm) periods (see Table 3-8). The third reason might be the rather long time between the calibration and validation periods. While the calibration period is 1979-1984, the validation period is 2007-2010 viz. a difference of more than 26 years between the two periods. With such a time difference, many changes that occurred in the basin are difficult to model when the parameters obtained during the calibration remain constant for the validation. As discussed in section 1.3.2, hydrologists often select the calibration and validation periods within more or less the same climatic conditions (Golmohammadi et *al.*, 2014; Cornelissen et *al.*, 2013; Sintondji et *al.*, 2013; Bossa, 2012; Hiepe, 2008). This selection poses a problem of transferability given (i) that the sets of parameters found as behavioural during the calibration and validation are used for the prediction over a long period in the future and (ii) the stochastic and non-stationary nature of climate variables. In the present study, the choice of the calibration and validation periods was governed by two conditions: the quality of the available data and the need to account for the stochastic and non-stationary behaviour of hydroclimatic variables which was implemented by the selection of the calibration and validation periods in opposite climatic conditions (drought versus humid period).

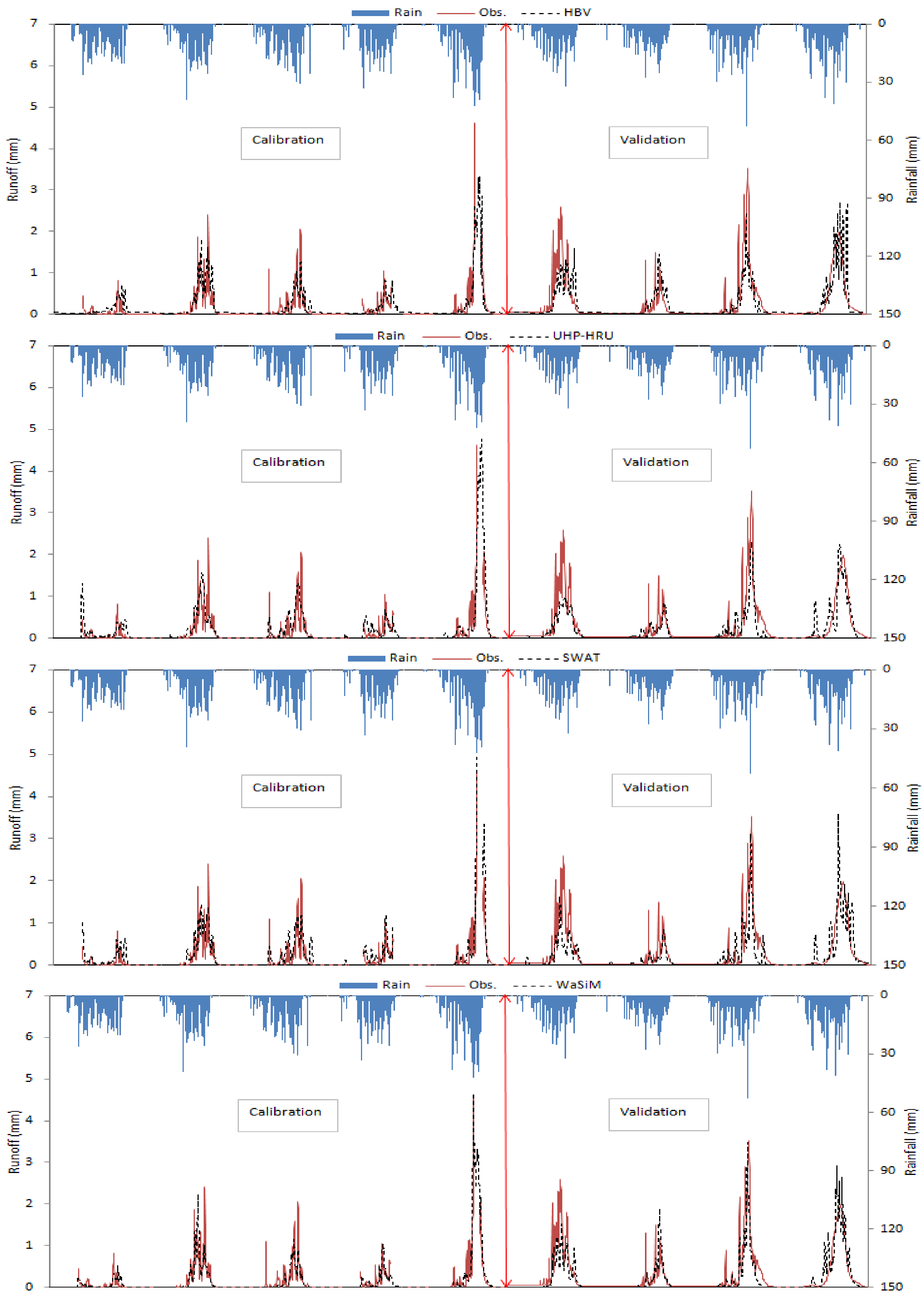


Figure 3-8: Observed and simulated daily average streamflow using HBV-light, UHP-HRU, SWAT and WaSiM during the calibration period (1984-1988) and the validation period (2005-2008) for the Yankin basin. The red arrow divides the calibration from the validation periods.

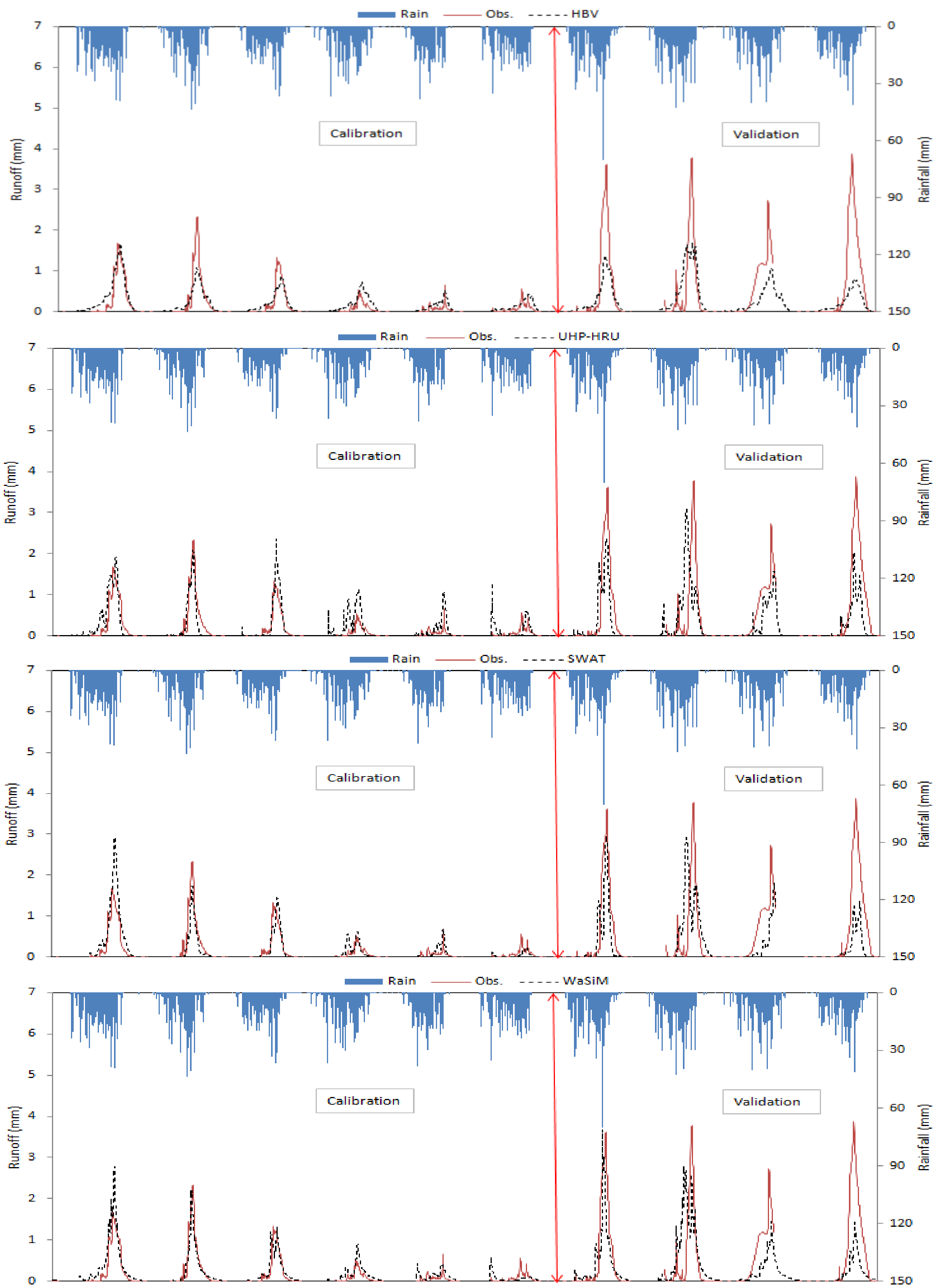


Figure 3-9: Observed and simulated daily average streamflow using HBV-light, UHP-HRU, SWAT and WaSiM during the calibration period (1979-1984) and the validation period (2007-2010) for the Kompongou basin. The red arrow divides the calibration from the validation periods.

The NKR metric shows that WaSiM was the best model followed by SWAT, HBV-light and then UHP-HRU. This ranking would have not been valid if the absPBIAS* was considered as the main ranking criterion as WaSiM performed the worst and SWAT the best. Here again, one can see that the decision of which model is the best highly depends on the performance criterion used and somehow subjective. Nevertheless, the analysis of the streamflow component supports the ranking done using the NKR measure. As a matter of fact, WaSiM only slightly underestimated baseflow but simulated acceptably direct runoff and interflow. On the contrary, SWAT simulated little baseflow (5% instead of a minimum of 46% as indicated in Table 3-7) while UHP-HRU simulated high baseflow.

The WaSiM model simulates interflow and surface runoff as the main streamflow components. For the SWAT and UHP-HRU models, it is rather surface runoff and baseflow and interflow which are the most dominant components. The results of the WaSiM model are similar to those obtained by the same model for the Térou basin (Cornelissen *et al.*, 2013) where surface runoff and interflow were found to be the principal streamflow components. As mentioned above, in the case of the SWAT model, baseflow and surface runoff were identified as the principal streamflow components in the nearby basins (Table 3-7) which differ from our findings. Similarly, the simulation of interflow and surface runoff as the major streamflow components by the UHP-HRU model for the Térou basin (Cornelissen *et al.*, 2013) and the Upper Ouémé basin (Giertz *et al.*, 2010) are inconsistent with the results presented here.

3.3.1.2 Bivariate analysis

In this section, streamflow was correlated among the models to check for systematic deviation. The idea was to detect which models overestimate/underestimate or had higher variability. To this end, for each basin, the model which performed the best was plotted against the three others and not against measured streamflow. Hence, for the Coubéri and Gbassè basins, streamflow simulated by UHP-HRU, SWAT and WaSiM were plotted against streamflow simulated by the HBV-light. For the Yankin and Kompongou basins, the streamflow simulated by HBV-light, UHP-HRU and SWAT was plotted against the streamflow simulated by WaSiM. The resultant figures (Figure 3-10 and Figure 3-11) were analysed by visual inspection (qualitative measure) and the use of the coefficient of determination, R^2, (quantitative measure).

Qualitative measure: Visual inspection

In the Coubéri basin, during the calibration, WaSiM captured well the streamflow simulated by HBV-light but SWAT overestimated it. During validation, while UHP-HRU fitted well, SWAT showed higher variability.

In the Gbassè basin, for the calibration, SWAT and WaSiM captured reasonably well the streamflow simulated by HBV-light but UHP-HRU showed high variability. During validation, WaSiM fitted well low-flow and mean flows but overestimated high discharge.

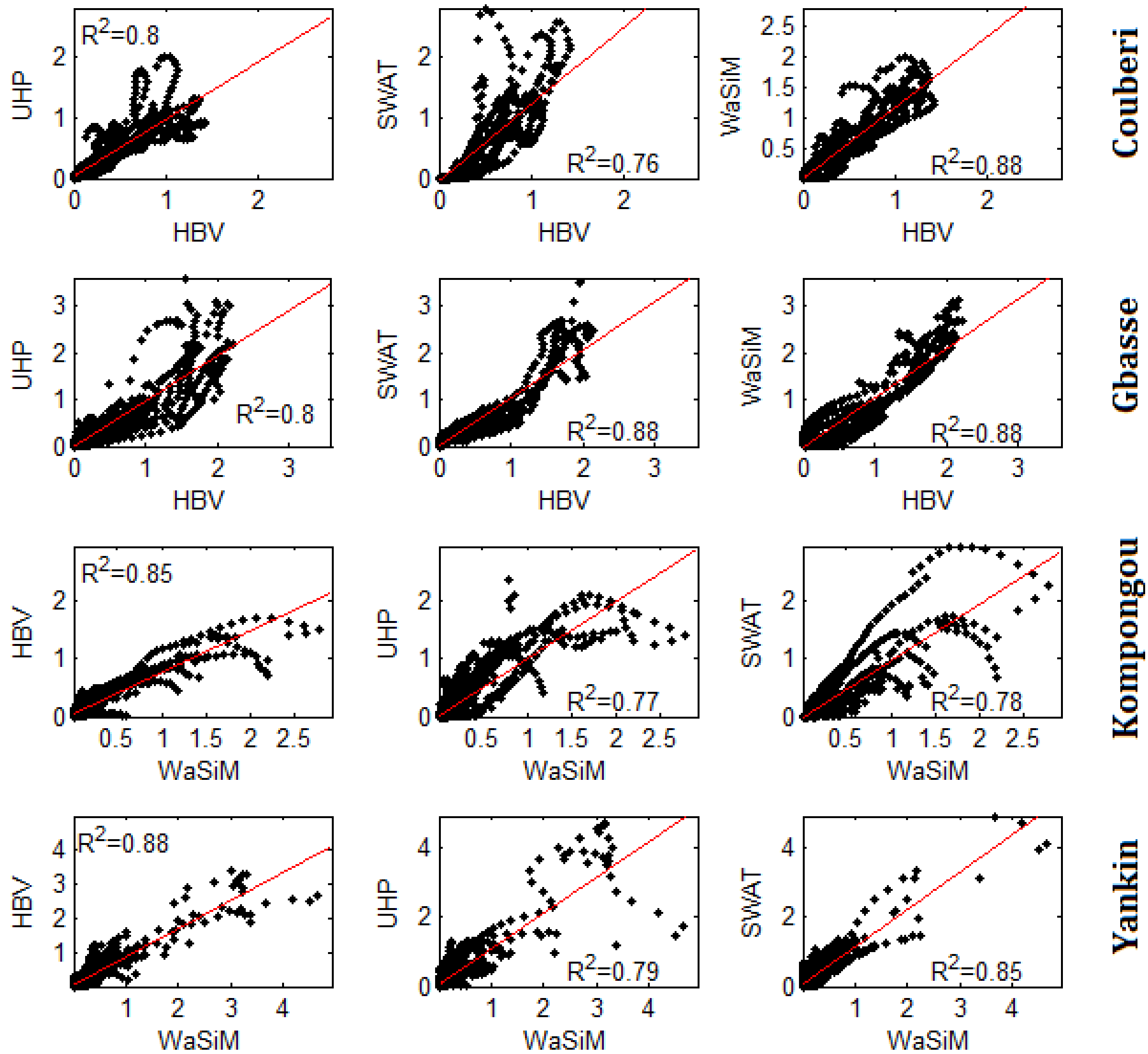


Figure 3-10: Bivariate analysis of the model simulations during the calibration period for the Coubéri, Gbassè, Kompongou and Yankin basins.

During the calibration in the Yankin basin, HBV-light yielded a very good fit. SWAT too but at a lesser extent. UHP-HRU underestimated high flows. The same pattern was observed for the HBV-light during the validation but SWAT overestimated the flows.

In the Kompongou basin, it was noticed that HBV-light captures very well the flow simulated by WaSiM during calibration but that SWAT overestimated it. However, during the validation, high flow was underestimated by all the three models, the HBV-light, SWAT and UHP-HRU.

Quantitative measure: R^2

The ranking of the models with respect to observed streamflow was conserved when the streamflow of the models are correlated with the streamflow of the model having the best performance in the Coubéri and Gbassè basins. For the Kompongou basin, SWAT had a better score than HBV-light when the comparison is done with observed streamflow but HBV-light had a higher score when the discharge of both models are compared with the discharge of WaSiM. Likewise, for the Yankin basin, UHP-HRU outperformed SWAT for the comparison with observed streamflow but the opposite was true when the simulated discharge from both was compared with simulated discharge of the WaSiM model.

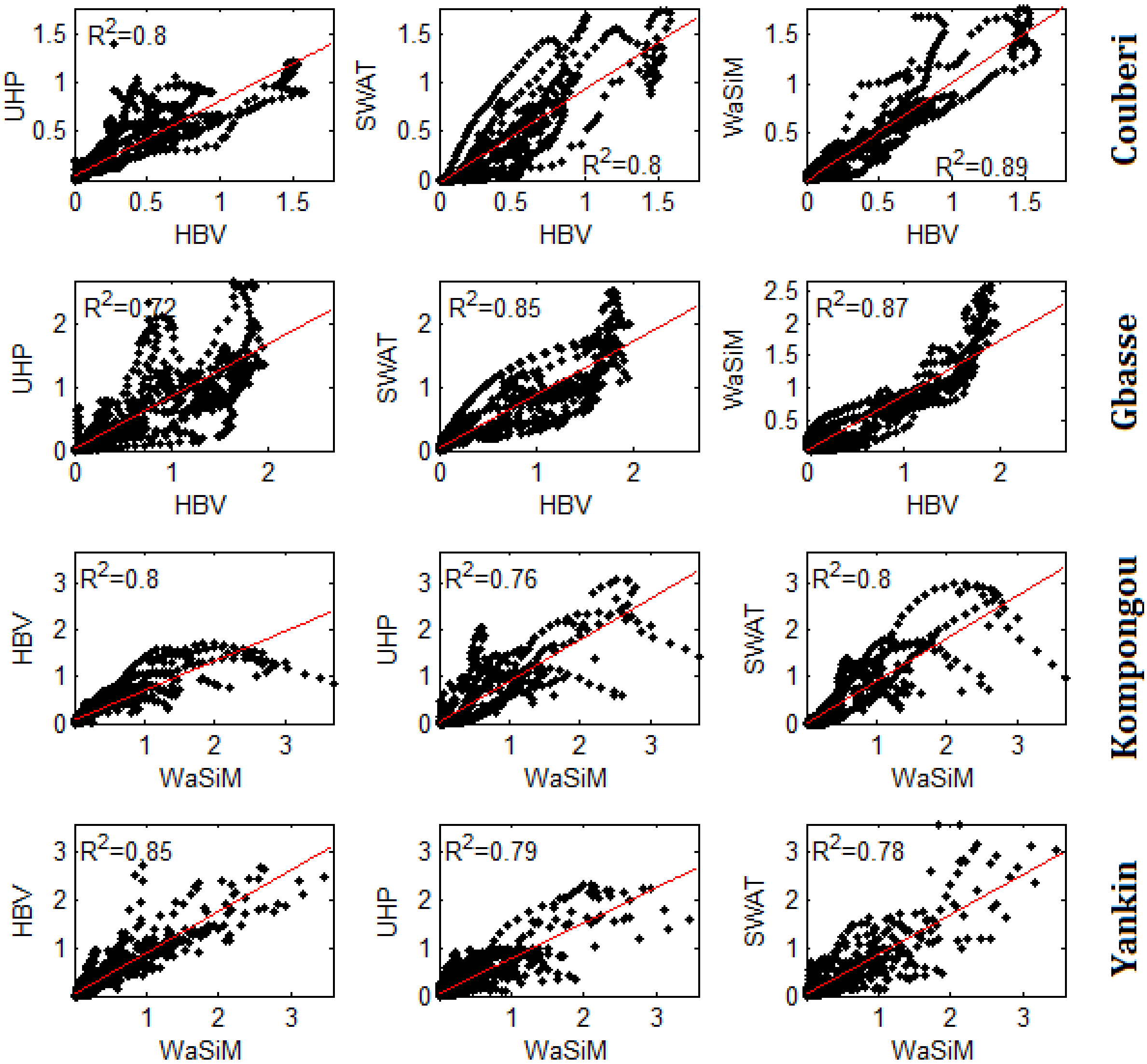


Figure 3-11: Bivariate analysis of the model simulations during the validation period for the Coubéri, Gbassè, Kompongou and Yankin basins.

Regardless of the basin, and regardless of the period (calibration and validation), strong correlations (R^2 ranging from 0.72 to 0.89) were recorded between the streamflow simulated by the models. This suggests that despite the different scores obtained when compared to observed streamflow, all the models respond nearly in the same manner to the forcing data (climate, land use, soil).

3.3.2 Discussion on the simulation of streamflow

The assessment of the ability of the models to simulate daily streamflow showed that the answer to the question “which model is the best?” depends upon the investigated area (Golmohammadi *et al.*, 2014). The difference between the results presented in this study is threefold: difference between the models within each of the four basins; difference between the models across the four investigated basins and difference with other basins. Within a given basin, as discussed in Section 3.3.1.1, the difference between the models might be due to the difference in the principal streamflow generation process which varies from one model to the other. Models of different structures represent differently processes, are not sensitive to the same parameter sets and therefore simulate differently streamflow processes. An example of such a difference is given for the Yankin basin for which UHP-HRU simulates baseflow as the predominant streamflow generation process, SWAT surface runoff and WaSiM interflow.

The difference across the four investigated basins might emanate from the difference in the basins characteristics and the difference in the input and observation variables. Though adjacent and sharing the same climate, the four basins have their own peculiarities (see Chapter 2) that could influence streamflow generation processes. For instance, while the Coubéri basin lies on 40% of sedimentary sandstone rock and 60% of hard rock and has a rather flat relief, the Kompongou basin lies entirely on basement rock and has a hilly relief. Difference in data range and data quality might also explain the deviation in the results. As a result of the data quality control, the calibration and validation periods were not consistent across the basins (Table 3-2) which could undoubtedly lead to different results.

To justify the difference between the results presented in this study and those reported for nearby basins located in West Africa (Table 3-7), in addition to the reasons evoked in the previous paragraph (difference in basin characteristics and data), one could mention the actual selection of the calibration and validation periods and the modeller uncertainty. As noted for the Kompongou basin (Section 3.3.11), in this study, the calibration and validation periods were chosen within significantly different climatic conditions what is often not the case in most hydrological modelling. The modeller uncertainty could also be one of the key reasons of the deviation between our findings and those reported in previous studies. A same model driven with the same input data by two different modellers might lead to significantly different results (Diekkrüger *et al.*, 1995)..

3.3.3 Simulation of soil moisture

3.3.3.1 Qualitative measure: visual inspection

The plots of the comparison between remotely-sensed and simulated soil moisture for the Coubéri, Gbassè, Yankin and Kompongou basins are displayed in Figure 3-12, Figure 3-12, Figure 3-14 and Figure 3-15 respectively. Three general observations can be made.

- o There is good timing between basin rainfall and remotely-sensed soil moisture for all the four basins.
- o Regardless of the basin, the remotely-sensed soil moisture never equals zero but shows a minimum of nearly 0.1cm^3/cm^3. This minimum corresponds to the residual moisture content, Θ_r and not zero. Normally, due to the presence of hygroscopic water in the soil, soil moisture never reaches zero. The fact that the remotely-sensed soil moisture has a minimum value higher than zero implies that it reflects the presence of hydroscopic water.
- o While WaSiM rarely overestimated high soil moisture values, SWAT often overestimated them and UHP-HRU frequently underestimated them. This difference in trends in soil moisture between the models might emanate from the difference between the procedures of soil moisture computation by the individual models. UHP-HRU only simulates the water available for plants, SWAT the moisture of the entire soil depth, and WaSiM the soil moisture of the layers specified by the modeller.

The aspects peculiar to each basin are presented and discussed below.

Coubéri

The first panel of Figure 3-12 shows that UHP-HRU reproduces very well the timing (and magnitude) of the remotely-sensed soil moisture. In particular, the model was able to reproduce the low values of soil moisture better than SWAT and WaSiM. In addition, SWAT simulated the highest values of soil moisture. While the WaSiM managed to capture the magnitude of high observed soil moisture reasonably well, there was too much variability. This high variablity is probably due to the exchange of fluxes between the uppermost soil layer and the atmosphere.

Gbassè

As depicted in Figure 3-13, SWAT overestimated the remotely-sensed soil moisture but to a lesser extent than in the case of the Coubéri basin. UHP-HRU, however, highly underestimated the remotely-sensed soil moisture. As explained above, UHP-HRU only simulates the water available for plant and requires the addition of Θ_r to reach the magnitude of the remotely-sensed soil moisture. Unlike UHP-HRU and SWAT, WaSiM simulated high soil moisture at the beginning of the rainy season. This difference might be due to the methodology used to infer the simulated soil moisture of the individual models. In the case of WaSiM, the simulated soil moisture is that of the uppermost 2cm which reflects a quick response of soil moisture to rainfall. The simulated soil moisture of SWAT and UHP-HRU, however, are deduced from the upper 1 m; a configuration that leads to a slow response of soil moisture to rainfall since water needs to percolate before an increase of soil moisture can be recorded.

Yankin

In the case of the Yankin basin (see Figure 3-14), UHP-HRU had almost a similar pattern with what was observed in the Coubéri basin. The simulated soil moisture never reaches zero. However, peaks were reasonably reproduced. SWAT displayed an unclear pattern. The peaks of the year 2006 and the decreasing limb of the same year were well simulated. Likewise, the peaks of the year 2007 were well captured. Nevertheless, the model overestimated the soil moisture of the years 2005 and 2008. As in the Coubéri and Gbassè basins, WaSiM depicted high variability and high soil moisture values at the beginning of the rainy season.

Kompongou

The performance of UHP-HRU in the Kompongou basin (Figure 3-15) is similar to what was observed for the Gbassè basin (Figure 3-153). In both cases, UHP-HRU underestimated the remotely-sensed soil moisture. The behaviour of SWAT in this basin could be considered as similar to what was observed for the Yankin basin (see Figure 3-14). The model simulated reasonably the soil moisture of two years (2007 and 2010) but overestimated it for the two other years (2008 and 2009). The observations made so far for WaSiM regarding the high variability and the behaviour at the beginning of the rainy season hold true here too.

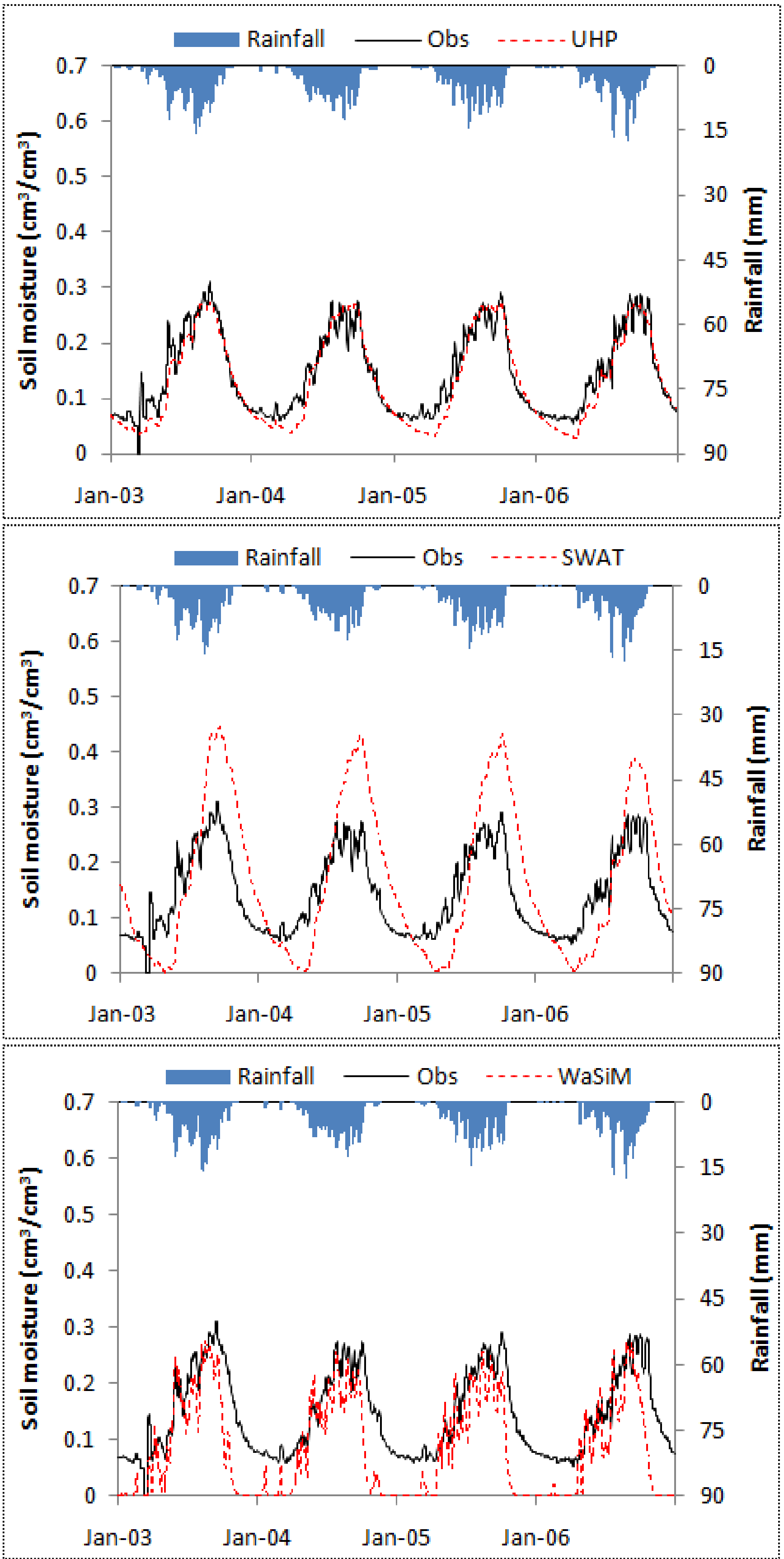


Figure 3-12: Remotely-sensed and simulated weekly soil moisture using UHP-HRU, SWAT and WaSiM during the validation period (2003-2006) for the Coubéri basin.

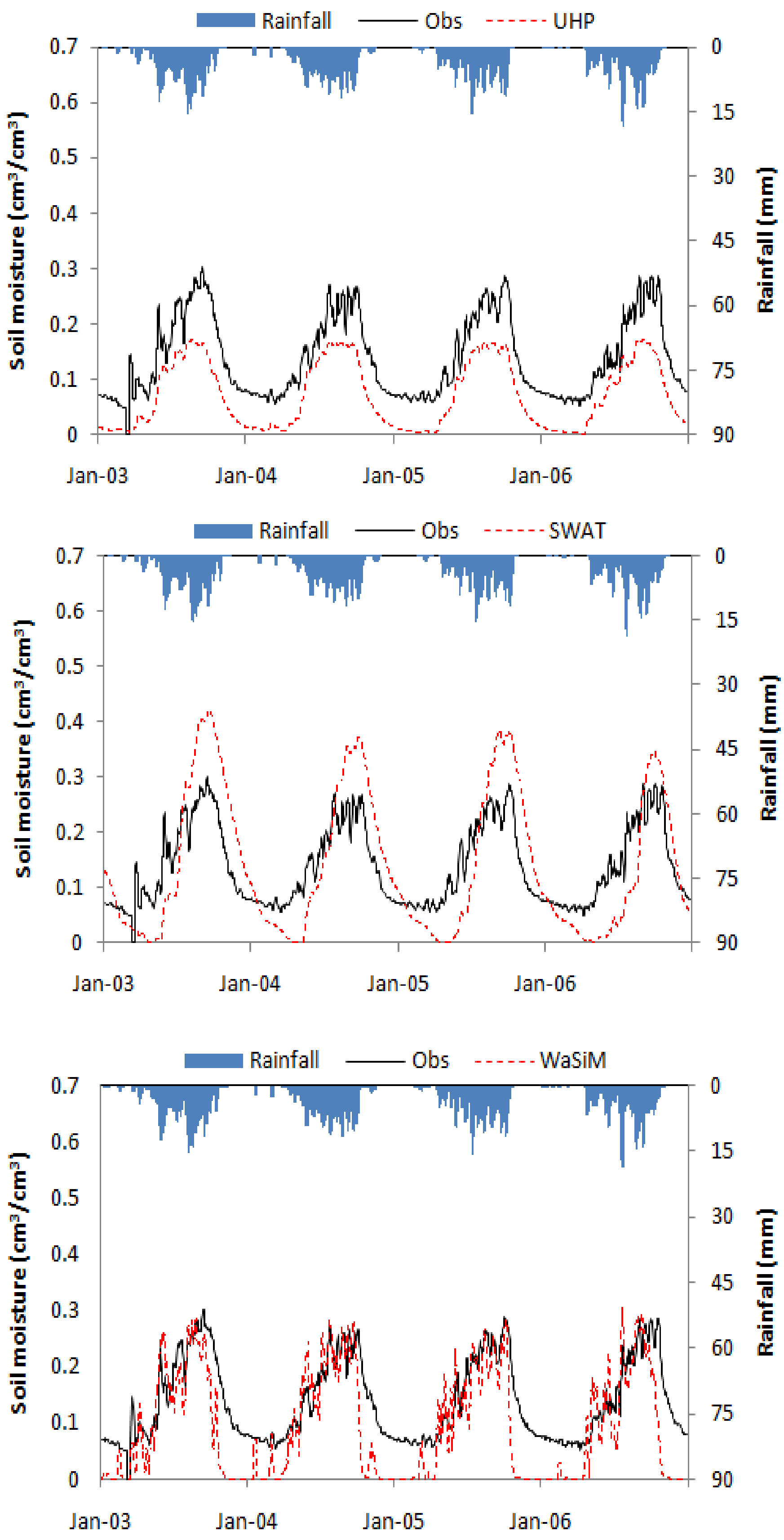


Figure 3-13: Remotely-sensed and simulated weekly soil moisture using UHP-HRU, SWAT and WaSiM during the validation period (2003-2006) for the Gbassè basin.

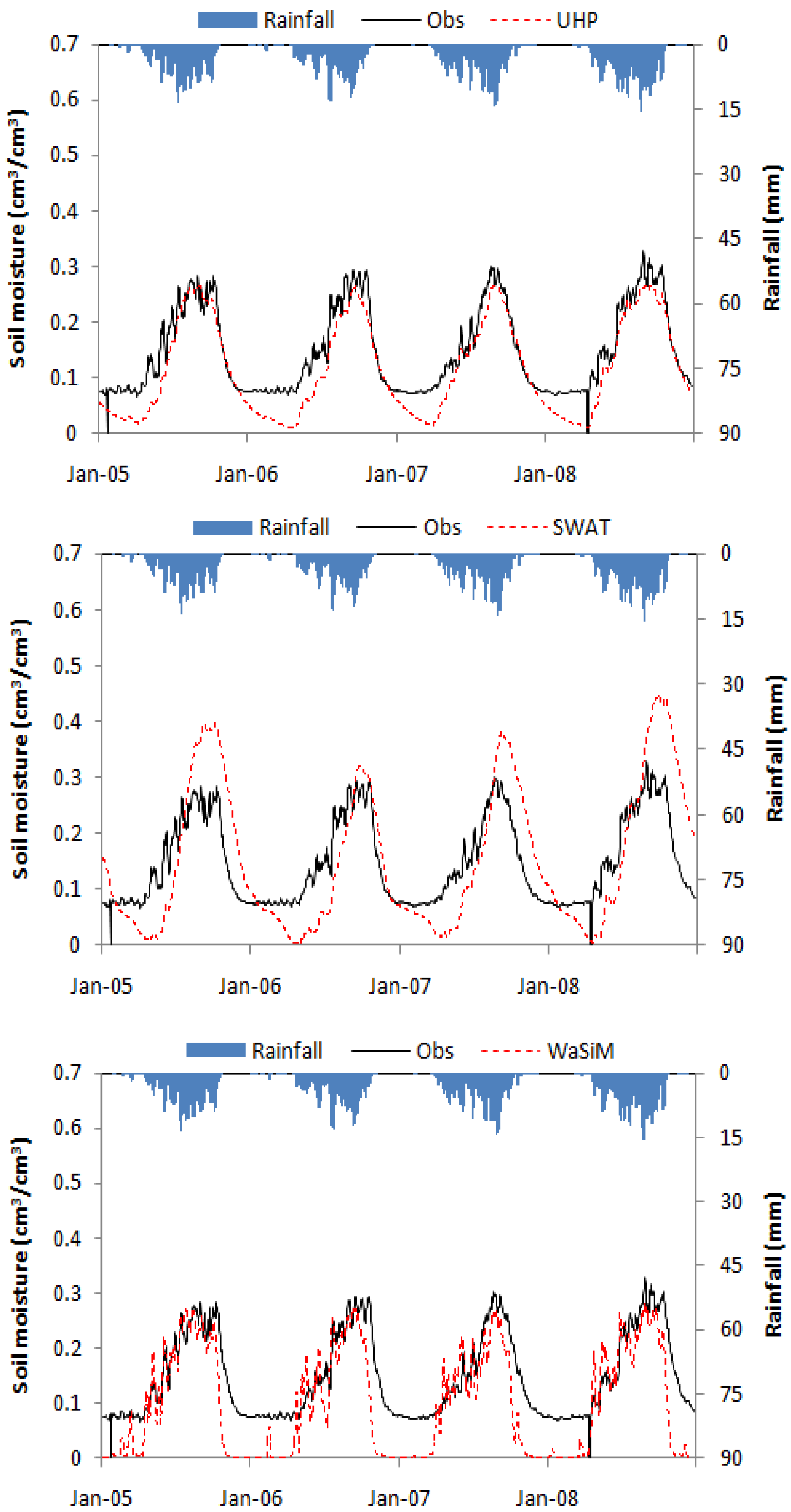


Figure 3-14: Remotely-sensed and simulated weekly soil moisture using UHP-HRU, SWAT and WaSiM during the validation period (2005-2008) for the Yankin basin.

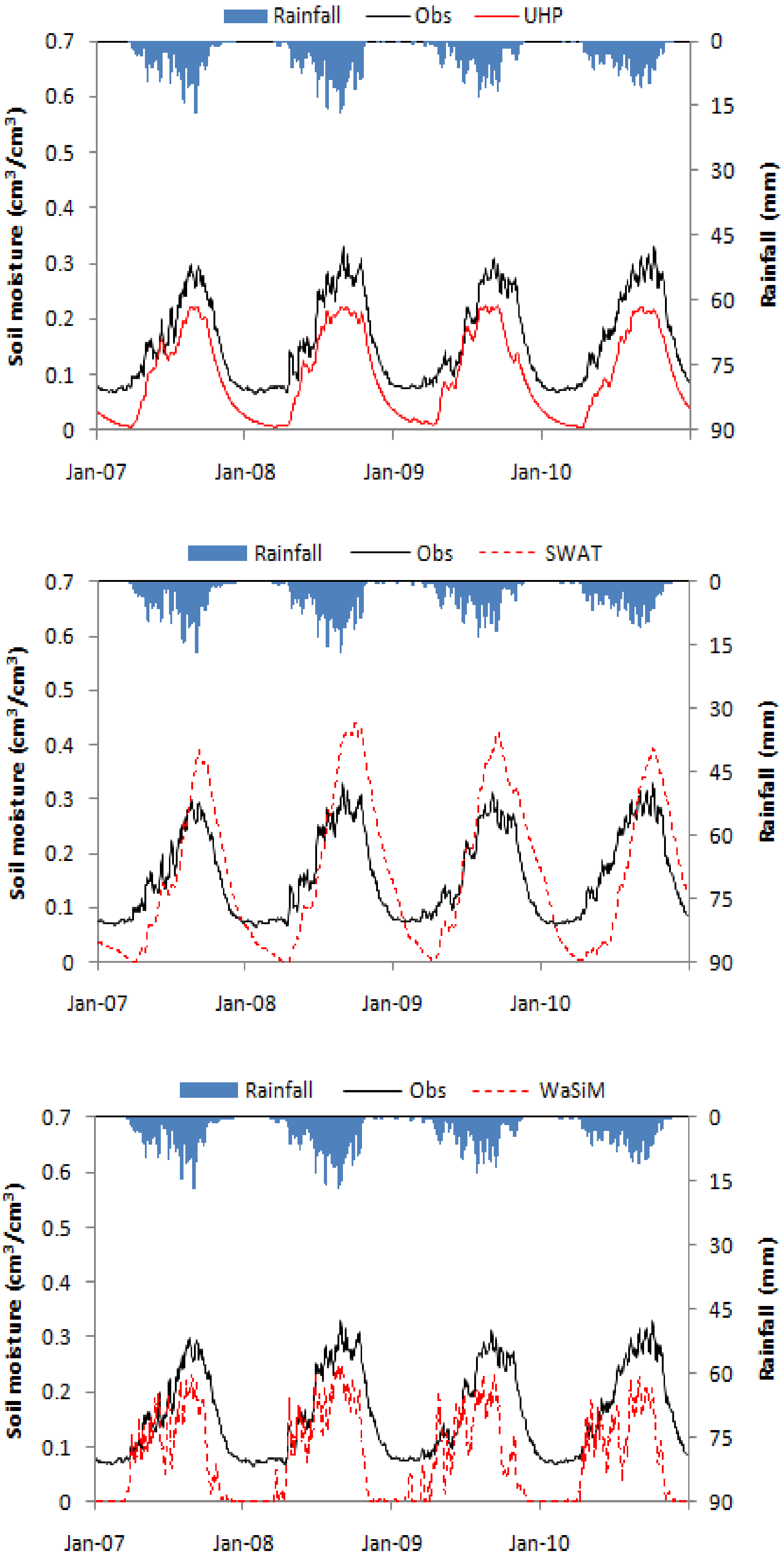


Figure 3-15: Remotely-sensed and simulated weekly soil moisture using UHP-HRU, SWAT and WaSiM during the validation period (2007-2010) for the Kompongou basin.

3.3.3.2 Quantitative measure: R^2 and bias

Table 3-9 summarises the results of the measures of goodness of fit between remotely-sensed and simulated soil moisture. As discussed in section 3.2.4.2, R^2 was used as the main criterion for ranking the models.

Table 3-9: Comparison of remotely-sensed and simulated soil moisture of the investigated catchments

Catchment	**Coubéri**			**Gbassè**			**Yankin**			**Kompongou**		
Hydrological models	**UHP**	**SWAT**	**WaSiM**	**UHP**	**SWAT**	**WaSiM**	**UHP**	**SWAT**	**WaSiM**	**UHP**	**SWAT**	**WaSiM**
Validation period	**2003-2006**			**2003-2006**			**2005-2008**			**2007-2010**		
Remotely-sensed soil moisture (cm^3/cm^3)	35.95	35.95	35.95	34.54	34.54	34.54	42.85	42.85	42.85	53.31	53.31	53.31
Simulated soil moisture (cm^3/cm^3)	33.22	42.91	21.25	17.87	35.31	23.38	34.40	45.77	29.52	33.43	55.06	27.53
Bias (cm^3/cm^3)	0.011	-0.029	0.060	0.069	-0.003	0.046	0.030	-0.010	0.048	0.060	-0.005	0.078
R^2	0.81	0.58	**0.48**	0.81	0.61	**0.45**	0.83	0.57	0.54	0.84	0.65	**0.39**

NB: Figures in bold indicate where the corresponding performance criterion is not met

The values of the bias seem to be in agreement with the qualitative analysis (visual inspection). Regardless of the basin, SWAT overestimated (negative bias) the remotely-sensed soil moisture. On the contrary UHP-HRU and WaSiM underestimated (positive bias) it. However, in terms of absolute bias, SWAT is the best model for the Gbassè, Yankin and Kompongou basins while UHP-HRU gets the best score only for the Coubéri basin.

With respect to the R^2 criterion, WaSiM performed the worst with R^2 values less than 0.5 for the Coubéri, Gbassè and Kompongou basins. As discussed above, this could be the result of the overestimation at the beginning of the rainy season and poor simulation of the low remotely-sensed soil moisture. Though SWAT simulated the high soil moisture, satisfactory results (R^2 values between 0.57 and 0.65) were obtained. UHP-HRU outperformed the two other models with its lowest R^2 value of 0.81. Hence, on the basis of the set criteria, UHP-HRU is the best of the three models for the simulation of soil moisture.

This finding, though, is different from the results of simulating streamflow. For example, for the Kompongou basin, it was found that WaSiM was the best model and UHP-HRU the worst to simulate daily streamflow.

3.4 Chapter summary

In this chapter, the capacities of HBV-light, UHP-HRU, SWAT and WaSiM to simulate daily streamflow and that of the later three to reproduce the timing of daily soil moisture were compared. HBV-light was not included in assessing the performance of the models to simulate soil moisture because this model has a conceptual soil moisture routine which is hard to compare with measurements. WaSiM, the most sophisticated and the most data-demanding of the four models was found to be the most appropriate to simulate the daily streamflow of two basins (Yankin and Kompongou). On the contrary, HBV-light the simplest model with the least data requirements yielded the best scores for the basins of Coubéri and Gbassè. Therefore, none of the models was consistently the best in simulating daily streamflow. While models with the simplest structures (HBV-light and UHP-HRU) did not always perform the best, neither were the more sophisticated ones (SWAT and WaSiM) always the worst. On the whole, all the four models were deemed suitable to simulate the daily discharge of the Coubéri basin, though preference was for the HBV-light and WaSiM which had the highest NKR scores. This result was also similar for the Kompongou basin, but with a preference for WaSiM and SWAT. Only HBV-light and SWAT were found appropriate for the streamflow simulation of the Gbassè basin but for the Yankin basin, WaSiM, HBV-light and UHP-HRU were found robust to simulate daily discharge.

For the simulation of soil moisture the results were different. Regardless of the basin, UHP-HRU outperformed the two other models and WaSiM performed the worst. These results seem to suggest that parsimonious hydrological model structures would be appropriate to simulate soil moisture than the sophisticated ones. However, UHP-HRU and SWAT were found to be adequate to model the temporal variation of daily soil moisture of the Coubéri, Gbassè and Kompongou basins, and all the three can be used for the Yankin basin.

The consideration of the ability of the models to simulate both daily streamflow and soil moisture showed that a model found robust in simulating streamflow is not necessarily robust in simulating soil moisture. For the Yankin basin, WaSiM was the best model for the simulation of streamflow but the least suitable one for the simulation of soil moisture. Likewise, for the Gbassè basin, UHP-HRU was the least suitable model for the simulation of streamflow but the most adequate one for the simulation of soil moisture. Hence, the streamflow-centred approach might be higly misleading.

As a consequence, for each basin, the models identified as the most suitable for the simulation of daily streamflow will be used to quantify the blue water resources while the models found appropriate for the simulation of soil moisture will be run to evaluate the green water resources. This is an unprecedented methodology suggested to have hydrological models applied depending on their demonstrated capacity to simulate particular water balance components.

4 Downscaling regional climate models for simulating blue and green water

Even if global climate models in the future are run at high resolution there will remain the need to 'downscale' the results from such models to individual sites or localities for impact studies.

DOE, 1996

4.1 Introduction

Modelling future water resources requires the use of climate data which are produced by General Circulation Models (GCMs) and Regional Climate Models (RCMs). However, the coarse scale of these data is not appropriate for impact studies. Consequently, some downscaling is required to bridge the gap between the scale of climate model outputs and the scale at which impact studies are undertaken. Since downscaled climate data under the new Intergovernmental Panel on Climate Change (IPCC) emission scenarios, the Representative Concentration Pathways (RCP), were not available for the study area, in this chapter, the outputs of three RCMs were downscaled to the point scale.

4.2 Downscaling climate data

Downscaling is useful to bridge the gap between the temporal and spatial scales of GCMs/RCMs and the scale desired for impact studies (Wilby and Dawson, 2007). Wood et *al.* (2004) reported that unless "bias-corrected", climate models outputs are not appropriate as hydrological model inputs. The climate science literature provides a range of techniques to correct GCMs/RCMs outputs for impact studies. To date, statistical and dynamical downscaling are the two common methods. While the dynamical downscaling disaggregates GCM outputs from the global scale (5°x5°) to the regional scale (0.5°x0.5°), the statistical approach downscales either GCM or RCM outputs to the point scale. The former is less attractive because it is computationally demanding, not directly transferable to new regions, and requires skills in parameterization. Notwithstanding, dynamical downscaling has the advantage to provide RCM outputs consistent with the host[7] GCM (Wilby and Dawson, 2007). The statistical downscaling is favoured because of its parsimony, its transferability to other regions and its less demand on computer resources. Statistical downscaling methods are further divided into weather typing, stochastic weather generators and transfer functions (Wilby and Dawson, 2007). In this study, a statistical downscaling technique was implemented.

[7] A RCM is nested within a GCM

4.2.1 Materials and method

4.2.1.1 Statistical DownScaling Model (SDSM)

Several statistical downscaling models exist, among which the Statistical Downscaling and Bias Correction (SDBC) approach of Ahmed *et al.* (2013), the Statistical DownScaling Model (SDSM) (Wilby and Dawson, 2007), the weather generator methods, the Artificial Neural Network (ANN) algorithms, the methods based “on grid point vorticity data as an atmospheric predictor variable” (Wilby *et al.*, 1998), etc.

In this study, the SDSM version 4.2 (Wilby and Dawson, 2007) was selected for downscaling the outputs of RCM to point scale because it is reported to be quite a robust approach (Kebede et al., 2013; Wilby and Dawson, 2012; Wetterhall et al., 2006) and has been worldwide applied (Wilby and Dawson, 2007). SDSM is “a hybrid of the stochastic weather generator and transfer function methods” (Wilby and Dawson, 2007). While the model offers seven steps for downscaling, only five steps (in italics below) were used in this study; the two two steps being not necessary:

a) *quality control and data transformation*;
b) screening of predictor variables;
c) *model calibration*;
d) weather generation (using observed predictors);
e) *statistical analyses*;
f) *graphing model output*;
g) *scenario generation (using climate model predictors)*.

The *quality control* step provides information on the quality of the input data (number of missing values, minimum, maximum and mean of a time-series, presence of outliers, etc.). During the *data transformation* step, raw input data are transformed (in case of need) using one of following functions: “natural logarithms, $\log_{10}$, squares, cubes, fourth powers, inversion, lag interval and binomial, together with the inverse transformations of the above where appropriate (Wilby and Dawson, 2007). Following the example of Kebede (2013), only rainfall data were transformed by using the fourth root transformation in this study. The *screening of predictor variables* helps identifying the most suitable predictors[8] to downscale a correspondent predictand[9]. This step is the most challenging and requires strong knowledge on the relationship between large scale variables (e.g. geopotential height, vorticity, etc.) and local climatology (Gutiérrez *et al.*, 2011). The *model calibration* step is self-explanatory.

[8] Predictor: “A variable that is assumed to have predictive skill for another variable of interest, the predictand. For example, day–to–day variations in atmospheric pressure may be a useful predictor of daily rainfall occurrence”. (Wilby & Dawson, 2007)

[9] Predictand : A variable that may be inferred through knowledge of the behaviour of one or more predictor variables (ditto)

During the *weather generation* stage, observed predictors (e.g. reanalysis data) are used to calibrate and then generate predictands for the present climate conditions. Conversely, with the *scenario generation* step, climate models predictors are used to produce predictands for the historical and future periods. The *statistical analyses* and *graphing model output* provide detailed statistics and graphical inspection of the results respectively. For further details on SDSM, readers are directed to the user manuals and the notes by Wilby and Dawson (2015, 2013, 2007, 2004).

4.2.1.2 Data used

As noted above, one of the most critical steps in statistical downscaling is the choice of the large scale predictors to be used for downscaling a given predictand (Gutiérrez et al., 2011; Wilby and Dawson, 2007). The choice of predictors requires expertise and sound knowledge of the relationship between the predictors and the predictands of interest; a bad choice could jeopardize the result of the downscaling. There is, however, an alternative to this challenging step viz. the downscaling of the outputs of RCMs. Instead of an “uncertain” choice of the large scale predictors, one can use RCM outputs as predictors following a direct predictor-predictand relationship. For example, to downscale the precipitation of a given rain gauge (predictand), one can used as predictor the precipitation from an RCM. This approach seems interesting as some RCMs provide all the climate variables needed to run hydrological models (precipitation, temperature, wind, humidity, radiation) and simply require disaggregation to the point scale. As in some previous works (e.g. Gobiet *et al.*, 2015, Kebede *et al.*, 2013, Themeßl *et al.*, 2011), RCM outputs were used as predictors in this study.

Access to data was the sole criterion which governed the choice of the RCMs used in this study and such access is not easy for West African researchers who rarely have good internet connectivity. The initial plan to use CORDEX (Coordinated Regional Climate Downscaling Experiment) archives did not work because the data were not accessible online. The second constraint was that the RCMs should provide not only precipitation and temperature but also wind speed, humidity and radiation data. This constraint emanates from the fact that some of the hydrological models (UHP-HRU, SWAT and WaSiM) require all these five variables to run. While most RCMs deliver precipitation and temperature data, only a few of them provide wind speed, humidity, and radiation data.

Eventually, three datasets of RCM were obtained, thanks to collaboration with researchers from Cheikh Anta Diop University in Senegal. These are the 2012 version of the Max Planck Institute Regional Climate System Models (MPI-RCSM-v2012), the Danish Meteorological Institute Regional Climate Model HIRHAM5 (DMI-HIRHAM5) and the Swedish Meteorological and Hydrological Institute Rossby Centre Regional Climate Model (SMHI-RCA4). The latter is nested in the National Oceanic and Atmospheric Administration- Geophysical Fluid Dynamics Laboratory - Earth

System Model (NOAA-GFDL-GFDL-ESM2M) whereas the two former models are nested in the Max Planck Institute - Earth System Model running on low resolution grid (MPI-ESM-LR) and the Earth System Model ICHEC-EC-EARTH respectively. All three RCMs have been developed in the framework of the CORDEX AFRICA-44 initiative (Giorgi *et al.*, 2009). Hereinafter, the RCMs are abbreviated as RCSM, HIRHAM5 and RCA4 for the MPI-RCSM-v2012, DMI-HIRHAM5 and SMHI-RCA4 respectively.

It was initially planned to use RCM outputs under RCPs 2.6 and 8.5 so as to consider the full range of uncertainties. However, the data obtained were limited to the RCPs 4.5 and 8.5. The RCPs are presented as the plausible scenarios of the climate system by 2100 and as such serve as a background for climate impacts studies and climate mitigation (Vuuren et al., 2011a). Besides, they implicitly account for future land use change through defining the future emissions pathways. This is so because land cover plays a key role (carbon sink, provision of ecosystem services and fuel) in the climate system (Thomson *et al.*, 2011). RCP2.6, RCP4.5, RCP6.0 and RCP8.5 are four greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014 (Moss *et al.*, 2008). Each of them indicates the quantity of radiative forcing per square meter by 2100. RCP8.5, for example, indicates a radiative forcing of 8.5 W/m^2 by the end of the century. Based on the implementation of climate mitigations policies, RCP4.5 is a stabilisation scenario (Thomson *et al.*, 2011). In this scenario, today’s population would rise slowly, peaking at 9 billion around 2065, and then declining to approximately 8 billion by 2100. There is also a substantial economic growth which reaches nearly 1000 of primary energy consumption. Conversely, RCP8.5 is the scenario of continuous higher population growth (more than 10 billion by 2050 and nearly 12 billion by 2100), lower income than projected for RCP 4.5 and no implementation of climate mitigation policies (Vuuren et *al.*, 2011a).

Downscaling also depends on *in situ* data. The data of four synoptic stations and 10 rainfall stations were used as observations (Table 4-1 and Figure 4-1). Radiation data was derived from sunshine duration data using the formula of Amoussa (1992).

Table 4-1: Observed climate data used during downscaling. + indicates that data are available and – indicates that data are not available. The data length is 1976-2005.

Stations	**Elev. (m)**	**Lat. (degree)**	**Long. (degree)**	**Rain. (mm)**	**Mean temp. (°C)**	**Rel. Hum. (%)**	**W. speed (m/s)**	**Rad.* (Wh/m2)**
Gaya	202	11.88	3.45	+	+	+	+	+
Kandi	290	11.13	2.93	+	+	+	+	+
Natitingou	460	10.32	1.38	+	+	+	+	+
Parakou	392	9.35	2.6	+	+	+	+	+
Alfakoara	282	11.45	3.07	+	-	-	-	-
Banikoara	310	11.3	2.43	+	-	-	-	-
Bembéréké	491	10.2	2.67	+	-	-	-	-
Ina	358	9.97	2.73	+	-	-	-	-

Kalalé	410	10.3	3.38	+	-	-	-	-
Kouandé	442	10.33	1.68	+	-	-	-	-
Malanville	160	11.87	3.4	+	-	-	-	-
Nikki	402	9.93	3.2	+	-	-	-	-

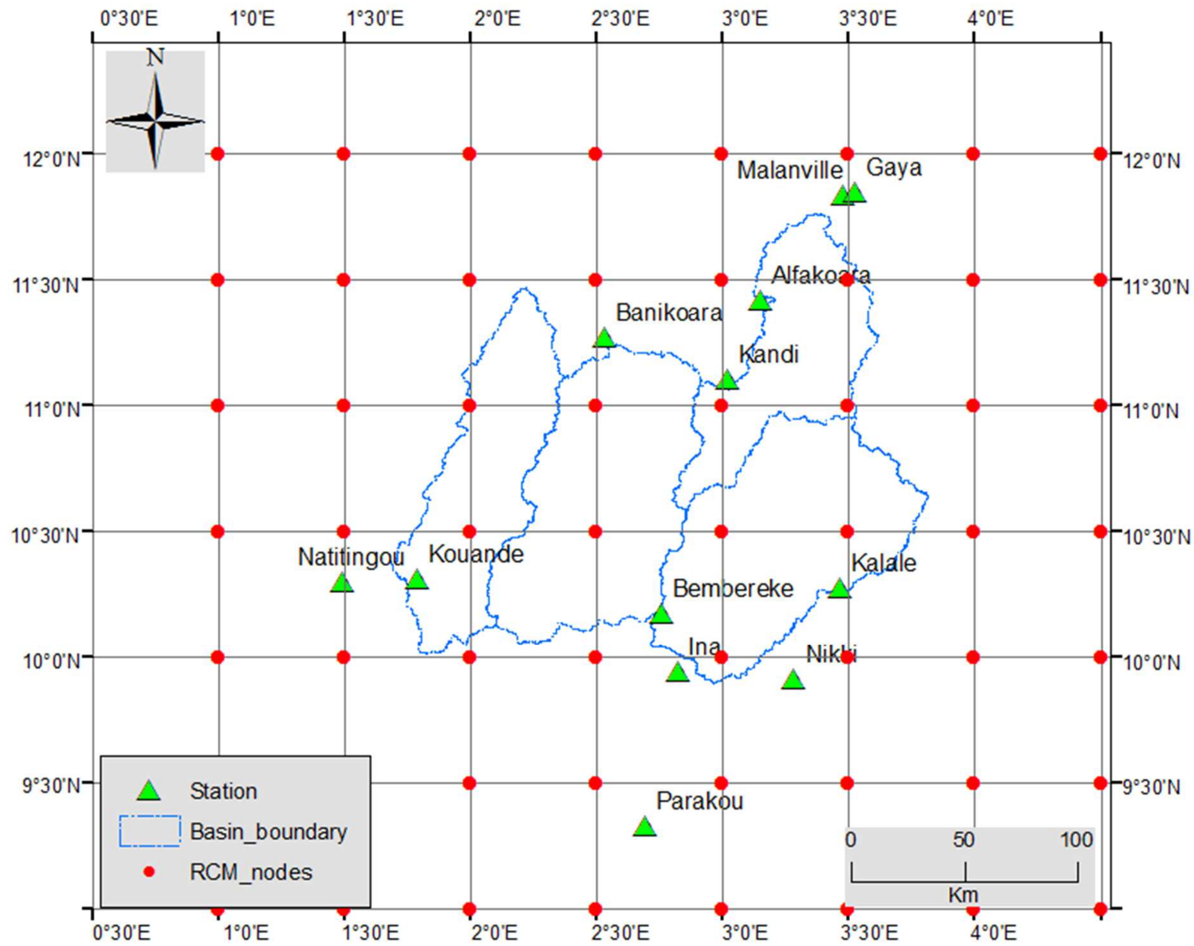


Figure 4-1: Grids of the regional climate models selected for the downscaling of climate variables

4.2.1.3 *Model set up, calibration and validation*

The RCMs archives covered the historical period (1950-2005) and the future (2006-2010). Since the hydrological models were calibrated and validated for the period 1977-2010, 1976-2010 (a period of 30 years as recommended in climatology) was chosen as the baseline period. The future period was limited 2021-2050 based on two reasons. First, the mid-century is a milestone for many planners who consider 2050 as their projects' or their action plans' time horizon. Secondly, from a hydrological modelling perspective, since the parameters obtained during the calibration/validation are used for future simulations, one is confronted with the issue of parameters validity when too long a future period is considered.

While SDSM reads only files in text format, the RCMs data were delivered in netCDF (network Common Data Form) format. The climate data operators (CDO) tool version 1.6.9 (Schulzweida, 2015) was therefore used to extract the RCMs data in the required format. The extracted RCMs variables were then standardised. The actual calibration process consisted of searching the statistical equation allowing the predictors to fit the predictands as best as possible. To obtain such a fit, a trial and error technique was used. During the validation stage, one verified whether the equation obtained during the calibration could be used to satisfactorily downscale an independent period. When the checking yields a satisfactory result, it was concluded that the equation obtained during calibration could be used to downscale RCMs data for the future.

As a result of the direct predictor-predictand relationships, all variables were downscaled as unconditional processes. An unconditional process is a process for which it is assumed a direct relationship between “regional forcing” and “local weather” (Wilby & Dawson, 2007). Considering the temperature at a given gauge (predictand) is a function of an RCM’ temperature (predictor) is such an example. Also, the temporal monthly time step was chosen as model type and a total of 20 ensemble simulations were generated for each downscaled variable. Though SDSM allows the generation of up to 100 ensembles, 20 were chosen because of limited computer resources. The idea behind the ensemble simulations is the consideration of the stochastic nature of climate variables (Biao *et al.*, 2016). Ensemble means were used for the comparison of downscaled against observed variables and to derive the statistics. Wilby et *al.* (2004) cited by Kebede *et al.* (2013) recommended that the ensemble mean be used wherever the objective “is only to see the general trend of the climate change in the future”.

4.2.2 Results and discussions

Though rainfall, temperature, radiation, humidity, and wind speed were all downscaled, only rainfall and temperature results are discussed in the following sections. This was made to facilitate comparison with previous studies which only focus on the downscaling of precipitation and temperature. Downscaled radiation, relative humidity and wind speed are given in Figure C.1, Figure C.2, and Figure C.3 respectively.

4.2.2.1 Precipitation

Figure 4-2 compares RCM rainfall and observed rainfall for the stations at Kandi and Natitingou, located centre and south west of the study area. The left hand panel of the diagram shows ‘raw’ (before application of the downscaling approach) and the right hand panel shows ‘corrected’ (i.e. downscaled) rainfall, both compared to historical observed rainfall records. Unlike the data of HIRHAM5 and RCSM, those of

RCA4 do not include leap years and therefore were plotted separately. In general, the RCMs rainfall captured the uni-modal rainfall regime of the study area. However, for the station of Natitingou, RCA4 rainfall overestimates the May and June rainfall. Moreover, the comparison of raw and downscaled RCM rainfall (Figure 4-2) shows that the biases in the raw data are successfully corrected indicating the appropriateness of the model SDSM to downscale the RCM outputs for the future.

Downscaled RCM projections are presented as changes relative to the baseline period. Rainfall will exhibit a positive trend for the models HIRHAM5 and RCSM, but will show a mixed-trend for the model RCA4. The changes under RCP4.5 are expected to be of the order of +4.6% (+47 mm) to +23.4% (+265 mm), +1.9% (+22 mm) to +23.3% (+264 mm), and -7.7% (-66 mm) to +17.3% (+215 mm) respectively for HIRHAM5, RCSM, and RCA4. Under RCP 8.5, the changes will reach +4.5% (+47 mm) to + 23.4% (+265 mm), + 1.7% (+19 mm) to +23.4% (+265 mm), and - 8.5% (-73 mm) to + 16.2% (+205 mm). For the particular case of the model RCA4, half of the stations depict negative trend (Figure 4-2)

The findings presented above are consistent with recent downscaling studies over Africa. The projected increase in rainfall for HIRHAM5 and RCSM is consistent with the conclusions of Oyerinde (2016) who reported an increase of 2 % (RCP 4.5) and 5 to 10% (RCP 8.5) from the middle to the end of the century over the Niger River Basin. Similarly, Kabore/Bontogho *et al.*(2015) found that in the Massili basin, Burkina Faso, rainfall will slightly increase for the period 2006-2050 in comparison with the period 1975-2000. Besides, the mixed-trend of rainfall projected by RCA4 can be compared to the findings of Kebede *et al.* (2013) who reported that in the Baro-Akobo basin of Ethiopia, downscaled rainfall by the model REMO (A1B and B1 scenarios) resulted in a change of -2% to 21%. The negative rainfall trend projected for some stations (see Figure 4-23) is consistent with the results found for the Ouémé basin of Benin, where a 9 to 12 % decrease in rainfall is expected when REMO rainfall (A1B and B1 scenarios) is bias-corrected (Bossa, 2012).
However, the fact that stations exhibit both positive and negative rainfall trend re-launches the debate on the importance of direction (rather magnitude) of change of future rainfall over West Africa (Druyan, 2011).

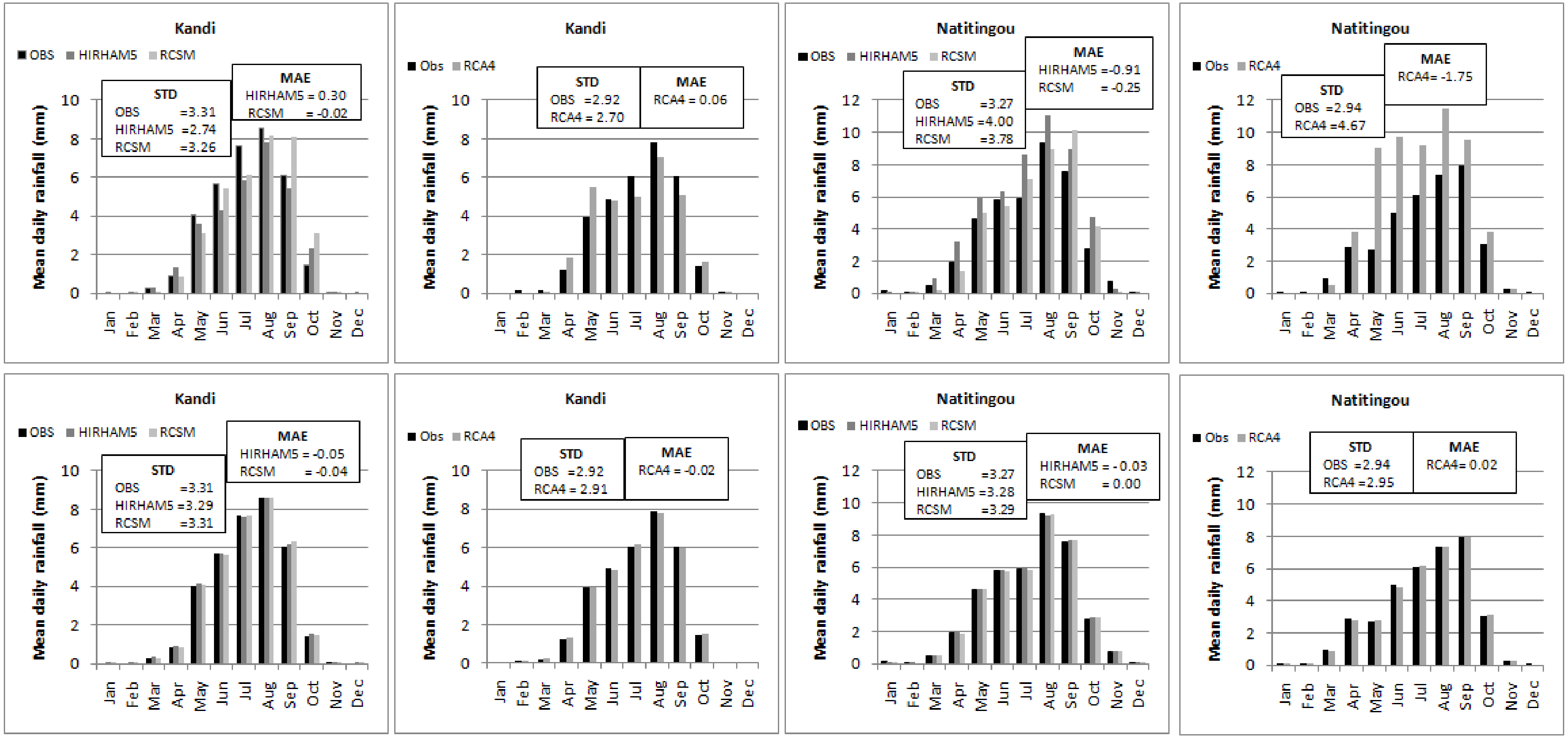


Figure 4-2: Comparison of raw (upper panel) and downscaled (lower panel) rainfall of the baseline period (1976-2005) for the stations at Kandi (near the Centre) and Natitingou (South West). STD and MAE stand for the standard deviation and mean absolute error respectively.

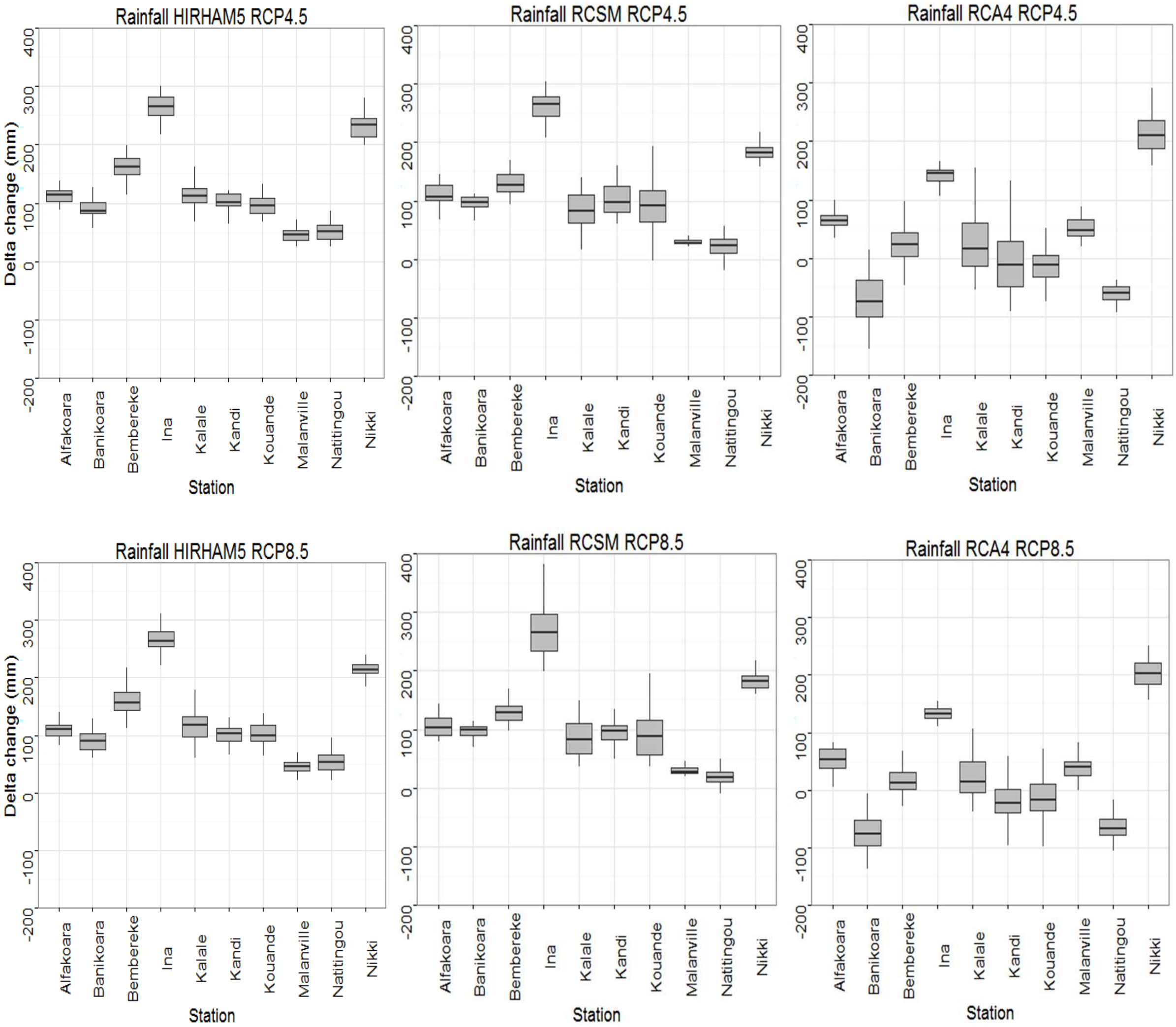


Figure 4-3: Box plots of the projected change in annual mean rainfall relative to the baseline period (1976-2005) under RCPs 4.5 (upper panel) and 8.5 (lower panel).

4.2.2.2 Temperature

Figure 4-4 displays the mean temperature at the stations at Kandi and Natitingou before (left panel) and after (right panel) the calibration/validation. Temperatures from the RCA4 climate model were plotted separately because unlike those of the climate models HIRHAM5 and RCSM, they do not include leap years. The three RCMs replicated reasonably well the pattern of the temperature. However, they underestimated the magnitude with the climate model RCSM depicting the strongest underestimation during the months of January and December. A visual inspection of the right hand side of Figure 4-4 shows a nearly perfect fit of downscaled and observed temperatures for the three RCMs with low standard deviation and mean absolute error values. These results indicate that SDSM is suitable for the downscaling of temperature over the study area.

Figure 4-5 shows the expected changes in mean temperature for the future period (2021-2050) relative to the historical period (1976-2005). Regardless of the scenario, HIRHAM5 and RCSM exhibited positive trends but RCA4 showed negative trends. It was also noticed that the station at Parakou will experience both the highest temperature increase (HIRHAM5 and RCSM) and the highest temperature decrease (RCA4). A change of 0.02°C to 0.38°C is predicted for the climate model HRHAM5 under RCP4.5 against a variation of 0.04°C to 0.35°C under RCP 8.5. In the case of the model RCSM, changes of -0.01°C to 0.48°C and -0.02°C to 0.45°C are projected under RCP 4.5 and RCP 8.5 respectively. The changes are expected to reach -0.34°C to 0.09°C and -0.37°C to 0.04°C under RCPs 4.5 and 8.5 for the model RCA4.

The projected increase in temperature for the models HIRHAM5 and RCSM corroborate the conclusions of Kabore/Bontogho *et al.* (2015) and Oyerinde (2016) where the former reported that temperature will increase by 1.8°C (RCP4.5) and 3.0°C (under RCP8.5) from 1971 to 2050 in Massili basin of Burkina Faso, and the later found that the Niger River basin would experience a temperature increase of the order of 5 to 10% under RCP4.5 and 5 to 20% under RCP8.5 from the beginning to the end of the century.

On the contrary, the negative trend of temperature projected for the climate model RCA4 is questionable since it is well established that global warming will continue during the rest of the century (IPCC, 2013). Nevertheless, it is not the first time that a decrease in temperature is reported in the literature. For example, Kebede *et al.* (2013) downscaled the minimum and maximum temperatures of the GCM CGCM 3.1(A1B scenario) and the RCM REMO (A1B and B1 scenarios), and obtained almost similar results to the ones observed here for the model RCA4. The results of Kebede *et al.* (2013) show that the majority of the investigated stations will experience a decrease in maximum temperature (for CGCM3.1) and half of these stations will exhibit a decrease in minimum temperature (for REMO).

Another aspect which requires attention is that higher temperatures are projected under RCP4.5 than under RCP8.5. These results are really surprising since it was exactly the opposite that would have been expected. However, Kebede *et al.* (2013) found almost similar results when they reported higher maximum temperature under B1 than under A1B for half of the stations and higher minimum temperature under B1 than under A1B for 40% of the stations. Now, given that Kebede *et al.* (2013) and the current study use the same downscaling model, SDSM, one wonders if the results imply an artefact (or systematic error) of the model.

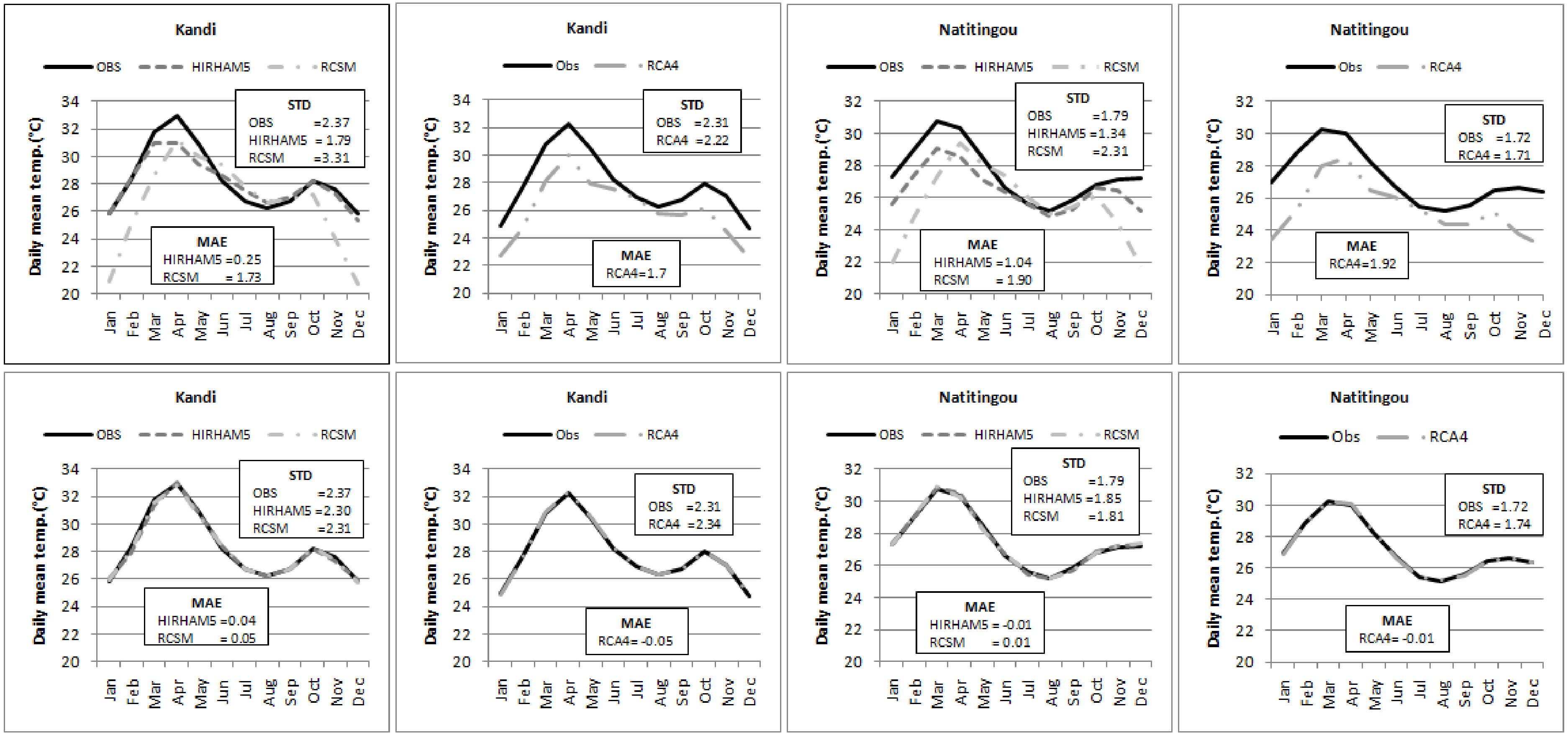


Figure 4-4: Comparison of raw (upper panel) and downscaled (lower panel) mean temperature of the baseline period (1976-2005) for the stations of Kandi (near the Centre) and Natitingou (South West). RCA4 is plotted separately because the RCM does not account for leap years.STD and MAE stand for the standard deviation and mean absolute error respectively.

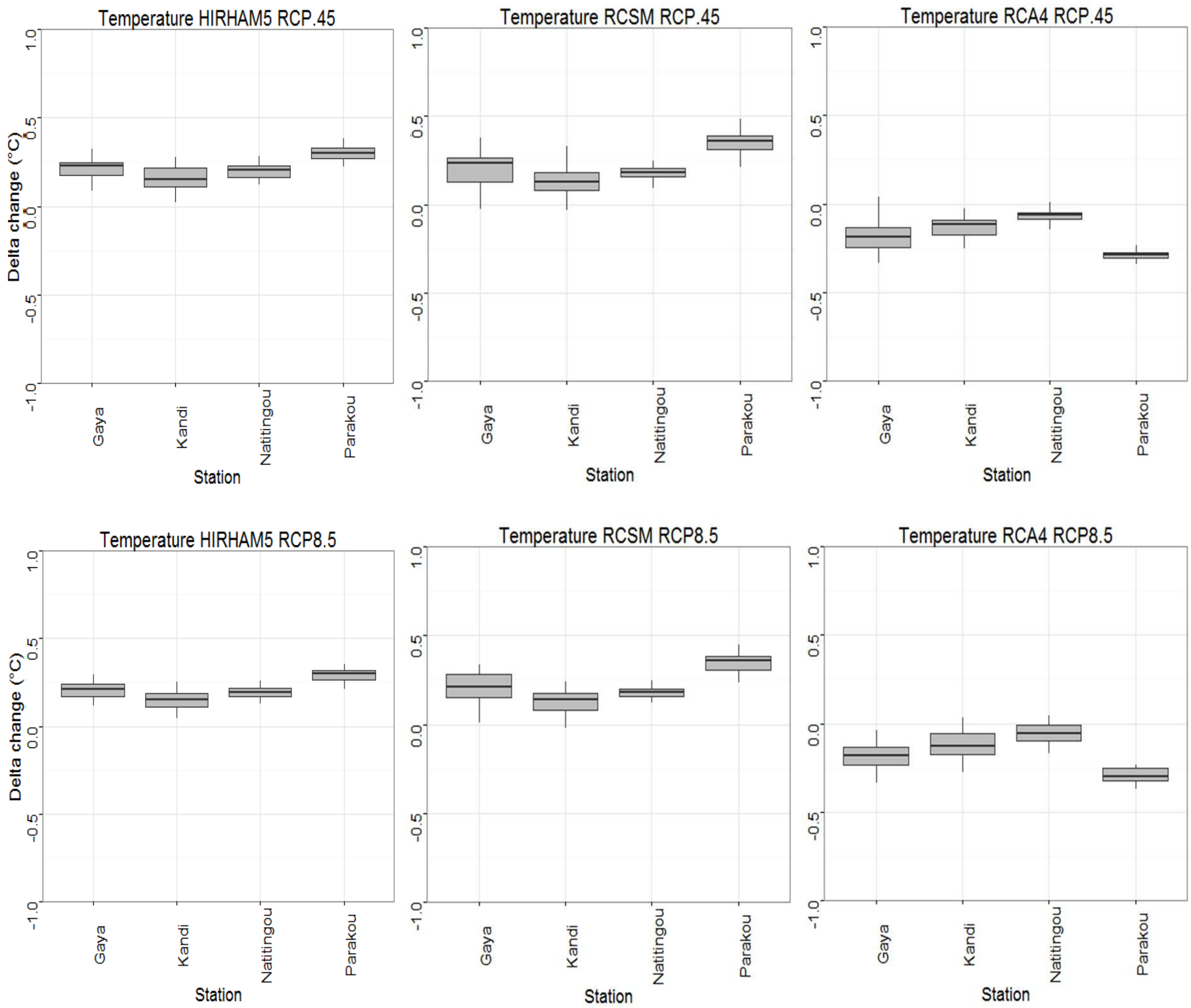


Figure 4-5: Box plots of the projected change in annual mean temperature relative to the baseline period (1976-2005) under RCPs 4.5 (upper panel) and 8.5 (lower panel).

4.3 Chapter summary

Downscaled climate variables are required to predict future water resources. and this chapter has focused on the downscaling of rainfall, temperature, radiation, relative humidity and wind speed of three RCM outputs, HIRHAM5, RCSM and RCA4 under two representative concentrations pathways, RCPs 4.5 and 8.5. Tested against historical data (1976-2005), the statistical downscaling model SDSM was found adequate for the study and was used to downscale the variables for the future (2021-2050).

The results suggest a general increase (1.7 % to 23.4%) in rainfall for the models HIRHAM5 and RCSM under both RCPs but a variation of -8.5% to 17.3% for the climate model RCA4. Also higher rainfall increase is projected under RCP4.5 than under RCP8.5.

By mid-century, mean temperatures are expected to increase for the models HIRHAM5 and RCSM but decrease for RCA4. The projected change in annual mean temperature will reach 0.02°C to 0.38°C (under RCP4.5) against 0.04°C to 0.35°C (under RCP8.5) for the model HIRHAM5, -0.1°C to 0.48°C (under RCP4.5) against -0.02°C to 0.45°C (under RCP8.5) for the model RCSM, and -0.34°C to 0.09°C (under RCP4.5) against -0.37°C to 0.04°C (under RCP8.5) for the climate model RCA4.

In the next chapter, the downscaled climate variables will be used to drive the hydrological models to evaluate the impact of climate change on future blue and green water resources of the study area.

5 Quantification of the impact of climate change on blue and green water and the associated uncertainty

Climate change will amplify existing stress on water availability for society and the natural environment in Africa.

IPCC, 2014

Uncertainty is an expression of confidence about what we "know", both as individuals and communities, and is, therefore, subjective. Uncertainty differs from ignorance, because ignorance involves a lack of awareness about our imperfect knowledge. It also differs from error, because this involves a specific departure from "reality".

Brown and Heuvelink, 2005

Uncertainty estimation is a means to address hydrologic research questions in an honest and robust way.

Juston et *al*., 2012

5.1 Introduction

To what extent will climate change impact blue water (BW) and green water (GW) availability in the future in comparison to the present? The current chapter quantifies the impact of climate change on BW and GW resources. The chapter uses results from chapters 3 and 4. In chapter 3, the most robust hydrological models for the simulation of BW and GW were identified, while in chapter 4 future climatic variables required to drive the hydrological models were downscaled. The results of the two chapters are combined to assess the impact of climate change on future BW and GW availability in the study basin. In addition, the uncertainty associated with the evaluation of BW and GW is quantified.

5.2 Methodology

5.2.1 Future blue and green water availability

In chapter 3 the HBV-light, UHP-HRU, SWAT and WaSiM models were found appropriate to simulate the daily streamflow of the Coubéri and Kompongou basins, the HBV-light and SWAT for the Gbassè basin, and the WaSiM, HBV-light and UHP-HRU for the Yankin basin. For the simulation of soil moisture, UHP-HRU and SWAT models were identified as adequate for the Coubéri, Gbassè and Kompongou basins, and UHP-HRU, SWAT and WaSiM for the Yankin basin.

For each basin, future BW was evaluated only with the hydrological models identified as robust to simulate streamflow while GW was quantified solely with the hydrological models judged suitable to simulate soil moisture using the downscaled variables of three RCMs, HIRHAM5, RCSM, and RCA4. This a novel approach suggested for the first in this thesis for a more accurate prediction of water resources.

Blue and green water resources were calculated with the equations 5-1 and 5-2 below:

$$BW = Q + deepAq \quad \text{(Equation5-1)}$$

$$GW = ET_{act} + \Delta S \quad \text{(Equation 5-2)}$$

where BW is the blue water resources, Q the total runoff, deepAq the deep aquifer recharge, GW the green water resources, ET_{act} the actual evapotranspiration, and ΔS the soil moisture storage.

Future BW and GW resources for the period 2021-2050 were compared to their counterparts for the present (assumed to be 1977-2010).

5.2.2 Uncertainty analysis

The evaluation of future BW and GW was not limited to the simple computation of the mean values of these variables but was extended to incorporate of the associated uncertainty. As discussed in section 1.3.2, uncertainty quantification shows how trustworthy the output of a modelling exercise is (Abbaspour, 2012, Brown & Heuvelink, 2005, Juston *et al.*, 2012, Kapangaziwiri *et al.*, 2012). As a result of time constraints, the analysis of the uncertainty was limited to the overall predictive uncertainty which implied lumping all the sources of uncertainties (input data, observation data, hydrological models, hydrological models parameters, climate models, and emissions scenarios). The two emission scenarios (RCP4.5 and RCP8.5), the three RCMs (HIRHAM5, RCA4 and RCSM), the four hydrological models (HBV-light, UHP-HRU, SWAT and WaSiM), and the N behavioural solutions of the hydrological models were considered to compute the number of model realizations as given by equation 5-3 below.

$$NMR = 2 \times 3 \times 4 \times N \quad \text{(Equation 5-3)}$$

where NMR is the number of model realizations.

N was set to a maximum of five but unfortunately some of the hydrological models yielded less than five behavioural solutions (see Table B.1 to Table B.4). The overall uncertainty was then presented in the form of box-plots drawn with all the elements of the NMR and discussed deliberately only in terms of inter-quartile ranges (the difference between the 75^{th} and 25^{th} percentiles). This quantification of predictive uncertainty enables the capturing the overall range of the expected uncertainty propagated through the modelling based on the different uncertain inputs used. The results of the BW and GW assessment as well the uncertainty quantification are reported and discussed in the following sections.

5.3 Results and discussion

5.3.1 Future blue and green water availability

The projected BW and GW of the first decade (2021-2030) and last decade (2041-2050) of the future time horizon are displayed in Tables 5-1 to 5-4 for the Coubéri, Gbassè, Yankin and Kompongou basins respectively. For each basin, the first set shows changes based on the RCP4.5, and the second set shows changes based on the RCP8.5.

Coubéri

WaSiM, HBV-light, and SWAT showed an increase of rainfall when HIRHAM5 and RCSM were used but a decrease when RCA4 was considered (see Table 5-1). UHP-HRU, however, resulted in a decrease in rainfall for the three RCMs with a rather small decrease under HIRHAM5 but a large decrease under RCA4. This difference in trends of rainfall is probably a result of the different spatial interpolation methods used by the models. WaSiM uses the inverse distance weighting method, while UHP-HRU uses the Thiessen Polygon method, and SWAT the stations closest to the centroid of the sub-basins. HBV-light uses average basin rainfall and in this study was fed with the basin rainfall obtained in WaSiM was chosen for use.

All the hydrological models predict a negative trend of BW by mid-century. For SWAT and UHP-HRU, it is not clear whether the decrease under RCP4.5 is stronger than under RCP8.5 since the decrease is more or less of the same order of magnitude for the two RCPs. In the case of the HBV-light and WaSiM, the decrease under RCP8.5 is slightly greater than under RCP4.5. However, GW is expected to increase in the basin with the increase under RCP4.5 nearly twice the increase under RCP8.5.

In conclusion, compared to the baseline scenario (1988-1992 and 2003-2006), rainfall will vary by between -0.6% ± 5.0% (RCP4.5) and between -1.5% ± 5.0% (RCP8.5) which will lead to a decrease in BW in the order of -37.5% ± 10.9% (RCP4.5) and -36.8% ± 8.1% (RCP8.5) and an increase of GW by 4.7% ± 3.7% (RCP4.5) against 3.4% ± 3.1% (RCP8.5).

Gbassè

Table 5-2 shows an increase in rainfall for HBV-light and SWAT but a decrease for UHP-HRU. Both the HBV-light and SWAT predicted a decrease in BW but with a mixed-pattern. While the decrease will be smaller under RCP4.5 than under RCP8.5 when HBV-light is considered, it will be smaller under RCP8.5 when SWAT is used.
The future trend for GW is consistent across the models with both UHP-HRU and SWAT predicting an increase in GW especially under RCP4.5.

Altogether, the deviation from the reference period (1986-1990 and 2003-2006) can be summarised as follows: an increase in rainfall by 4.2% ± 8.2 % under RCP4.5 and 3.4% ±

8.2% under RCP8.5 that will induce a reduction in BW by -50.6% ± 37.5% under RCP4.5 against -49.3 ± 33.7% under RCP8.5 and an increase in GW by 16.3%± 13.8% under RCP4.5 against 15.0% ± 13.1% under RCP8.5.

Yankin

The expected change in BW and GW resources relative to the baseline (1984-1988 and 2005-2008) are presented in Table 5-3 along with the variation in rainfall. Rainfall will increase for the climate models HIRHAM5 and RCSM (with a higher increase under RCP4.5) but decrease for the climate model RCA4 (along with a higher decrease under RCP8.5). Regardless of the climate models and the RCPs, BW will decrease but GW is expected to increase. In addition, the decrease in BW is slightly higher under RCP8.5 while the increase in GW is rather slightly higher under RCP8.5. RCA4 leads to unrealistic results (ETact>rainfall) when run with SWAT model and the results are not shown in the table.

On the whole, rainfall is expected to increase by 5.6% ± 5.4% under RCP 4.5 and by 5.1% ± 5.5% under RCP8.5. This increase in rainfall will be accompanied by a reduction in BW of -25% ± 1.0% under RCP4.5 and -26.0% ± 0.9% under RCP8.5 but with an increase in GW of 10.9% ±8.1% under RCP4.5 and 10.1 ± 7.8% under RCP8.5.

Kompongou

The projected BW and GW of the Kompongou basin (Table 5-4) have different trends in comparison with their counterparts for the three other basins. The first difference is that, unlike the other catchments, rainfall will increase for all the combinations of climate and hydrological models with only one exception, UHP-HRU when run with RCA4. The second peculiarity of the Kompongou catchment is that a mixed-trend (an increase and a decrease) and not a decrease (as it was the case for the other basins) in BW is projected. Also, unlike the other basins, an increase in GW is not always predicted but UHP-HRU showed a decrease in GW when run with RCA4 and RCSM data. Of the four basins, the highest increase in rainfall and the lowest decrease in BW are expected in Kompongou.

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Table 5-1: Projected rainfall, blue water and green water trends under climate scenarios for the Coubéri basin. Deviation (as %) from the reference period are shown in brackets.

Couberi	REFERENCE	HIRHAM5_RCP4.5		RCA4_RCP4.5		RCSM_RCP4.5	
	[1988-1992 & 2003-2006]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]
HBV-Light							
Rainfall (mm a^{-1})	1043	1094.3 (5)	1093.1 (5)	1008.1 (-3)	1013.3 (-3)	1088.2 (4)	1076.4 (3)
BW (mm a^{-1})	81.5	59.2 (-27)	59.2 (-27)	46.3 (-43)	47.1 (-42)	58.9 (-28)	57.3 (-30)
GW* (mm a^{-1})	961	1035.6	1032.4	959.9	964	1030.2	1018.9
UHP-HRU							
Rainfall (mm a^{-1})	1021.5	970.7 (-5)	966.9 (-5)	875.8 (-14)	880.7 (-14)	976.2 (-4)	961.9 (-6)
BW (mm a^{-1})	219.5	145.5 (-34)	144.7 (-34)	65.6 (-70)	68.1 (-69)	147.9 (-33)	149 (-32)
GW (mm a^{-1})	801.5	825.2 (3)	822.2 (3)	810.2 (1)	812.6 (1)	828.3 (3)	812.9 (1)
SWAT							
Rainfall (mm a^{-1})	1074	1130.7 (5)	1126 (5)	1035.3 (-4)	1039.8 (-3)	1127.7 (5)	1112.8 (4)
BW (mm a^{-1})	86.5	36.3 (-58)	64.3 (-26)	9.6 (-89)	13.6 (-84)	42.6 (-51)	45.5 (-47)
GW (mm a^{-1})	988	1094.4 (11)	1061.7 (7)	1025.7 (4)	1026.2 (4)	1085.1 (10)	1067.3 (8)
WaSiM							
Rainfall (mm a^{-1})	1043	1094.3 (5)	1092.9 (5)	1007 (-3)	1012.3 (-3)	1087.5 (4)	1075.6 (3)
BW (mm a^{-1})	91.5	51.2 (-44)	53.5 (-42)	31.7 (-65)	32.6 (-64)	51.9 (-43)	54.1 (-41)
GW* (mm a^{-1})	951.5	1043.1	1039.4	975.3	979.7	1035.6	1021.5

Couberi	REFERENCE	HIRHAM5_RCP8.5		RCA4_RCP8.5		RCSM_RCP8.5	
	[1988-1992 & 2003-2006]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]
HBV-Light							
Rainfall (mm a^{-1})	1043	1086.8 (4)	1090.5 (5)	995.1 (-5)	1001.8 (-4)	1071.4 (3)	1078 (3)
BW (mm a^{-1})	81.5	58.2 (-29)	58.9 (-28)	44.5 (-45)	44.8 (-45)	56.5 (-31)	57.4 (-30)
GW* (mm a^{-1})	961	1030.8	1032	953.9	952	1016.8	1017.2
UHP-HRU							
Rainfall (mm a^{-1})	1021.5	961.6 (-6)	966.4 (-5)	865.2 (-15)	868.2 (-15)	953.9 (-7)	960.5 (-6)
BW (mm a^{-1})	219.5	143.5 (-35)	145.5 (-34)	64.4 (-71)	65.4 (-70)	142.8 (-35)	146.7 (-33)
GW (mm a^{-1})	801.5	818.1 (2)	820.9 (2)	800.8 (0)	802.8 (0)	811.1 (1)	813.8 (2)
SWAT							
Rainfall (mm a^{-1})	1074	1121 (4)	1126.2 (5)	1023.2 (-5)	1028.5 (-4)	1103 (3)	1110.3 (3)
BW (mm a^{-1})	86.5	53.8 (-38)	46.2 (-47)	12.1 (-86)	21.3 (-75)	55.2 (-36)	60.1 (-31)
GW (mm a^{-1})	988	1067.2 (8)	1080 (9)	1011.1 (2)	1007.2 (2)	1047.8 (6)	1050.2 (6)
WaSiM							
Rainfall (mm a^{-1})	1043	1086.5 (4)	1090.3 (5)	994.1 (-5)	1000.9 (-4)	1070.5 (3)	1077.2 (3)
BW (mm a^{-1})	91.5	50.5 (-45)	53.9 (-41)	30.3 (-67)	30.1 (-67)	49.2 (-46)	52.7 (-42)
GW* (mm a^{-1})	951.5	1036	1036.4	963.8	970.8	1021.3	1024.5

* *signifies that the related model is not suitable to predict that variable and that the variable is not considered in the next stage of the analysis (see Section 3.4)*

Table 5-2: Projected rainfall, blue water and green water trends under climate scenarios for the Gbassè basin. Deviation (as %) from the reference period are shown in brackets.

Gbassè	REFERENCE	HIRHAM5_RCP4.5		RCA4_RCP4.5		RCSM_RCP4.5	
	[1986-1990 & 2003-2006]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]
HBV-light							
Rainfall (mm a^{-1})	1050.5	1140.9 (9)	1138 (8)	1050 (0)	1054.1 (0)	1128.2 (7)	1116.2 (6)
BW (mm a^{-1})	122	100.9 (-17)	101.2 (-17)	77.4 (-37)	78.7 (-35)	99.4 (-19)	98 (-20)
GW* (mm a^{-1})	928	1038.6	1036.3	971.3	974	1030.8	1019.6
UHP-HRU							
Rainfall (mm a^{-1})	1044.5	1034.5 (-1)	1028 (-2)	931.5 (-11)	935 (-10)	1036 (-1)	1021 (-2)
BW* (mm a^{-1})	294	231.6	231.6	121	124.6	234.5	235.9
GW (mm a^{-1})	752	802.9 (7)	796.4 (6)	810.5 (8)	810.4 (8)	801.5 (7)	785.1 (4)
SWAT							
Rainfall (mm a^{-1})	1033.5	1196.5 (16)	1189.1 (15)	1091.4 (6)	1094.7 (6)	1191.5 (15)	1175.3 (14)
BW (mm a^{-1})	141.5	31.7 (-78)	63.1 (-55)	6.4 (-95)	10 (-93)	40.8 (-71)	42.2 (-70)
GW (mm a^{-1})	892	1164.8 (31)	1126 (26)	1085 (22)	1084.7 (22)	1150.7 (29)	1133.1 (27)
WaSiM							
Rainfall (mm a^{-1})	1050.5	1141.1	1138.4	1049.5	1053.5	1129.3	1117.5
BW* (mm a^{-1})	116	77.6	80.2	47.9	50.2	78.2	80.2
GW* (mm a^{-1})	934	1063.5	1058.2	1001.6	1003.3	1051.1	1037.3

Gbassè	REFERENCE	HIRHAM5_RCP8.5		RCA4_RCP8.5		RCSM_RCP8.5	
	[1986-1990 & 2003-2006]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]
HBV-Light							
Rainfall (mm a^{-1})	1050.5	1133.4 (8)	1137.6 (8)	1038.2 (-1)	1045.6 (0)	1110.8 (6)	1117 (6)
BW (mm a^{-1})	122	99.6 (-18)	101.1 (-17)	74.6 (-39)	75.5 (-38)	96.3 (-21)	98.5 (-19)
GW* (mm a^{-1})	928	1034.3	1037.1	964.6	966	1017.2	1017.7
UHP-HRU							
Rainfall (mm a^{-1})	1044.5	1025.9 (-2)	1031.1 (-1)	922.3 (-12)	927.7 (-11)	1009.7 (-3)	1016.6 (-3)
BW* (mm a^{-1})	294	230.8	233.5	118.7	121.4	225.5	232.8
GW (mm a^{-1})	752	795.1 (6)	797.6 (6)	803.6 (7)	806.3 (7)	784.2 (4)	783.8 (4)
SWAT							
Rainfall (mm a^{-1})	1033.5	1187.3 (15)	1192.9 (15)	1080.7 (5)	1088.9 (5)	1162.4 (12)	1169.3 (13)
BW (mm a^{-1})	141.5	52.6 (-63)	38.5 (-73)	8.4 (-94)	15.7 (-89)	53.1 (-62)	59.8 (-58)
GW (mm a^{-1})	892	1134.7 (27)	1154.4 (29)	1072.3 (20)	1073.2 (20)	1109.3 (24)	1109.5 (24)
WaSiM							
Rainfall (mm a^{-1})	1050.5	1133.9	1137.8	1037.5	1044.7	1111.6	1118.2
BW* (mm a^{-1})	116	77.1	80.7	45.7	47.1	74.7	79
GW* (mm a^{-1})	934	1056.8	1057.1	991.8	997.6	1036.9	1039.2

* *signifies that the related model is not suitable to predict that variable, and that the variable is not considered in the next stage of the analysis (see Section 3.4)*

Table 5-3: Projected rainfall, blue water and green water trends under climate scenarios for the Yankin basin. Deviation (as %) from the reference period are shown in brackets.

Yankin	REFERENCE	HIRHAM5_RCP4.5		RCA4_RCP4.5		RCSM_RCP4.5	
	[1984-1988 & 2005-2008]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]
HBV-light							
Rainfall (mm a^{-1})	1021	1117.8 (9)	1116.8 (9)	1000.9 (-2)	1006 (-1)	1117.5 (9)	1109.2 (9)
BW (mm a^{-1})	78	67 (-14)	67.3 (-14)	39.5 (-49)	39.8 (-49)	66.6 (-15)	65.7 (-16)
GW* (mm a^{-1})	943.5	1049.3	1047	963	968	1049	1041.4
UHP-HRU							
Rainfall (mm a^{-1})	945	984.7 (4)	980 (4)	857.2 (-9)	859.9 (-9)	974.1 (3)	967.6 (2)
BW (mm a^{-1})	170	157.3 (-7)	156.9 (-8)	66.2 (-61)	67.7 (-60)	160.1 (-6)	161.7 (-5)
GW (mm a^{-1})	775.5	827.4 (7)	823.1 (6)	791 (2)	792.2 (2)	814 (5)	805.9 (4)
SWAT							
Rainfall (mm a^{-1})	996	1126.1 (13)	1121.2 (13)	-	-	1118.7 (12)	1112.2 (12)
BW* (mm a^{-1})	84	8.3	41	-	-	18.7	15.5
GW (mm a^{-1})	912	1117.8 (23)	1079.8 (18)	-	-	1100 (21)	1096.7 (20)
WaSiM							
Rainfall (mm a^{-1})	1022	1116.3 (9)	1114.8 (9)	1002.5 (-2)	1007.7 (-1)	1115.1 (9)	1107 (8)
BW (mm a^{-1})	76	73.8 (-3)	67.8 (-11)	33.8 (-56)	30.3 (-60)	73 (-4)	66.3 (-13)
GW (mm a^{-1})	945	1042.5 (10)	1047 (11)	968.7 (3)	977.4 (3)	1042.1 (10)	1040.7 (10)

Yankin	REFERENCE	HIRHAM5_RCP8.5		RCA4_RCP8.5		RCSM_RCP8.5	
	[1984-1988 & 2005-2008]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]
HBV-light							
Rainfall (mm a^{-1})	1021	1109.6 (9)	1115.2 (9)	989.8 (-3)	996.8 (-2)	1104.8 (8)	1113.5 (9)
BW (mm a^{-1})	78	65.9 (-16)	66.9 (-14)	39 (-50)	38.6 (-51)	65.2 (-16)	65.9 (-16)
GW* (mm a^{-1})	943.5	1042.4	1046.6	951.4	957	1038.3	1045.4
UHP-HRU							
Rainfall (mm a^{-1})	945	976.1 (3)	981.5 (4)	845.2 (-11)	849.8 (-10)	964.1 (2)	972 (3)
BW (mm a^{-1})	170	154.6 (-9)	157.3 (-7)	63.3 (-63)	61.2 (-64)	158.9 (-7)	161.6 (-5)
GW (mm a^{-1})	775.5	821.5 (6)	824.2 (6)	781.9 (1)	788.6 (2)	805.2 (4)	810.4 (5)
SWAT							
Rainfall (mm a^{-1})	996	1116.1 (12)	1119.9 (12)	-	-	1109.5 (11)	1115.5 (12)
BW* (mm a^{-1})	84	28.5	14	-	-	32.6	31.9
GW (mm a^{-1})	912	1087.6 (19)	1106.1 (21)	-	-	1076.9 (18)	1083.6 (19)
WaSiM							
Rainfall (mm a^{-1})	1022	1107.7 (8)	1113.4 (9)	989.6 (-3)	996.6 (-2)	1102.8 (8)	1111.5 (9)
BW (mm a^{-1})	76	72.7 (-4)	68.6 (-10)	33.5 (-56)	28.4 (-63)	71.4 (-6)	66 (-13)
GW (mm a^{-1})	945	1035 (10)	1044.8 (11)	956.1 (1)	968.2 (2)	1031.4 (9)	1045.5 (11)

* *signifies that the related model is not suitable to predict that variable and that the variable is not considered in the next stage of the analysis (see Section 3.4).*

Table 5-4: Projected rainfall, blue water and green water trends under climate scenarios for the Kompongou basin. Deviation (as %) from the reference period are shown in brackets.

Kompongou	REFERENCE	HIRHAM5_RCP4.5		RCA4_RCP4.5		RCSM_RCP4.5	
	[1979-1984]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]
HBV-light							
Rainfall (mm a^{-1})	987	1144 (16)	1144.1 (16)	1024.9 (4)	1027.8 (4)	1149.2 (16)	1140.5 (16)
BW (mm a^{-1})	57	26.3 (-54)	25.8 (-55)	15.5 (-73)	15.1 (-74)	27.2 (-52)	25.6 (-55)
GW* (mm a^{-1})	930	1126.2	1114.8	1022.6	1009	1133.1	1114.3
UHP-HRU							
Rainfall (mm a^{-1})	927	964.9 (4)	963.3 (4)	846.3 (-9)	847.3 (-9)	972.7 (5)	962.4 (4)
BW (mm a^{-1})	150	181.6 (21)	182.2 (21)	89.4 (-40)	90.6 (-40)	191 (27)	190.3 (27)
GW (mm a^{-1})	777	783.3 (1)	781.1 (1)	756.9 (-3)	756.7 (-3)	781.7 (1)	772.1 (-1)
SWAT							
Rainfall (mm a^{-1})	981	1148.2 (17)	1147.1 (17)	1019.7 (4)	1020.6 (4)	1154.8 (18)	1142.7 (16)
BW (mm a^{-1})	72	89.7 (25)	99.3 (38)	65.1 (-10)	68.7 (-5)	108.8 (51)	108.9 (51)
GW (mm a^{-1})	910	1058.5 (16)	1047.8 (15)	954.6 (5)	951.9 (5)	1046 (15)	1033.8 (14)
WaSiM							
Rainfall (mm a^{-1})	986	1143.2 (16)	1143.3 (16)	1024.9 (4)	1027.8 (4)	1148.3 (16)	1139.8 (16)
BW (mm a^{-1})	57	61 (7)	61.2 (7)	30.4 (-47)	30.6 (-46)	64.5 (13)	61.3 (8)
GW* (mm a^{-1})	929	1082.2	1082.1	994.5	997.2	1083.8	1078.5

Kompongou	REFERENCE	HIRHAM5_RCP8.5		RCA4_RCP8.5		RCSM_RCP8.5	
	[1979-1984]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]	[2021-2030]	[2041-2050]
HBV-light							
Rainfall (mm a^{-1})	987	1138.4 (15)	1146.1 (16)	1017.9 (3)	1027.5 (4)	1132 (15)	1143.4 (16)
BW (mm a^{-1})	57	25.9 (-55)	26.4 (-54)	15 (-74)	14.8 (-74)	25.4 (-55)	25.8 (-55)
GW* (mm a^{-1})	930	1124.9	1119.6	1019.2	1007	1119.6	1115.3
UHP-HRU							
Rainfall (mm a^{-1})	927	959.7 (4)	967.3 (4)	840.6 (-9)	849.5 (-8)	960.1 (4)	972.1 (5)
BW (mm a^{-1})	150	179 (19)	183.3 (22)	88.9 (-41)	87.4 (-42)	190.3 (27)	191.9 (28)
GW (mm a^{-1})	777	780.7 (0)	784 (1)	751.7 (-3)	762.1 (-2)	769.8 (-1)	780.2 (0)
SWAT							
Rainfall (mm a^{-1})	981	1144 (17)	1152.9 (18)	1012.9 (3)	1023.6 (4)	1140 (16)	1153.4 (18)
BW (mm a^{-1})	72	98 (36)	111.8 (55)	73.6 (2)	71.4 (-1)	113.1 (57)	127.9 (78)
GW (mm a^{-1})	910	1046 (15)	1041.1 (14)	939.3 (3)	952.2 (5)	1026.9 (13)	1025.5 (13)
WaSiM							
Rainfall (mm a^{-1})	986	1137.9 (15)	1145.3 (16)	1017.5 (3)	1027 (4)	1131.4 (15)	1142.9 (16)
BW (mm a^{-1})	57	61.4 (8)	64 (12)	29.9 (-48)	29.4 (-48)	60.9 (7)	61.2 (7)
GW* (mm a^{-1})	929	1076.5	1081.3	987.6	997.6	1070.5	1081.7

** signifies that the related model is not suitable to predict that variable and that the variable is not considered in the next stage of the analysis (see Section 3.4).*

The distinctive behaviour of rainfall, BW and GW in the Kompongou basin could be explained by the big difference of climate conditions between the period of reference (1979-1984) and the future time horizon (2021-2050). In this basin, as discussed in Section 3.3.1*,* the hydrological models produced satisfactory results only during the calibration period (1979-1984). The baseline period for comparison with the future was therefore limited to that calibration period. Unfortunately, the problem is that 1979-1984 coincides with a period of drought in the basin (Badou *et al.,* 2016 in press). Hence when compared to the period of drought, some models (e.g. SWAT and WaSiM when driven by HIRHAM5 and RCSM data) predict an increase in future BW while UHP-HRU when driven by RCA4 and RCSM data predicts a decrease in GW.

In total, compared to the baseline period (1979-1984), rainfall will vary by between 9.1% ± 6.2% (RCP4.5) and by between 8.9% ± 6.10% (RCP8.5). This variation in rainfall will lead to a change in BW of the order of -8.4% ± 36.2% (RCP4.5) and -6.2% ± 41.0% (RCP8.5) but to an increase of GW by 5.5% ± 8.7% (RCP4.5) against 4.9% ± 7.9% (RCP8.5).

5.3.2 Discussion on the future blue and green water availability

On average, a decrease in BW is projected while GW is expected to increase for the study area. The increase in GW is linked to the projected global warming and the intensification of the hydrological cycle in the coming decades. The warmer the atmosphere the greater the evaporative demand leading to an increase in GW. This in turn, leads to less water to run off and/or to percolate and reach the deep aquifer so the decrease in BW. These results are partly in agreement with the conclusions of some previous studies in nearby basins. Using four hydrological models, Cornelissen *et al.* (2013) investigated the impact of climate change (REMO under A1B and B1 scenarios) and land use change on the water balance of the Térou basin, a tributary of the Ouémé River in Benin. Regardless of the emissions scenarios, two models (UHP-HRU and GR4J) predicted a decrease of discharge (i.e. BW) while the two others (SWAT and WaSiM) predicted an increase of discharge (i.e. BW). Bossa (2012) conducted a similar study with the SWAT model to evaluate the influence of climate scenario (REMO under A1B and B1) and land use change on the sediment yield and the water balance of the Donga-Pont and the Ouémé-Bonou basins in Benin and the results indicated a decrease in water yield, surface runoff and groundwater flow (i.e. BW), and actual evapotranspiration (i.e. GW). However, land use change would induce an increase in surface runoff and water yield (i.e. BW) but a decrease in the others water balance components. Zannou (2011) reported that the Ouémé basin will experience a 41% decrease in water resources (i.e. BW) by 2025. In a recent study (Oyerindé, 2016) where 8 GCM products were used, it was found that annual streamflow (i.e. BW) will slightly increase by the end of the century at the stations at Malanville and Kainji located in the Niger River basin. Finally, Toure *et al.*

(2016) found that climate change will lead to a decrease of groundwater resource (i.e. BW) in the Klela basin of Mali.

5.4 Uncertainty analysis

Coubéri

Uncertainty quantification in the Couberi basin was based on 90 model realizations and is presented in Figure 5-1 which shows that rainfall and BW will decrease but GW will increase. Rainfall is expected to decrease by -2.9% to -4.0% (median) with an inter-quartile range of 8.7 to 9.2 %. BW will also decrease in the order of -38.4% to -41.3% (median) with an inter-quartile range of 16.1% to 21.6%. The median projected change in GW is approximately 1.5% to 2.5% with an inter-quartile range of 2.2% to 2.7%. The values of the inter-quartile ranges show that GW evaluation is associated with lesser uncertainty than that of rainfall while the assessment of BW resources is the least certain.

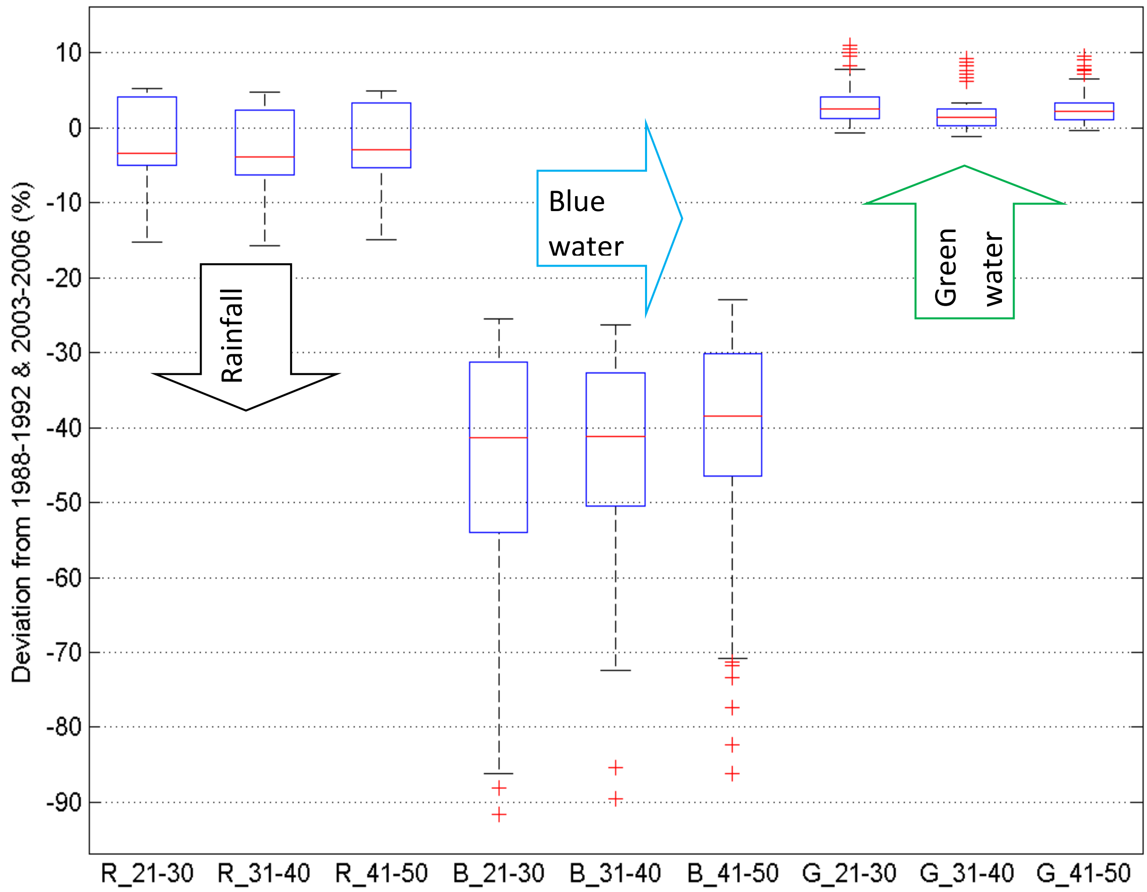

Figure 5-1: Ensemble percentiles (lower quartile, median and upper quartile) projected interannual rainfall, blue water and green water trends relative to 1988-1992 and 2003-2006 in the Coubéri basin. X_21-30, X_31-40, X_41-50 denotes the values of rainfall (X=R), blue water (X=B) and green water (X=G) during the decades 2021-2030, 2031-2041 and 2041-2050.

Gbassè

In the Gbassè basin, 48 models realizations were used to assess the uncertainty (see Figure 5-2). Rainfall is expected to increase by 5.2% to 6.3% (median) along with an associated inter-quartile range of 8.2% to 8.72 %. Similarly, GW will increase by 12.4% to 14.0% (median) with an inter-quartile range of 18.4% to 19.1%. BW, however, will decrease by -21.3% to -23.2% (median) with an inter-quartile range of 18.5% to 20.2%. Based on the inter-quartile ranges, it can be concluded that the evaluation of change in rainfall is associated with lesser uncertainty than the quantification of BW and GW.

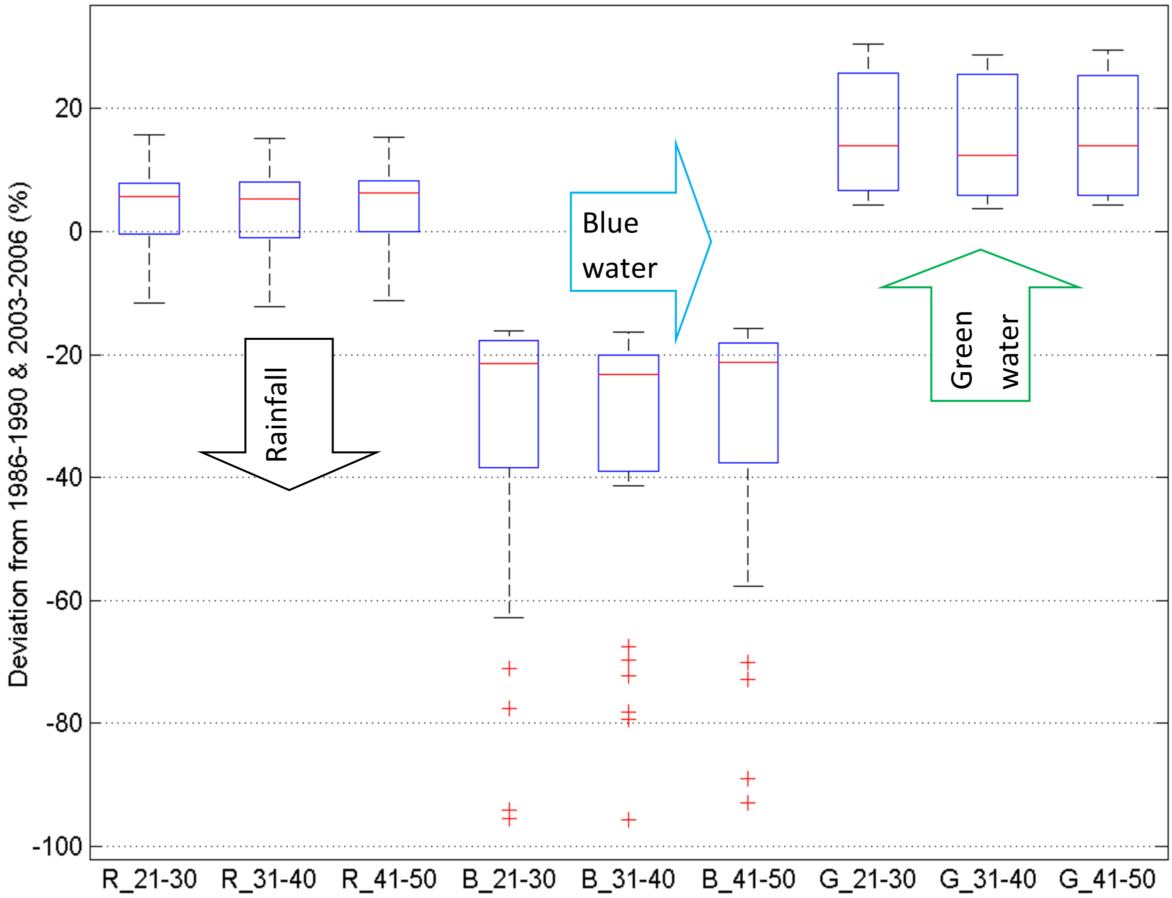

Figure 5-2: Ensemble percentiles (lower quartile, median and upper quartile) projected interannual rainfall, blue water and green water trends relative to 1986-1990 and 2003-2006 in the Gbassè basin. X_21-30, X_31-40, X_41-50 denotes the values of rainfall (X=R), blue water (X=B) and green water (X=G) during the decades 2021-2030, 2031-2041 and 2041-2050.

Yankin

In the case of the Yankin basin, 78 model realizations were used to assess the uncertainty (Figure 5-3). An inspection of Figure 5-3 reveals that rainfall change will exhibit positive trends of 7.7% to 8.6% (median) along with an inter-quartile range of 10.5% to 11.2%. However, BW is predicted to decrease by -15.2% to -17.8% (median) while GW is projected to augment by 9.3% to 10.0% (median). The associated inter-quartile ranges will be of the order of 36.5% to 42.2% and 6.8% to 7.3% for BW and GW respectively. As in the case of the Coubéri basin, GW evaluation is associated with lesser uncertainty than the evaluation of rainfall while the assessment of BW resources is the least certain.

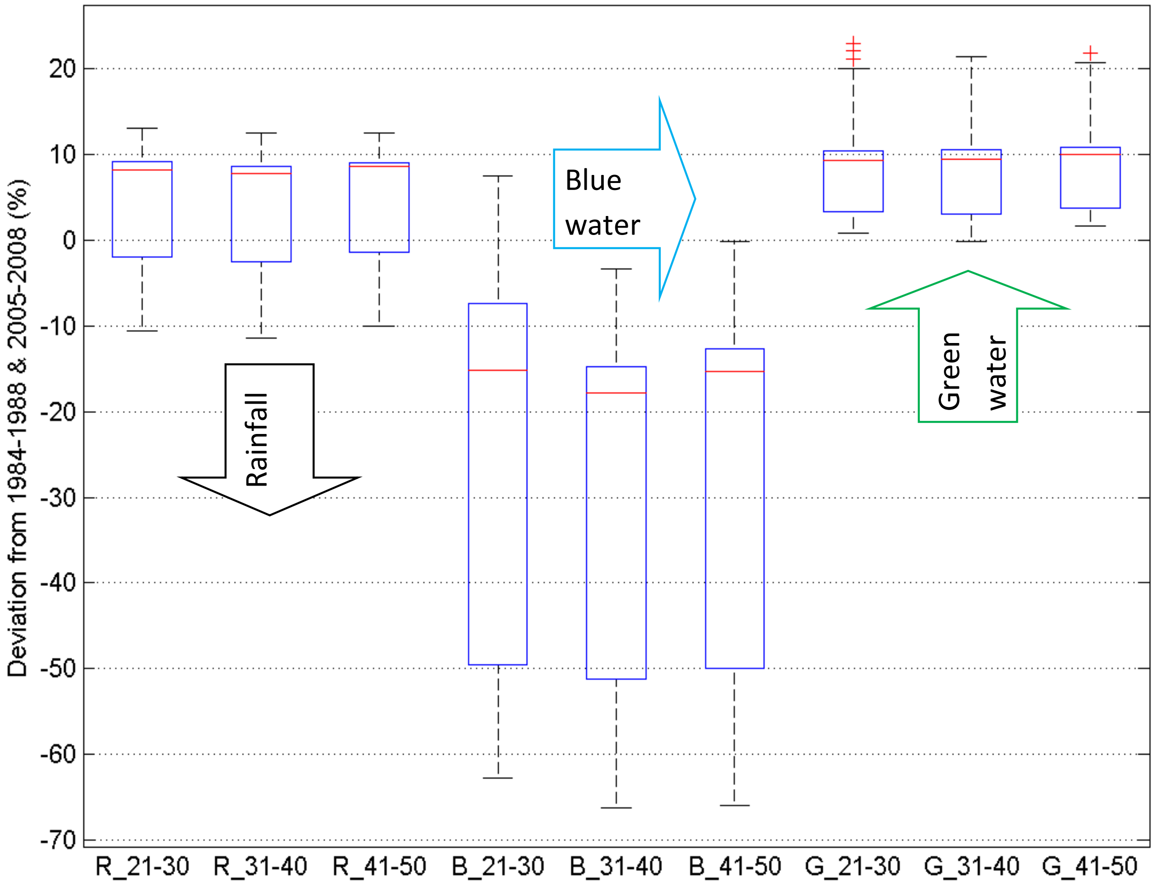

Figure 5-3: Ensemble percentiles (lower quartile, median and upper quartile) projected interannual rainfall, blue water and green water trends relative to 1984-1988 and 2005-2008 in the Yankin basin. X_21-30, X_31-40, X_41-50 denotes the values of rainfall (X=R), blue water (X=B) and green water (X=G) during the decades 2021-2030, 2031-2041 and 2041-2050.

Kompongou

For the Kompongou basin, the combination of climate models, emissions scenarios, hydrological models and behavioural hydrological models parameters resulted in 24 model realizations, which is the smallest number of model realizations of all the basins. The reason is that only one behavioural hydrological model parameter set was retained after the calibration and validation procedure (Table B.4). The analysis of the uncertainty is represented in the Figure 5-4 below.

The median projected change in rainfall is approximately 8.8% to10.2% with an inter-quartile range of 11.9% to 12.4%. This increase in rainfall will lead to an increase in both BW and GW. While BW is expected to increase by 0.2% to 4.5% with an inter-quartile range of 70.7% to 73.1%, GW is predicted to augment by 2.0% to 2.8%

along with an inter-quartile range of 12.7% to 13.2%. Thus, the evaluation of BW is associated with the largest uncertainty in comparison with the assessment of rainfall and GW for which the inter-quartile ranges are smaller.

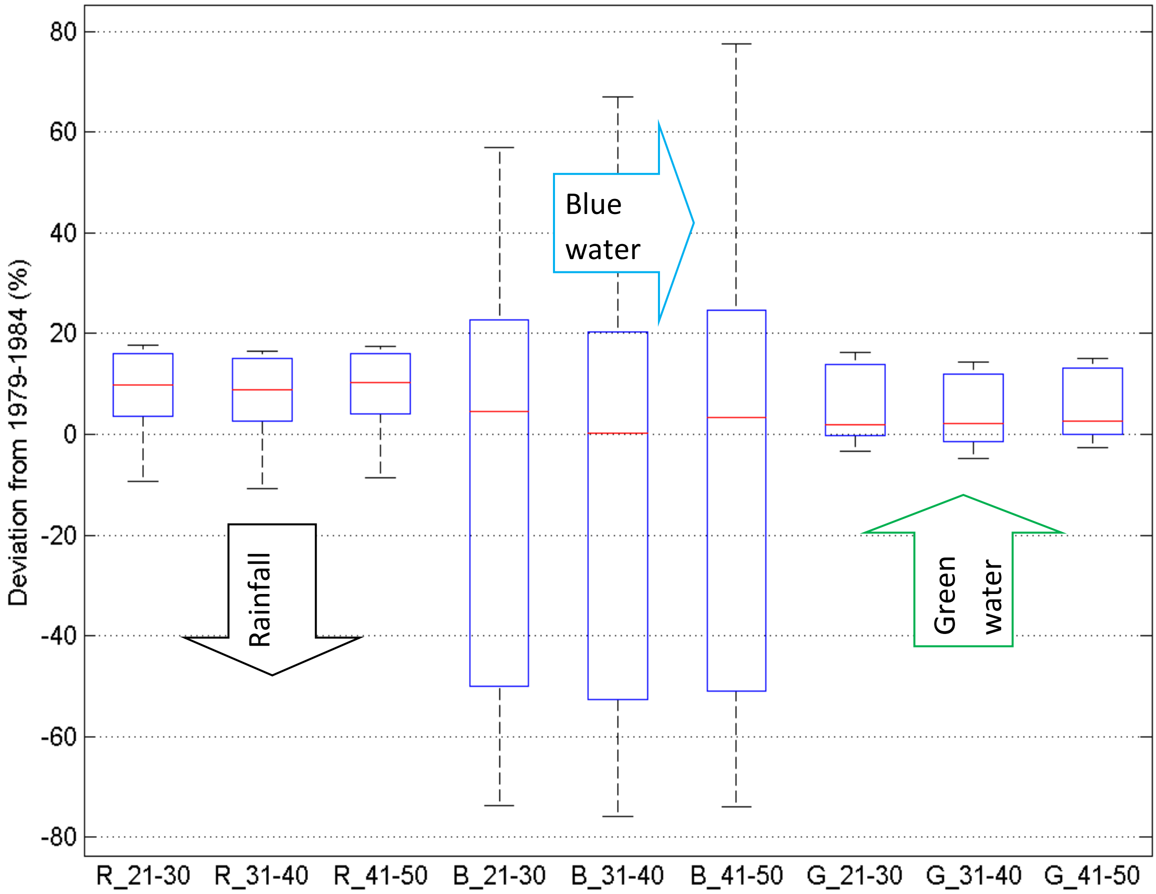

Figure 5-4: Ensemble percentiles (lower quartile, median and upper quartile) projected interannual rainfall, blue water and green water trends relative to 1979-1984 in the Kompongou basin. X_21-30, X_31-40, X_41-50 denotes the values of rainfall (X=R), blue water (X=B) and green water (X=G) during the decades 2021-2030, 2031-2041 and 2041-2050.

5.4.1 Discussion of the uncertainty analyses

The key outcome of the uncertainty analyses is that BW quantification is associated with larger uncertainty than GW evaluation. Two main reasons can explain it. First, BW evaluation was done with four hydrological models of very distinct structures: a conceptual lumped model (HBV-light), two conceptual semi-distributed model (UHP-HRU and SWAT), and a distributed physically based model (WaSiM). On the contrary, GW was assessed solely with the hydrological models (UHP-HRU, SWAT, and WaSiM) having more or less a physically meaningful soil moisture routine. Secondly and most important, while the approaches used by the models to compute evapotranspiration (i.e GW) are nearly similar, the ones used to derive streamflow components (i.e. BW) are different. UHP-HRU, SWAT and WaSiM use the Penman-Monteith method (Monteith, 1965, Penman, 1956) to compute actual evapotranspiration. On the contrary, to derive surface runoff (a component of BW), HBV-light uses a triangular function, WaSiM a method based on the Richards equation, and UHP-HRU and SWAT the SCS CN method (see Sections 3.2.1.1, 3.2.1.2, 3.2.1.3, 3.2.1.4 and Table 3-1).

5.5 Chapter summary

This chapter considered the assessment of climate change impact on future BW and GW resources and the quantification of the associated uncertainty. BW was evaluated with the hydrological models identified as suitable to simulate daily streamflow while GW was quantified with only the hydrological models judged robust to simulate soil moisture (see Section 3.4). In either case, the hydrological models were then run with downscaled climate variables from HIRHAM5, RCA4 and RCSM under RCP4.5 and 8.5. Median BW and GW were computed using all the combinations of regional climate models and “filtered” hydrological models. The uncertainty analysis was presented in the form of box-plots and discussed in terms of inter-quartile range It was found that, as a result of global warming, GW will increase in all the four investigated basins while BW will only augment in the Kompongou basin. The median decrease in BW is projected to approximate -38% to -41% in the Coubéri basin, -21% to -23% in the Gbassè basin, -15% to -18% in the Yankin basin but a median increase of 0.2% to 4.5% is predicted in the Kompongou basin. The median increase in GW will approximate 2% to 3% in Coubéri, 12% to 14% in Gbassè, 9% to 10% in Yankin and 2% to 3% in Kompongou. The results also suggest that, in terms of inter-quartile ranges, BW evaluation is associated with larger uncertainty than GW quantification. A variation of the inter-quartile ranges of 16% to 21% in BW against 2% to 3% in GW for the Coubéri basin, 19% to 20% in BW against 18% to 19% in GW for the Gbassè basin, 37% to 42% in BW against 7% in GW for the Yankin basin, and 71% to 73% in BW versus 13% in GW for the Kompongou basin was noted.

6 Conclusions, outlook, recommendations, and deliverables

Four objectives were defined for the study in the first chapter and this final chapter summarises the main findings of each of the objectives and addresses some outlooks and recommendations. Finally, the outputs of the present study as deliverables are presented at the end of the chapter.

6.1 Conclusions

Since water is life, hydrological modelling thus constitutes a crucial tool for the development of human society. This role of hydrological modelling is rendered even more prominent given the current population growth and global warming which lead to more pressure on water resources. However, most contemporary quantitative hydrological predictions are mostly streamflow-centred which makes them fundamentally uncertain. Given that total runoff represents much less than half of the total incoming rainfall in the investigated basins, an alternative approach using soil moisture and evapotranspiration was explored to improve hydrological prediction. From a theoretical perspective, water resources were treated as blue water (BW, sum of streamflow and deep aquifer recharge) and green water (GW, sum of evapotranspiration and soil moisture). The theoretical aspect also addressed the problem related to the use of a single hydrological model and adopted a multi-model approach. This theoretical framework was applied to the Benin Portion of the Niger River Basin (BPNRB), a conglomerate of four understudied and poorly gauged catchments (Coubéri, Gbassè, Yankin and Kompongou). This area provides a number of ecosystems functions and services whose sustenance requires, at least but not exclusively, a better hydrological knowledge. To this end and to document the potential impact of climate change on the BW and GW resources of the BPNRB, four objectives were defined.

Objective 1: Selection of hydrological models for modelling blue and green water

Given the plurality of hydrological models, the selection of the models to apply in any given study could be difficult task. In this study, the capacity of WaSiM, a physically-based distributed model, SWAT and UHP-HRU, two semi-distributed conceptual models, and HBV-light, a conceptual lumped model to simulate daily streamflow, and the ability of UHP-HRU, SWAT and WaSiM to reproduce daily soil moisture observed by satellites, were compared. HBV-light was not included in the soil moisture simulation because this model has a conceptual soil moisture routine which is hard to compare with measurements. The motivation behind this methodology is that a single model is unlikely to be robust enough to simulate all the water balance components. Thus, only the models found robust to simulate daily streamflow would be used to quantify BW resources while those found suitable to simulate soil moisture would be applied to quantify GW resources. The application of such a methodology requires lot of data types including soil hydrological properties (texture, bulk density, saturated hydraulic conductivity, organic matter content, water content at pF2.5, and water content at pF4.2) which were not available for the study area. To fill in this gap, a soil survey was conducted and primary data on these soil properties were generated.

WaSiM, the most sophisticated and the most data-demanding of the four models was found to be the most appropriate to simulate the streamflow of two basins (Yankin and Kompongou). On the contrary, HBV-light the simplest and the least data-demanding yielded the best scores for the other two basins (Coubéri and Gbassè). Thus, for the simulation of daily streamflow, none of the models outperformed all the others. All the four models performed well for the simulation of streamflow of the Coubéri basin, though HBV-light and WaSiM were preferred based on them having the highest performance scores. This finding also holds true for the Kompongou basin but with a preference for WaSiM and SWAT. Only HBV-light and SWAT performed well to simulate the streamflow in the Gbassè basin while WaSiM, HBV-light and UHP-HRU were judged suitable for the Yankin basin.

The results were however different for the simulation of soil moisture. Regardless of the basin, UHP-HRU outperformed the other two models used and WaSiM was the worst. While UHP-HRU and SWAT performed well in the Coubéri, Gbassè and Kompongou basins, all the three models were deemed good enough in the Yankin basin.

Objective 2: Downscaling regional climate models for simulating blue and green water

Downscaled climate models variables are required for the prediction of future water resources impacts and availability at finer scales. Consequently, the second objective of the study was to downscale the outputs (rainfall, temperature, radiation, relative humidity, and wind speed) of three regional climate models (RCMs), HIRHAM5, RCSM, and RCA4 based on two representative concentration pathways (RCPs), RCP 4.5 and 8.5. Tested against historical data (1976-2005), the statistical downscaling model SDSM was found adequate for the assignment and was thus used to downscale the variables for the future (2021-2050).

The results suggest that rainfall will increase (1.7 % to 23.4%) in the future for the climate models HIRHAM5 and RCSM under both RCPs but will vary by between -8.5% and 17.3% for the model RCA4 and higher rainfall increase would be expected under RCP4.5 than under RCP8.5. By mid-century, mean temperatures would be expected to increase for the climate models HIRHAM5 and RCSM but decrease when the model RCA4 is considered. The projected change in annual mean temperature will reach 0.02°C to 0.38°C (for RCP4.5) against 0.04°C to 0.35°C (for

RCP8.5) for the model HIRHAM5, -0.1°C to 0.48°C (for RCP4.5) against -0.02°C to 0.45°C (for RCP8.5) for the model RCSM, and -0.34°C to 0.09°C (for RCP4.5) against -0.37°C to 0.04°C (for RCP8.5) for the RCA4.

Objective 3: Assessment of climate change impact on blue and green water

As a result of climate change, and more generally subsequent to global change, decision makers, water planners as well as stakeholders are concerned about the availability of water resources in the future. The third objective was thus devoted to the assessment of the climate change impact on future BW and GW resources. BW was only evaluated with the hydrological models identified as suitable to simulate daily river streamflow (see Section 3.4).while GW was quantified only with those hydrological models that managed reasonably daily soil moisture (see Section3.4) for each of the study basins. The hydrological models were thus run with the downscaled variables from the RCMs HIRHAM5, RCA4 and RCSM under RCP4.5 and 8.5. Median BW and GW resources were computed using all the possible combinations of chosen regional climate models and selected hydrological models.

It was found that GW will increase in all the four investigated basins while BW will only increase in the Kompongou basin. The median decrease in BW is projected to approximate -38% to -41% in the Coubéri basin, -21% to -23% in the Gbassè basin, -15% to -18% in the Yankin basin but a median increase of 0.2% to 4.5% is predicted in the Kompongou basin. The median augmentation in GW is expected to reach between 2% to 3% in the Coubéri basin, 12% to 14% in the Gbassè basin, 9% to 10% in the Yankin basin and 2% to 3% in the Kompongou basin.

Objective 4: Quantifying the uncertainty associated with the evaluation of future blue and green water

As noted in the first chapter, uncertainties are an inherent part of hydrological modelling from a range of sources that include the model structure and the data used to drive the models. The present study thus attempted to describe the total predictive uncertainty related to the quantification of BW and GW, and the following was done:

- A multi-hydrological model evaluation (four distinct hydrological models) along with the consideration of five behavioural parameter sets was adopted instead of the use of one single hydrological model;
- A bivariate validation of hydrological models (using discharge and soil moisture) was undertaken instead of the classical approach that is often centred on streamflow only;
- A constraining selection of the calibration and validation periods was done which used calibration during a generally drought period (1979-1992) with validation period taken during a generally humid period (2003-2010). This has the advantage to take into account the stochastic and non-stationary behaviour of hydro-climatic variables;

- A multi-climate model evaluation (three regional climate models under two emissions scenarios) was considered.

Despite the “safeguard” taken to limit the uncertainties, it is necessary to quantify them because hydrological models are simple representations of much more complex processes occurring in the nature, and are therefore fundamentally uncertain. As a result of time constraints, the actual quantification of these uncertainties was limited to the overall uncertainty which was presented as box-plots and discussed mainly in terms of inter-quartile range.

The results suggest that, BW evaluation is associated with larger uncertainty than GW evaluation. An inter-quartile range of 16% to 21% in BW against 2% to 3% in GW for the Coubéri basin, 19% to 20% in BW against 18% to 19% in GW for the Gbassè basin, 37% to 42% in BW against 7% in GW for the Yankin basin, and 71% to 73% in BW versus 13% in GW for the Kompongou basin was noted. The large uncertainty in BW could possibly be explained by the difference in the methods adopted in the individual hydrological models to compute BW components while the small uncertainty in GW could be explained by the similarity of the approaches used by the models in the soil moisture accounting modules from which evapotranspiration was derived.

6.2 Outlook and recommendations

Science without conscience is but the ruin of the soul.

François Rabelais

The Lord works from the inside to the outside. The world operates from the outside to the inside...
The world changes men by changing their environment. Christ changes men, who then change their environment.

Ezra Taft Benson

Mother Earth has always intrigued me. Its magnificence is beyond words... Time & again poets have tried to capture the beauty of nature. In this poem, I try to do the same reminding ourselves that we too have to do our part to save nature for children's children...

Roger Joseph Lurshay, 2012

Although the multi-model evaluation performed in this study explored new avenues to improve the prediction of water resources, there is still potential to improve the analysis. These ideas are briefly addressed below:

- A multi-variate assessment of hydrological models: in addition to streamflow and soil moisture, the use of groundwater data to assess the performance of hydrological models is a promising path towards more robust comparison of hydrological models. Groundwater recharge data can be obtained from Benin water directorate (DGEau) database and/or field survey. Considering groundwater levels is challenging as observation and model scale do not fit and a methodology to handle the scale dependency has to be developed;

- A more physically-based extraction of the simulated soil moisture: In this study, the soil moisture of UHP-HRU and SWAT was extracted for the upper first meter then downscaled to the topmost 2 cm for comparison with the remotely-sensed soil moisture which was available for the upper cm 0.5-2cm. It would worth exploring a more physically-based extraction of the soil moisture where the relative mean soil depth (SWAT) and mean root depth (UHP-HRU) could be used. Moreover, given that observed soil moisture is often available for the uppermost few cm (for remotely-sensed data) and for a soil depth ranging from 4cm to 50 cm (for *in situ* data, as in Rötzer *et al.* (2014)), more research could be done (e.g. modification of the structure of SWAT and UHP-HRU to enable the extraction of the uppermost soil moisture) to facilitate the comparison of observed and simulated soil moisture;

- An incorporation of land use scenarios: though the new emissions scenarios, the representative concentration pathways implicitly take into account future land use changes (Thomson *et al.*, 2011), separate land use scenarios could be included in the evaluation of future blue and green water availability. The data could be obtained from the recent study of Ahmed *et al.* (2016) developed future land use scenarios for West Africa;

- An incorporation of soil scenarios: in the study the ORSTOM soil map was used as well as the soil hydrological properties of the year 2014. The integration of future soil data (as a consequence of climate and land use changes) could improve the findings presented here;

- The use of several models/techniques for the downscaling: in the study only one downscaling model was used (SDSM). Applying two or more downscaling techniques would broaden and improve the uncertainty analysis initiated in this study;

- A regionalization scheme: regionalize the results found at Kompongou and Yankin to the un-gauged parts of the Mékrou River and the Alibori River (both 5,000 km^2) (see Figure 2-1) could improve our knowledge of the hydrology of the study area. Despite this perspective, it is hoped that the study area will be better equipped (hydrometric stations, lysimeters, etc) and better monitored to generate more observed datasets;

- A focus on the hydrology of W-Park: The W-Park is the biggest wildlife park in Benin, an area of tourism and biodiversity. An extension of the study to the hydrology of the W-Park with an emphasis on the green water aspect will be of great benefit to the Benin ministry of tourism.

The main finding of this study is that though rainfall would have a positive trend in the future, that increase in rainfall will be accompanied by a decrease in blue water (BW) resources, the easily accessible water resources but with an augmentation of green water (GW) resources. Given the current population growth in the study area (from 1,579,006 in 2014 to 5,600,000 in 2050, see Section 2.8), this is rather an alarming message for decision makers and water planners. Less BW resources implies less water for municipal uses, less water for agriculture and possibly more conflicts between farmers and cattle breeders, less water for fishery and for navigation, and less water for industrial use. The IPCC (Carabine *et al.*, 2014) alerted that “climate change will amplify existing stress on water availability for society and the natural environment in Africa”. Two sets of solutions could be explored to address the problem. This first set deals with BW and the second with GW.

In order to meet the increasing water demand with the predicted decrease in BW, a rational use of BW is mandatory. In my opinion, the solution is more sociological than technical, and therefore more attention should be given to the sociological dimension of adaptation to climate change. Wherever a technical solution is necessary, the human dimension should also be included. In the study area, belief in the gods is still very strong and often hazards are seen as the gods' curses (Vissin, 2007). Unfortunately, this aspect is often not taken into account in the United Nations' and other institutions' recommendations. This explains the failure of most of these programs in Africa. The director of the Sustainable Development Solutions Network, Jeffrey Sachs (2016), wrote that we need to "educate ourselves and those around us on the challenges and opportunities of the next fifteen years as we pursue a more sustainable planet". More research is needed to bridge the gap between technical solution and their relevance for the people to implement them. Another solution to address the issue of the projected decrease in BW is the use of grass and alfalfa lands to dampen runoff (Kharel *et al.*, 2016). This technique limits runoff and increases deep aquifer recharge which has a buffer effect against climate change (Vouillamoz *et al.*, 2015).

The second set of solutions is based on the projected increase in GW. An increase in GW implies an increase in either transpiration (i.e. more plant growth) and/or evaporation (i.e. more water loss). To face the probable increase in evaporation, here again, more research is needed to limit this situation, by for example documenting techniques of soil and water conservation that easily be applied in the study area. Rodriguez-Juan *et al.*, (2015) conducted such as study for the Mestferki basin located in North-East of Morocco.

As specified in Section 1.3.4, the study area provides many ecosystem functions and services (W-Park, protected forests, largest cotton and vegetable production, as well as cattle breeding zone of Benin), the ultimate goal of this study was to provide sound hydrological information for beneficial use of these functions and services. Therefore, the results and conclusions of this study could be of great benefit at different levels. In addition to contribution to the scientific debate on the use of blue and green water, the study could contribute to the promotion of an integrated land and water resources management (Falkenmark & Rockström, 2006). It is hoped that the ministry of agriculture; the non-governmental organisations involved in the agriculture sector, as well as the cooperatives of farmers will find in the present study solid baseline information to develop adaptation strategies to the potential impact of climate change on livelihoods and food security. At the regional level, the W-Park stretching from Benin to Burkina Faso and Niger, these findings could be useful for the agencies in charge of the management of the park (e.g. CENAGREF in Benin). Last but not the least, the study area being an active part of the Niger River, the Niger Basin Authority (NBA) could also be interested in the results of this study.

6.3 Outputs of this study as deliverables

6.3.1 Publications

Badou, D.F., Diekkrüger, B., Carsten Montzka, Kapangaziwiri, E., & Afouda, A. A. (submitted). Satellite soil moisture data as a surrogate to streamflow measurements for the hydrological modelling of a poorly gauged tropical basin, Coubéri in the Niger River Basin. *Episodes*. Manuscript submitted in August 2016 for publication.

Badou, D. F. (submitted). The need of paradigm shift in quantitative hydrological modelling: a narrative framework. *Episodes*. Communication submitted in August 2016 for publication.

Badou, D.F., Kapangaziwiri, E., Diekkrüger, B., Hounkpè, J. & Afouda, A. A. (in press). Evaluation of recent hydro-climatic changes in four tributaries of the Niger River basin (West Africa). *Hydrological Sciences Journal*. Manuscript accepted for publication.

Badou, D. F., Afouda, A. A., Diekkrüger, B. & Kapangaziwiri. E (2015). Investigation on the 1970s and 1980s droughts in four tributaries of the Niger River basin (West Africa*). E-proceedings of the 36th IAHR World Congress* 28 June – 3 July, 2015, The Hague, the Netherlands. http://89.31.100.18/~iahrpapers/87455.pdf

6.3.2 Conferences

Badou, D.F., Diekkrüger, B., Kapangaziwiri, E., & Afouda, A. A. Investigation on the 1970s and 1980s droughts in four tributaries of the Niger River basin (West Africa). Presented during the Fourth Scientific Day on Water Resources in Benin on the 28th August 2015 in Cotonou, Benin. (Oral Presentation)

Badou, D.F., Diekkrüger, B., Kapangaziwiri, E., & Afouda, A. A. Comparative study of five statistical techniques of climate change analysis in the Niger River basin (West Africa). Presented during the international conference "Our Common Future under Climate Change", 07 to 10 July 2015 in Paris, France. (Poster Presentation).

Badou, D.F., Diekkrüger, B., Afouda, A. A., Kapangaziwiri, E., Hounkpè, J. & Steup G. Soil hydrological properties of a tropical basin: the case study of the Beninese part of the Niger River. Presented during the Dresden Nexus Conference, 25 to 27 March 2015 in Dresden, Germany. (Poster Presentation).

Badou, D.F., Diekkrüger, B., Kapangaziwiri, E., & Afouda, A. A. Quantifying uncertainties in modelling blue and green water variability under climate and land use changes in the Beninese Basin of Niger River. Presented during the Third Scientific Day on Water Resources in Benin on the 18th June 2014 in Cotonou, Benin. (Oral Presentation). Link: http://www.benin.ird.fr/toute-l-actualite/l-actualite/3eme-journee-scientifique-des-projets-griba-jeai-aqui-benin-amma-catch-et-associes-theme-ressources-en-eau-au-benin

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Appendixes

Appendix A

Annual water balance for the basins during calibration and validation periods. $Flow_{obs}$ is the observed discharge, $Flow_{sim}$ the simulated discharge, ET_{pot} the potential evapotranspiration, and ET_{actsim} the simulated actual evapotranspiration.

Table A.1: Coubéri basin.

Coubéri basin	Variable	Calibration period						Validation period				
		1988	1989	1990	1991	1992	Average	2003	2004	2005	2006	Average
Measured	$Flow_{obs}$ (mm)	46	74	43	154	38	71	87	99	60	58	76
HBV-light	Rainfall (mm)	1018	1107	910	1185	913	1027	1148	1030	1036	1020	1059
	ETpot (mm)	1850	1918	2163	2350	2344	2125	1880	2072	2427	2544	2231
	$ETact_{sim}$ (mm)	857	940	995	1080	888	952	983	1008	1040	974	1001
	$Flow_{sim}$ (mm)	83	103	64	98	49	79	124	82	67	61	84
	Soil storage (mm)	-	-	-	-	-	-5	-	-	-	-	-26
UHP-HRU	Rainfall (mm)	921	1126	881	1182	889	1000	1085	1032	1077	978	1043
	ETpot (mm)	2032	2102	2107	2039	2005	2057	2138	2098	2113	2138	2122
	$ETact_{sim}$ (mm)	729	828	749	855	736	779	827	840	828	777	818
	$Flow_{sim}$ (mm)	72	97	57	116	63	81	88	67	82	71	77
	Deep aq Recharge (mm)	124	165	105	192	95	136	161	126	159	133	145
	Soil storage (mm)	-	-	-	-	-	3	-	-	-	-	3
	Fraction of surface runoff (%)	33.8	35.4	29.9	37	42.1	36	30.1	29.2	26	28.6	28
	Fraction of interflow (%)	26.5	25.8	28	25.2	23.1	26	28	28.4	29.6	28.5	29
	Fraction of baseflow (%)	39.7	38.8	42.1	37.8	34.8	39	41.9	42.5	44.4	42.8	43
SWAT	Rainfall (mm)	978	1173	930	1265	925	1054	1142	1085	1128	1023	1094
	ETpot (mm)	-	-	-	-	-	2061	-	-	-	-	2064
	$ETact_{sim}$ (mm)	-	-	-	-	-	903	-	-	-	-	1002
	$Flow_{sim}$ (mm)	-	-	-	-	-	82	-	-	-	-	68
	Deep aq Recharge (mm)	-	-	-	-	-	11	-	-	-	-	12
	Soil storage (mm)	-	-	-	-	-	58	-	-	-	-	13
	Fraction of surface runoff (%)	-	-	-	-	-	56	-	-	-	-	56
	Fraction of interflow [lat Q] (%)	-	-	-	-	-	2	-	-	-	-	3
	Fraction of baseflow (%)	-	-	-	-	-	42	-	-	-	-	41
WaSiM	Rainfall (mm)	1018	1107	910	1185	913	1027	1147	1031	1036	1021	1059
	ETpot (mm)	2911	2960	3127	2876	3032	2981	2920	2974	3123	3181	3050
	$ETact_{sim}$ (mm)	907	991	888	1018	884	938	1011	996	982	936	981
	$Flow_{sim}$ (mm)	98	112	58	147	59	95	119	68	73	91	88
	Soil storage (mm)	-	-	-	-	-	-6	-	-	-	-	-10
	Fraction of surface runoff (%)	48.6	51.7	42	55.1	44.5	48	46.6	37.1	35.4	46.2	41
	Fraction of interflow (%)	39.8	36.7	36.8	35	34.8	37	41.4	42.2	46.5	39.9	43
	Fraction of baseflow (%)	11.5	11.6	21.1	9.9	20.7	15	11.8	20.7	18.2	13.9	16

Table A.2: Gbassè basin.

Gbassè basin	Variable	Calibration period						Validation period				
		1986	1987	1988	1989	1990	Average	2003	2004	2005	2006	Average
Measured	$Flow_{obs}$ (mm)	65	40	94	159	96	90.8	104	181	176	118	144.75
HBV-light	Rainfall (mm)	882	861	1096	1187	968	999	1158	1097	1077	1076	1102
	ETpot (mm)	1768	1845	1788	1786	1725	1782	1735	1733	1697	1671	1709
	$ETact_{sim}$ (mm)	833	814	918	968	938	894	979	973	936	933	955
	$Flow_{sim}$ (mm)	68	63	133	163	104	106	155	133	129	135	138
	Soil storage (mm)	-	-	-	-	-	-2	-	-	-	-	9
UHP-HRU	Rainfall (mm)	839	843	1042	1217	956	979	1152	1098	1135	1056	1110
	ETpot (mm))	2070	2104	2001	2064	2057	2059	2103	2056	2077	2101	2084
	$ETact_{sim}$ (mm)	707	729	714	790	688	726	792	797	771	747	777
	Deep aquifer recharge (mm)	76	68	204	263	178	158	227	195	236	196	214
	Soil storage (mm)	6	-4	-3	9	-9	0	0	-2	1	3	1
	$Flow_{sim}$ (mm)	50	50	127	155	99	96	133	108	127	110	120
	Fraction of surface runoff (%)	32.9	41.3	29.5	26.3	21.5	30	24.6	20.1	18.2	21.2	21
	Fraction of interflow (%)	15.9	13.8	16.6	17.4	18.5	16	18.5	19.7	20.1	19.4	19
	Fraction of baseflow (%)	51.2	44.9	53.9	56.3	60	53	56.8	60.2	61.6	59.4	60
SWAT	Rainfall (mm)	-	-	-	-	-	973	-	-	-	-	1094
	ETpot (mm)	-	-	-	-	-	2198	-	-	-	-	2064
	$ETact_{sim}$ (mm)	-	-	-	-	-	862	-	-	-	-	952
	Deep aquifer recharge (mm)	-	`	-	-	-	37	-	-	-	-	53
	Soil storage (mm)	-	-	-	-	-	-16	-	-	-	-	-14
	$Flow_{sim}$ (mm)	-	-	-	-	-	89	-	-	-	-	104
	Fraction of surface runoff (%)	-	-	-	-	-	56	-	-	-	-	56
	Fraction of interflow (%)	-	-	-	-	-	41	-	-	-	-	41
	Fraction of baseflow (%)	-	-	-	-	-	3	-	-	-	-	4
WaSiM	Rainfall (mm)	882	861	1097	1188	969	999	1157	1096	1077	1076	1102
	ETpot (mm)	2646	2890	2655	2697	2837	2745	2666	2704	2827	2872	2767
	$ETact_{sim}$ (mm)	867	853	895	987	908	902	990	1015	989	945	985
	$Flow_{sim}$ (mm)	50	40	162	183	95	106	159	103	109	134	126
	Soil storage (mm)	-	-	-	-	-	-9	-	-	-	-	-10
	Fraction of surface runoff (%)	17.9	27.6	38.7	41.9	29.1	31	35.1	21.5	25.2	33.1	29
	Fraction of interflow (%)	67.4	55.3	56.6	53.3	62	59	59.3	69.2	66.9	60.5	64
	Fraction of baseflow (%)	14.7	17.1	4.7	4.8	8.9	10	5.6	9.4	7.9	6.3	7

Table A.3: Yankin basin.

Yankin basin	Variable	Calibration period						Validation period				
		1984	1985	1986	1987	1988	Average	2005	2006	2007	2008	Average
Measured	$Flow_{obs}$ (mm)	14	63	45	23	61	41.2	118	42	128	117	101.25
HBV-light	Rainfall (mm)	971	991	954	871	1110	979	1044	948	1061	1198	1063
	ETpot (mm)	1747	1741	1768	1845	1788	1778	1697	1671	1636	1632	1659
	$ETact_{sim}$ (mm)	912	899	904	845	953	903	979	892	972	990	958
	$Flow_{sim}$ (mm)	37	82	51	42	111	65	89	63	78	134	91
	Soil storage (mm)	-	-	-	-	-	12	-	-	-	-	14
UHP-HRU	Rainfall (mm)	859	922	931	802	1103	923	954	811	958	1144	967
	ETpot (mm)	2153	2102	2111	2129	2028	2105	2107	2130	2074	2118	2107
	$ETact_{sim}$ (mm)	785	756	766	743	741	758	795	719	790	850	789
	Deep acq Recharge (mm)	26	101	86	35	216	93	97	48	94	161	100
	$Flow_{sim}$ (mm)	36	68	62	36	153	71	67	36	81	119	76
	Soil storage (mm)	12	-3	17	-12	-7	1	-5	8	-7	14	3
	Fraction of surface runoff (%)	62.3	21.1	27.4	49.1	25.2	37	19.8	26.6	35.9	25.3	27
	Fraction of interflow (%)	9.9	20.7	19.1	13.4	19.7	17	20.5	18.8	16.4	19.1	19
	Fraction of baseflow (%)	27.7	58.1	53.6	37.5	55.1	46	59..8	54.7	47.8	55.6	53
SWAT	Rainfall (mm)	919	977	955	851	1095	959	1029	876	1018	1208	1033
	ETpot (mm)	-	-	-	-	-	2136	-	-	-	-	1939
	$ETact_{sim}$ (mm)	-	-	-	-	-	847	-	-	-	-	928
	Deep acq Recharge (mm)	-	-	-	-	-	1	-	-	-	-	2
	Soil storage (mm)	-	-	-	-	-	27	-	-	-	-	22
	$Flow_{sim}$ (mm)	-	-	-	-	-	84	-	-	-	-	81
	Fraction of surface runoff (%)	-	-	-	-	-	96	-	-	-	-	94
	Fraction of interflow (%)	-	-	-	-	-	4	-	-	-	-	4
	Fraction of baseflow (%)	-	-	-	-	-	0	-	-	-	-	2
WaSiM	Rainfall (mm)	971	991	954	871	1111	980	1045	949	1061	1199	1064
	ETpot (mm)	2516	2598	2496	2723	2622	2591	2475	2550	2446	2413	2471
	$ETact_{sim}$ (mm)	995	926	936	874	920	930	1032	947	991	1013	996
	$Flow_{sim}$ (mm)	19	66	39	31	145	60	78	51	90	150	92
	Soil storage (mm)	-	-	-	-	-	-11	-	-	-	-	-25
	Fraction of surface runoff (%)	36.6	24.9	27.4	34.1	44.6	34	16.7	21.7	36.9	37.4	28
	Fraction of interflow (%)	55.5	68.4	65.5	57.9	50.1	59	70.5	68.2	53.8	51.9	61
	Fraction of baseflow (%)	7.9	6.7	7.1	8	5.2	7	12.8	10.1	9.3	10.7	11

Table A. 4: Kompongou basin.

Kompongou basin	Variable	Calibration period							Validation period				
		1979	1980	1981	1982	1983	1984	Average	2007	2008	2009	2010	Average
Measured	$Flow_{obs}$ (mm)	80	85	54	20	13	17	44.83	140	121	119	183	140.8
HBV-light	Rainfall (mm)	1184	993	977	988	819	959	987	1104	1248	986	959	1074
	ETpot (mm)	1636	1638	1645	1606	1702	1634	1644	1596	1587	1521	1526	1558
	$ETact_{sim}$ (mm)	1059	1001	978	930	913	874	959	980	1017	988	936	980
	$Flow_{sim}$ (mm)	108	66	55	50	27	33	57	83	132	78	61	89
	Soil storage (mm)	-	-	-	-	-	-	-29	-	-	-	-	6
UHP-HRU	Rainfall (mm)	1150	889	879	926	767	949	927	993	1191	994	967	1036
	ETpot (mm)	2183	2175	2166	2101	2160	2143	2155	2062	2094	2044	2011	2053
	$ETact_{sim}$ (mm)	884	705	715	778	700	884	778	764	825	793	756	785
	Deep aquifer recharge (mm)	173	117	110	81	52	27	93	144	220	126	130	155
	Soil storage (mm)	-6	1	-11	12	-15	12	-1	-9	11	1	2	1
	$Flow_{sim}$ (mm)	99	66	65	55	30	26	57	94	135	74	79	96
	Fraction of surface runoff (%)	8.3	7.5	10.9	23.4	10.4	44.3	17	18.6	13.4	10	12.9	14
	Fraction of interflow (%)	25	25.2	24.3	20.9	24.5	15.2	23	23	24.5	25.4	24.6	24
	Fraction of baseflow (%)	66.6	67.2	64.8	55.7	65.1	40.4	60	58.4	62.1	64.6	62.5	62
SWAT	Rainfall (mm)	-	-	-	-	-	-	981	-	-	-	-	1096
	ETpot (mm)	-	-	-	-	-	-	1850	-	-	-	-	1783
	$ETact_{sim}$ (mm)	-	-	-	-	-	-	881	-	-	-	-	888
	Deep aquifer recharge (mm)	-	-	-	-	-	-	21	-	-	-	-	33
	Soil storage (mm)	-	-	-	-	-	-	29	-	-	-	-	82
	$Flow_{sim}$ (mm)	-	-	-	-	-	-	51	-	-	-	-	92
	Fraction of surface runoff (%)	-	-	-	-	-	-	92	-	-	-	-	90
	Fraction of interflow (%)	-	-	-	-	-	-	3	-	-	-	-	4
	Fraction of baseflow (%)	-	-	-	-	-	-	5	-	-	-	-	6
WaSiM	Rainfall (mm)	1183	994	976	988	818	959	986	1105	1247	987	960	1075
	ETpot (mm)	2447	2484	2564	2453	2725	2559	2539	2464	2369	2273	2315	2355
	$ETact_{sim}$ (mm)	1062	939	964	951	829	949	949	988	1009	955	938	973
	$Flow_{sim}$ (mm)	119	75	62	42	28	17	57	112	173	70	54	102
	Soil storage (mm)	-	-	-	-	-	-	-20	-	-	-	-	0
	Fraction of surface runoff (%)	45.8	36.2	37.3	28.5	21.2	40.9	35	50.4	50.7	32.3	39.9	43
	Fraction of interflow (%)	48.6	57.6	55.3	63.6	70.8	51.2	58	45.1	44.2	60.3	52.2	50
	Fraction of baseflow (%)	5.6	6.3	7.4	7.8	8	7.8	7	4.5	5.1	7.4	7.9	6

Appendix B

Behavioural solutions and performance of the hydrological models in the basins.

Table B.1: Coubéri basin.

Coubéri basin	Number of behavioural solutions	Indexes	NSE			KGE			absPbias			R^2		
			min	mean	max	min	mean	max	min	mean	max	min	mean	max
WASIM														
Calibration	3	14;44; 97	0.77	0.78	0.79	0.77	0.79	0.83	20.80	17.60	13.20	0.80	0.80	0.81
Validation		3;13; 27	0.51	0.53	0.55	0.71	0.72	74.00	19.40	15.70	10.50	0.62	0.64	0.65
SWAT														
Calibration	2	24; 130	0.53	0.53	0.53	0.72	0.73	0.74	12.40	6.60	0.80	0.64	0.66	0.69
Validation		3;13	0.50	0.54	0.57	0.72	0.72	0.73	19.20	14.00	8.80	0.64	0.64	0.64
UHP-HRU														
Calibration	5	348;555;636;819;907	0.57	0.58	0.59	0.71	0.74	0.75	6.00	3.90	0.70	0.58	0.60	0.60
Validation		139;225;260;331;365	0.62	0.63	0.64	0.74	0.78	0.80	6.10	4.10	0.70	0.62	0.64	0.66
HBV-light														
Calibration	5	2;4;19;25;35	0.71	0.71	0.71	0.77	0.78	0.78	1.50	0.50	0.03	0.71	0.71	0.71
Validation		2;4;19;25;35	0.71	0.71	0.72	0.82	0.82	0.83	10.70	9.90	8.40	0.76	0.76	0.76

Table B. 2: Gbassè basin.

Gbassè basin	Number of behavioural solutions	Indexes	NSE			KGE			Pbias			R2		
			min	mean	max	min	mean	max	min	mean	max	min	mean	max
WASIM														
Calibration	1	79		0.80			0.89			1.80			0.83	
Validation		76		0.48			0.60			11.00			0.49	
SWAT														
Calibration	1	3		0.78			0.86			6.60			0.81	
Validation		3		0.50			0.59			9.70			0.51	
UHP-HRU														
Calibration	1	132		0.66			0.83			4.60			0.70	
Validation		24		0.41			0.57			14.30			0.43	
HBV-light														
Calibration	5	1;5;6;7;10	0.80	0.81	0.81	0.89	0.89	0.90	5.90	4.90	3.60	0.81	0.82	0.82
Validation		22;26;27;28;31	0.60	0.60	0.60	0.69	0.71	0.71	5.10	2.50	1.40	0.60	0.60	0.60

Table B.3: Yankin basin.

Yankin basin	Number of behavioural solutions	Indexes	NSE			KGE			absPbias			R2		
			min	mean	max	min	mean	max	min	mean	max	min	mean	max
WaSiM														
Calibration	5	2;4;7;11;15	0.58	0.65	0.71	0.71	0.77	0.86	17.80	9.80	2.90	0.72	0.73	0.74
Validation		1;2;3;4;5	0.66	0.69	0.72	0.73	0.81	0.84	18.00	8.80	2.70	0.68	0.71	0.73
SWAT														
Calibration	2	7 ; 10	0.62	0.63	0.64	0.50	0.52	0.54	43.30	41.00	38.70	0.76	0.77	0.78
Validation		187; 206	0.57	0.57	0.58	0.63	0.63	0.64	24.20	22.90	21.60	0.59	0.59	0.59
UHP-HRU														
Calibration	1	286		0.51			0.66			23.00			0.57	
Validation		41		0.66			0.59			25.20			0.68	
HBV-light														
Calibration	5	2;4;6;8;9	0.73	0.74	0.74	0.72	0.73	0.73	21.80	20.50	19.40	0.74	0.74	0.74
Validation		32;34;36;38;44	0.60	0.60	0.60	0.68	0.69	0.70	11.30	10.10	9.10	0.60	0.60	0.61

Table B.4: Kompongou basin.

Kompongou basin	Number of behavioural solutions	Indexes	Nash			KGE			absPbias			R2		
			min	mean	max	min	mean	max	min	mean	max	min	mean	max
WaSiM														
Calibration	1	66		0.75			0.73			24.80			0.78	
Validation		66		0.42			0.43			31.10			0.45	
SWAT														
Calibration	1	440		0.65			0.80			6.80			0.72	
Validation		8		0.37			0.37			39.10			0.41	
UHP-HRU														
Calibration	1	512		0.62			0.68			24.30			0.72	
Validation		18		0.42			0.41			34.60			0.45	
HBV-light														
Calibration	1	45		0.72			0.65			22.30			0.74	
Validation		43		0.43			0.27			41.90			0.58	

Appendix C

Projected box plots of chosen climatic variables for 2021-2050 under RCP 4.5 and 8.5 relative to the baseline 1976-2005

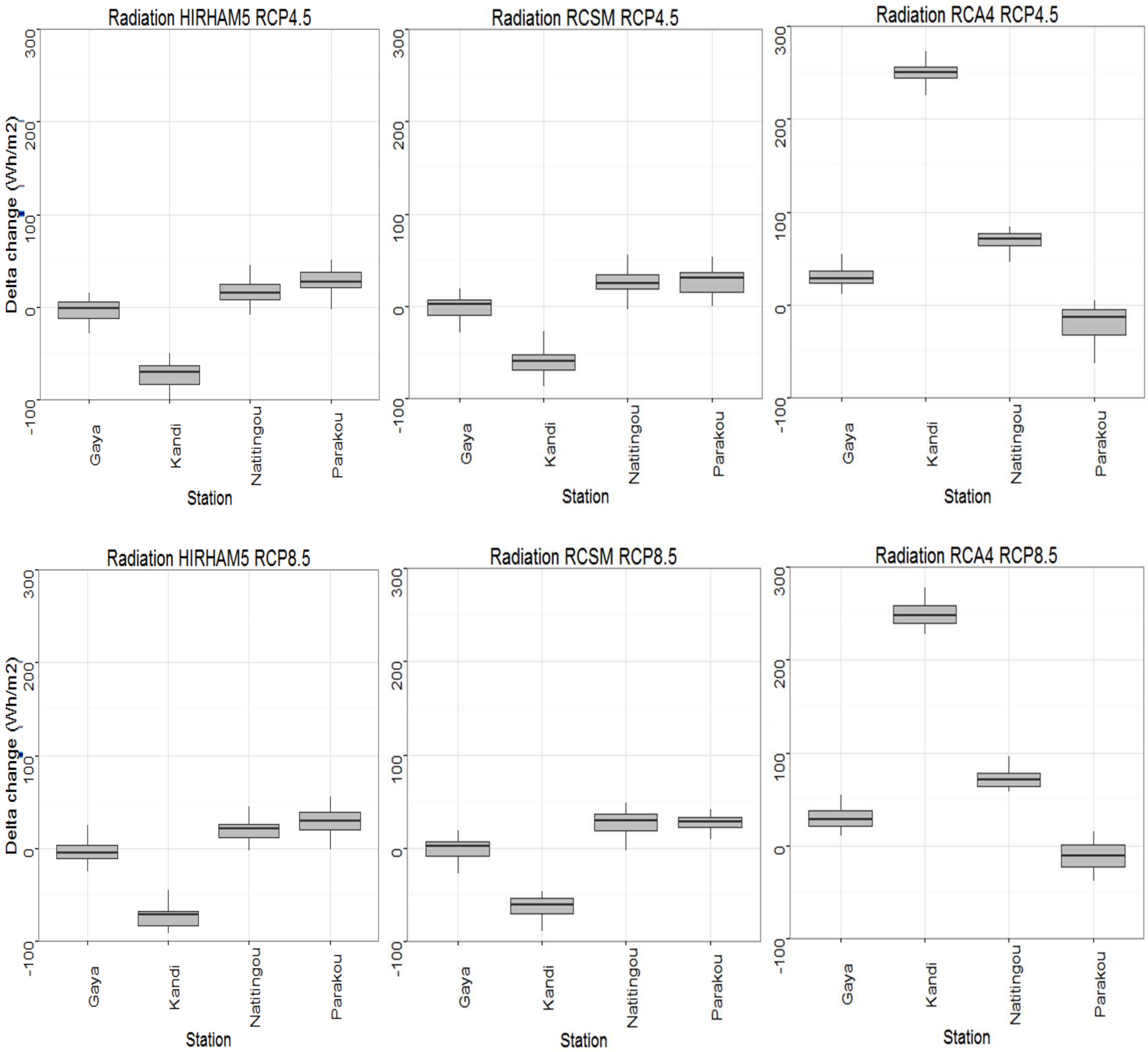

Figure C.1: Annual radiation

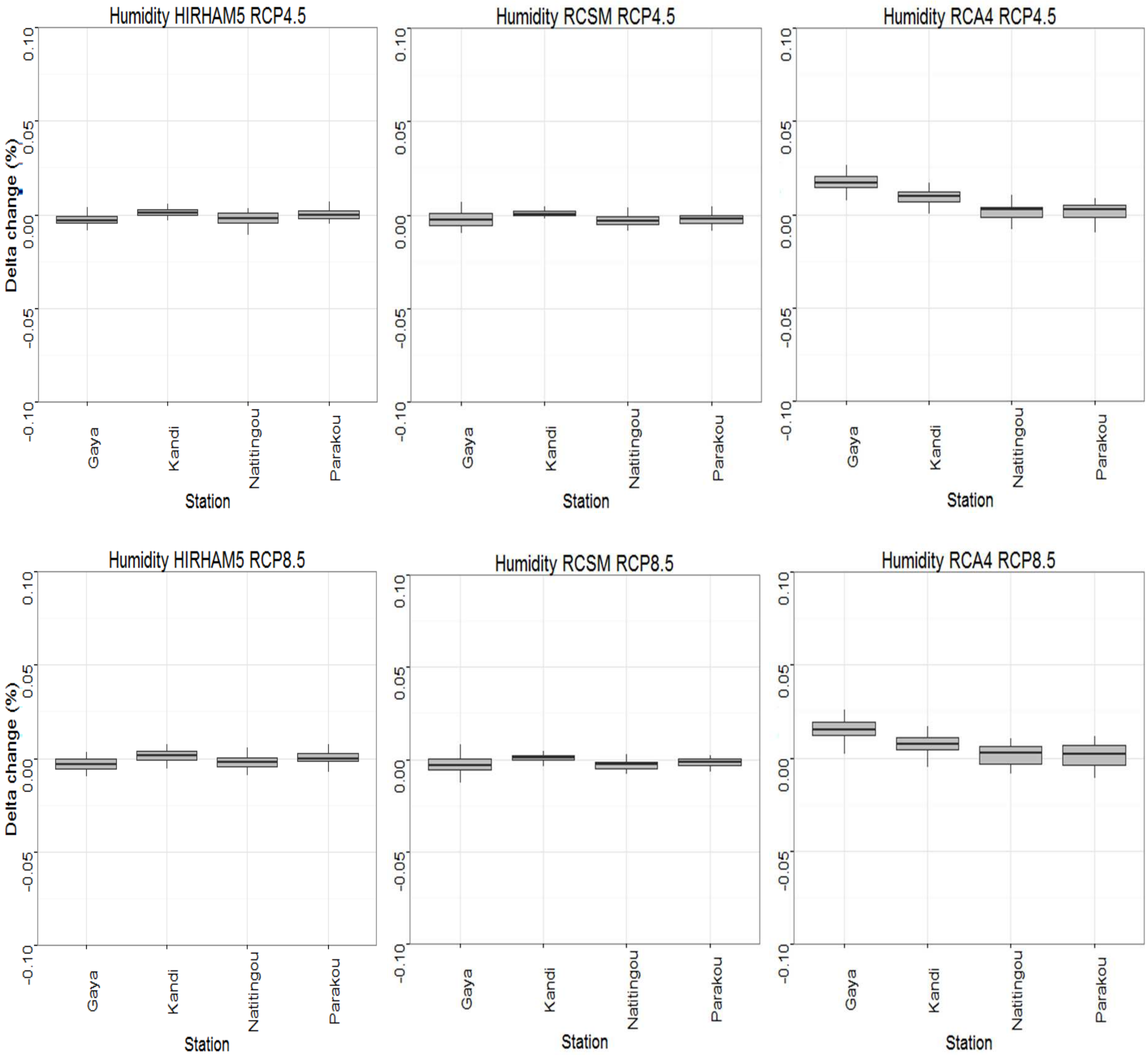

Figure C.2: Relative humidity

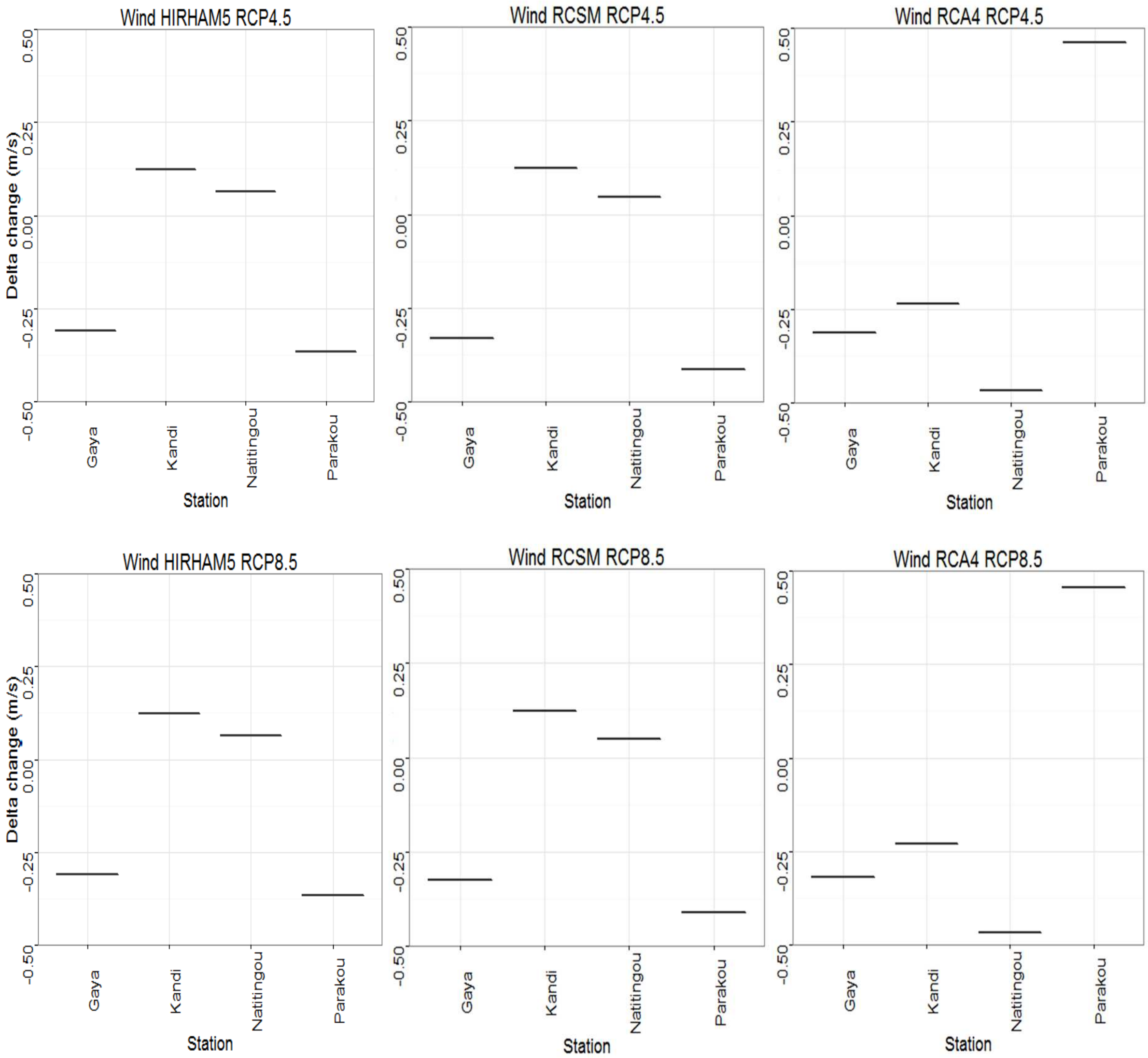

Figure C.3: Wind speed