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Adaptation strategies to climate change in inland valleys in Dano, Burkina Faso

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ABSTRACT

The agriculture in Sub Saharan Africa at many locations is under-performing and lags behind the other continents in terms of yields as well as productivity. The recent progression in the produced quantities is mainly due to an increase in the croplands, which has major effects on the environment. In West Africa, climate variability is one of the causes of low yields as most of the cropping systems are rainfed and the region has one of the most variable precipitation pattern in the World. Climate change, on the other hand, brings more uncertainties to the weather and can be considered as a threat, knowing the severe problem of food insecurity in the continent. The strategies towards a more performing and resilient agriculture comprise the use of inland valleys for intensive agriculture. The use of irrigation and water control infrastructures inside inland valleys is assessed in this study to apprehend the potential for agriculture inside inland valleys, under current and probable future climatic conditions.

Four inland valleys located within the Dano basin have been investigated, in the South West of Burkina Faso, two with reservoirs and irrigated schemes, one with contour bunds, and the last with drainage canals. The four schemes have been equipped to monitor the different water fluxes such as the runoff from the upstream catchment, the water level inside the reservoirs, the shallow groundwater levels with piezometers in the uplands and the bottomlands, and the drainage. The performance inside the four schemes revealed important losses by infiltration and evaporation inside the reservoir-based schemes and high drainage ratio for the others. The water quality showed very low mineral contents for nitrates, nitrites, orthophosphates, and potassium, due to the low fertilizer input, for both the surface water and the groundwater.

The climate records from the city of Dano has been examined to understand the precipitation pattern and the future climate trends with statistical tools. In one out of six and half years, the monthly rainfalls decline by around 80% in June and October corresponding to the beginning and the end of the rainy season, while the seasonal sum from June to October is reduced by 45%. The anomalies detected on eleven models under the scenarios RCP4.5 and RCP8.5 revealed high uncertainties on the precipitation amounts, while the rainy days and the temperatures are expected to respectively decrease from -4% to -35% and increase from +1.3° to +6.8° C.

The effects of selected climate scenarios have been evaluated for rainfed rice in the four schemes with a crop growth model. The AquaCrop model was applied to simulate the effect of the expected increase in temperature and CO_2-level and decrease in precipitation on crop yield and biomass. Results show a rise of yield and water productivity due to higher CO_2-level, whereas rising temperature is lowering these indicators. The effects of water stress are variable and influenced by the soil types and the shallow groundwater levels. The adaptation strategies to climate variability and change are possible only with better storage systems and with improved management. The comparison of the four valleys shows more profits for the reservoir-based schemes in terms of outputs and level of organization of the farmers for the maintenance of the infrastructures, despite the losses by evaporation and infiltration. The other schemes, although benefitting from low investment for their construction, and disposing of flexibility in their use and expansion, lack the required control over the water inflows and outflows, and fail to be productive. The use of shallow groundwater has not been assessed in this study in terms of potential for supplementing the cropping systems in the future and may switch the attention on their exploitation for agriculture in the future.

KURZFASSUNG

Die Landwirtschaft in Subsahara-Afrika schöpft an vielen Orten Potenziale nicht aus und liegt sowohl in Bezug auf die Erträge als auch die Produktivität hinter den anderen Kontinenten zurück. Der jüngste Anstieg der produzierten Mengen ist hauptsächlich auf eine Ausdehnung der Anbauflächen zurückzuführen, was allerdings erhebliche Auswirkungen auf die Umwelt verursacht. In Westafrika ist die Variabilität des Klimas eine der Ursachen für niedrige Erträge, da die meisten Anbausysteme im Regenfeldbau betrieben werden und die Region ein Niederschlagsmuster mit einer der weltweit höchsten Variabilitäten aufweist. Der Klimawandel erhöht die Variabilität meteorologischer Größen und kann als Bedrohung angesehen werden, wenn man das ernste Problem der Nahrungsunsicherheit auf dem Kontinent betrachtet. Die Strategien für eine leistungsstärkere und widerstandsfähigere Landwirtschaft umfassen die Nutzung von Binnentälern für den intensivierte landwirtschaftlichen Anbau. In dieser Studie wird die Durchführung der Bewässerung und weiterer Maßnahmen zur Wasserbewirtschaftung in Binnentälern eingeschätzt, um das Potenzial für die Landwirtschaft in Binnentälern unter den aktuellen und erwarteten zukünftigen klimatischen Bedingungen abzuschätzen.

Im Einzugsgebiet von Dano, im Südwesten von Burkina Faso, wurden vier Binnentäler untersucht: zwei verfügen über Wasserspeicher und Bewässerungssysteme; eines besitzt Konturwälle und ein weiteres nutzt Entwässerungsgräben zur Wasserbewirtschaftung. Alle vier Untersuchungsgebiete wurden mit Messeinrichtungen ausgestattet, um die verschiedenen Wasserflüsse (wie beispielsweise den Zufluss aus oberliegenden Teilen der Einzugsgebiete der Binnentäler), den Wasserstand in den Speichern, die oberflächennahen Grundwasserspiegel mit Piezometern in Hang- sowie Talbereichen und die Entwässerungsabflüsse zu erfassen. Die Auswertung im Hinblick auf die Durchführung von Bewirtschaftungsmaßnahmen innerhalb der vier Systeme belegte erhebliche Verluste durch Infiltration und Evaporation in den Speicher-gestützten Systemen und zeigte hohe Entwässerungsanteile für die anderen Systeme. Die Wasserqualität zeigte aufgrund des geringen Düngemitteleinsatzes sehr niedrige Mineraliengehalte für Nitrate, Nitrite, Orthophosphate und Kalium, und zwar, sowohl für das Oberflächen- als auch das Grundwasser.

Klimadaten der Stadt Dano wurden übersucht, um das Niederschlagsmuster und die Klimatrends mit statistischen Methoden zu ermitteln. In einem aus sechseinhalb Jahren nehmen die monatlichen Niederschläge im Juni und Oktober um rund 80% ab, was dem Beginn und dem Ende der Regenzeit entspricht, während der saisonale Summe um 45% reduziert wird. In elf Modellen unter den Szenarien RCP4.5 und RCP8.5 wurden hohe Unsicherheiten bei den Niederschlagsmengen festgestellt. Die Anzahl der Regentage werden voraussichtlich im Bereich von -4% auf -35% sinken und die Temperaturen im Bereich von +1,3° auf +6,8° C steigen.

Die Auswirkungen ausgewählter Klimaszenarien auf den Regenreisanbau wurden für die vier Untersuchungsgebiete mit einem Pflanzenwachstumsmodell bewertet. Das AquaCrop-Modell wurde genutzt, um die Auswirkungen des erwarteten Anstiegs von Temperatur und CO2-Gehalt sowie der Abnahme der Niederschläge auf den Pflanzenertrag und die Wasserproduktivität zu simulieren. Die Ergebnisse zeigen die Zunahme des Ertrages und der Wasserproduktivität mit steigendem CO2-Gehalt, wohingegen die Zunahme der Temperatur diese Indikatoren negativ verändert. Dagegen ergibt sich in Bezug auf den Wasserstress kein genereller Trend (aufgrund des Einflusses unterschiedlicher Bodenverhältnisse und oberflächennaher Grundwasserstände). Die Anpassungsstrategien an Klimawandel und -variabilität sind nur mit besseren Speichersystemen und einem verfeinerten Management möglich. Im Vergleich der vier Binnentäler erweisen sich dass die Speicher-gestützten Systeme als vorteilhaft in Bezug auf die Erträge und den Organisationsgrad der Landwirte für die Instandhaltung der Infrastrukturen, trotz der Verluste durch Infiltration und Evaporation. Die anderen Wassermanagementsysteme erfordern zwar geringere Investitionen für den Bau und bieten Vorteile in Bezug auf flexible Nutzung und Erweiterungsmöglichkeiten, verfügen aber nicht über die erforderliche Kontrolle der Wasserzu- und -abflüsse und sind daher wenig produktiv. Die Nutzung von

oberflächennahem Grundwasser wurde in dieser Studie nicht auf das Potenzial für eine zukünftige Ergänzung der Anbausysteme bewertet, verdient aber Beachtung bei zukünftigen Untersuchungen im Hinblick auf eine Nutzung für landwirtschaftliche Zwecke.

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LIST OF ABBREVIATIONS

DANIDA	Danish International Development Agency
AIC	Akaike's Information Criterion
BIC	Bayesian Information Criterion
C:CA	Catchment to Cultivated Area ratio
CILSS	Permanent Interstate Committee for Drought Control in the Sahel
CMIP3	Coupled Model Intercomparison Project – Phase 3
CMIP5	Coupled Model Intercomparison Project – Phase 5
CORDEX	COordinated Regional Climate Downscaling Experiment
DGM	General Directorate for Meteorology
ECOWAS	Economic Community of West African States
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FFEM	Global French Environment Facility
HI	Harvest Index
IAASTD	International assessment of agricultural knowledge, science and technology for development
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
MAH	Ministry of Agriculture and Hydraulics
MARHASA	Ministry of Agriculture, Hydraulic Resources, Sanitation and Food Security
CRWS	Cumulative Relative Water Supply
MDG	Millenium Development Goal
MECV-BF	Ministry of Environment and Living Environment –Burkina Faso
NAPA	National Adaptation Programme of Action
NEPAD	New Partnership for Africa's Development
NERICA	New Rice for Africa
NO2-	Nitrites
NO3-	Nitrates
ONBAH	National Office for Dams and Hydraulic Infrastructures
PARIIS-SIIP	Sahel irrigation initiative *Project*
RCP	Representative Concentration Pathways
REY	Rice Equivalent Yield
RWS	Relative Water Supply
SDG	Sustainable Development Goal
SPI	Standardized Precipitation Index
SSA	Sub Saharan Africa
UNDP	United Nations Development Programme
UNECA	United Nations Economic Commission for Africa
WHO	World Health Organization
WP	Water Productivity

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1 Introduction

1.1 General context and problem statement

1.1.1 Water scarcity

Water is nowadays a key factor in global development agenda. The Sustainable Development Goals (SDGs), adopted for the 2015-2030 period by the United Nations, have dedicated their sixth goal to water and sanitation (United Nations General Assembly, 2015), an evolution compared to the Millennium Development Goals (MDGs) where it was principally embodied in the environmental sustainability goal, among others. The SDGs on water address the access to clean water, the water pollution, the efficiency in the use of water for different sectors, the integrated management of water, the protection and restoration of water-related ecosystems, the cooperation and participation at the international and local level inter alia. Water can be considered as the "common currency" between the different SDGs and some regions in the World are expected to be impacted by a reduction of up to six percent of their GDP because of water shortage (World Bank, 2016). Water shortage is identified as a threat worldwide and particularly in developing countries where the consequences go beyond the economic aspects and touch the social and environment with migrations, civil conflicts, and degradation of the environment. The World Economic Forum in his annual global risk report (2017), ranks water crisis as the third global risk in terms of impact.

The African continent is in gross well-watered with an average 670 mm of rainfall per year, but with a high spatial and temporal variability (United Nations et al., 2000). Central Africa receives an annual average of 1430 mm whilst North Africa witnesses the lowest precipitation with 71 mm. With an interannual variability of 40% around the mean, the continent faces the highest uncertainties on its precipitation compared to others. Africa also registers a very low mobilisation of the water resources with a share of only twenty percent of total precipitation transformed into renewable surface and ground water, a factor that drops to six percent in the Sudano-Sahelian region. This reflects important losses in the water cycle principally through evaporation. Some places like the Sudano-Sahelian region are undergoing a growing water scarcity because of manifold issues. From the resource side, the high variability of the rainfall, the changing climate, and the land use change are increasing the unreliability of the precipitation and decreasing its availability as renewable share. From the demand side, the increasing population, the increasing temperatures, the pollution of water, the lack of infrastructures of access and storage of water and their poor management, don't allow an adequate and sustainable use of the resources.

The Intergovernmental Panel on Climate Change (IPCC) fifth report (Niang et al., 2014) described Africa as one of the most vulnerable continents, regarding the climate projection impacts on different sectors and the low capacity of its population to adapt to the related effects. Water and agriculture in the continent will be hugely impacted in the future. The report found high confidence in the warming of the continent during the last century. The increase of the existing stress on the water resources and ecosystems and the aggravation of the vulnerability of agriculture systems is manifested through a reduction of yields especially in semi-arid parts. Nowadays there's a global awareness of climate change as a new global threat, but some studies (Delaney, 2012) have revealed that the Sahel region in West Africa, with a multi-decadal variability in the rainfall pattern, experienced extreme fluctuations in the 50s with a series of floods until the 60s, followed by a series of droughts in the 70s and the 80s. Jung and Kunstmann (2007) in their research on climate modeling for the Volta region in West Africa, worked on two-time slices 1991-2000 and 2030-2039 and concluded in a significant annual increase in mean temperatures by 1.2 to 1.3°C. According to their research, rainfall also will be affected by a delayed onset and an increasing interannual precipitation variability in the early stage of the rainy season. The predictions on Climate Change are based on global and regional models, the results are broad and sometimes contradictory on rainfalls, but experts agree on severe and erratic weather pattern in the future with more intense rainfalls.

SSA has the highest population growth rate in the World with an expected increase from around 1.2 billion in 2016 to 2.4 billion in 2050 (UNECA, 2016) and the part of the population living in water-stressed countries is projected to increase from above 30% in 2006 to 85% in 2025 (UNDP, 2006). The urbanization is a further factor increasing the water demand, as the consumption in rural areas in Africa is sometimes less than the required daily 20 liters per person in many countries, while in the wealthy cities or inside the residential suburbs, the daily access can reach 200 to 300 liters per person (Jacobsen et al., 2013; Ledant, 2013). Africa is the least but fastest urbanizing region in the World and is expected to have a predominant urban share by 2050. To the rising demand for clean water for human consumption is associated the increasing demand of water for economic activities such as agriculture, energy and industries. The population growth is a driver of land use changes, which impacts the water cycle but also leads to pollution.

1.1.2 Impacts in Africa

The droughts in the 70s and the 80s in the Sahel and the Horn of Africa regions have risen the awareness on the vulnerability of the drylands to climate shocks. The IPCC defines the vulnerability as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes". From 1970 to 2014, an estimated 390 millions of people were affected by droughts and floods with more than half a million deaths in Africa (Dingel et al., 2016). The drylands in Africa which cover 46% of the continent area and include the dry sub-humid, the semi-arid and the arid zones, are home to a third of the African population whose livelihoods depend on the exploitation of natural resources, predominantly through agriculture (Morris et al., 2016). The drylands produce 70% of SSA crops and 66% of its cereal and hold 82% of its livestock. Their exposure to climate shocks is hence an issue at the continental level. As a consequence of climate shocks, environmental induced migration is expected to grow together with conflicts whose emergence is correlated with water crisis (Niang et al., 2014). Yet, climate shocks in relation to extreme events such as floods and droughts are not the only water disasters to the low crop productivity in SSA. The high intra-seasonal rainfall variability causes dry spells that are very impactful to crop growth and induces yield loss. According to S. P. Wani et al. (2009), in semi-arid and dry sub-humid tropical environments, the occurrence of dry spells or rainfall deficit of 2 to 5 weeks is 2 out of 3 years and 1 out of 10 years for droughts, causing low productivity and food insecurity. Also, research made by Falkenmark and Rockström in 2004 (Wani et al., 2009), shows that inappropriate on-farm water management causes water stress to plant and leads to yield loss, by reducing the rainfall available as soil moisture for plants from a range of 70-80% for well-managed soils to 40-50% for poorly managed soils. The combined effects of climate variability, climate changes, population growth, land degradation and inappropriate management of water is a concern for the future of the continent in terms of food security, a concern that should be addressed through appropriate strategies.

1.1.3 Adaptation Strategies

The New Partnership for Africa's Development (NEPAD) in collaboration with the African Union, has adopted an agenda for the fifty years to come from 2013, in which one of the seven goals is dedicated to climate resilient and environmentally sustainable economies and communities for the first ten years. The Agenda 2063 (African Union et al., 2016) addresses in its seventh goal the conservation of the biodiversity and the sustainable management of natural resources, the water security, the resilience to climate and the preparedness to natural disasters. Strategies to reach the goal comprehend at the national level the integration of weather and climate resilience policies on planning, budgeting and monitoring, the development and implementation of mitigation and adaptation to the effects of climate change on all sectors of the economy, the promotion of climate-smart agriculture, etc.

In West Africa, the Economic Community of West African States (ECOWAS) has developed an environmental policy (ECOWAS Commission, 2008), in which it identifies the land degradation, erosion and desertification, the degradation of river and lake water resources, and the global environmental problems as part of the major challenges of the region. The policy adopted four strategies among which the strengthening of environmental governance and the promotion of sustainable management of the resources. The organization has mandated the Permanent Interstate Committee for Drought Control in the Sahel (CILSS) for the implementation of its environmental policies. CILSS was created in 1973 following the droughts during this year to formulate and coordinate strategies and policies in thirteen countries of West and Central Africa. One of the main goals of the CILSS is to combat desertification through the development of regional programs, like currently on adaptation to climate change (FFEM/AOC and ACCIC/DANIDA) and on the development of small-scale irrigation (PARIIS-SIIP) (CILSS).

At the country level, the National Adaptation Program of Action (NAPA) has been designed at the global stage as the adapted tool to comprehend the impacts of climate change on different sectors in the country and also to take action plans to adapt and be more resilient in the future (LDC Expert Group, 2009). In Burkina Faso, the NAPA (MECV-BF, 2007) has identified the four most impacted sectors by climate change, among which water and agriculture. Concerning the water sector, the water reservoirs are described as under the threat of the variability of precipitations with extreme events, of rising temperatures and wind speeds, causing damages on infrastructures and increasing water scarcity. On agriculture, the same threats are impacting the crop yields and degrading the soil quality. As for the action plan, twelve priority projects are defined, on which seven concern water and agriculture on the development of irrigation, and the protection of the water resources.

At different levels in the continent, country scale in Burkina Faso, regional scale in West Africa and the continent scale, the question of water and food security in the different policies and programs are related and both vulnerable to climate change. The improvement of the management of land and water is raised as a strategic adaptation solution. Nonetheless, the different policies, strategies, and programs although based on expert knowledge, either lack the integration of scientific assessment of the impacts of climate change on the different sectors or fail to address appropriately the related issues. At the continental and regional scales, the top-down approach towards country-based adaptation strategies doesn't permit an integrated strategy. The African Union together with the NEPAD do not have yet a specified adopted strategy toward climate change or water scarcity, the topic is rather integrated into diverse sectoral programs. The NAPA in Burkina Faso has integrated different models in the assessment of the impacts of climate change: a climate model for climate scenarios, a crop model for the impact on yields and a water model for the impacts on the hydrology. The results show a prediction of a 3.4% and 7.3% reduction in precipitation, and a 0.8°C and 1.7°C increase in temperature respectively by 2025 and 2050, causing decrease and increase of production depending on crops and of location, a deficit of the annual discharge of 55% and 73% for the Mouhoun basin (Black Volta) as an example, respectively in 2025 and 2050. However, there’s no scenario which integrates and assesses the twelve priority projects or any national plan in terms of effectiveness on the resilience of the country. Erguavoen and Wahren (2015) in an assessment of the elaboration process of the NAPA in Burkina Faso, noted the closeness between already existing development programs and climate change adaptation actions. This raises the question of the contribution of the different strategies to a more resilient country, region or continent, but also on the necessity to prioritize the options based on scientific research.

The research on adaptation to future water stresses is manifold and many studies on the impacts of and adaptations to climate change on African agriculture, identified improved water management techniques as a way to improve and secure crops yields from unpredictable precipitations (Dinar et al., 2008; Ngigi, 2009; van de Giesen et al., 2010; Jägermeyr et al., 2016). The lands under irrigation in SSA represent only 4% of the arable lands (IAASTD, 2009), a very low percentage which is not due to water scarcity. Water scarcity has been assessed and qualified by the International Water Management Institute (Molden et al., 2007) to be the results of economical reason in most of SSA countries regarding the small percentage of water withdrawal on the water available (less than 25%), a percentage which can be increased through more investment in infrastructures for storage and exploitation. An adverse impact of climate change is the progression towards physical water scarcity, which is the lack of water resources available to meet the demands of socio-economic activities and environment. Storage is an obvious solution to adapt to future water scarcity and among the different options, inland valleys are described as the untapped potential in SSA.

1.1.4 Inland valleys

According to Rodenburg et al. (2014), “Inland valleys can be defined as seasonally flooded wetlands comprising valley bottoms (fluxial) and hydromorphic fringes (phreatic) but excluding river flood plains” with an estimated area of 190 M ha in Africa. These valley bottoms, in particular, are given different names like bas-fond or fadama in West Africa and are known for their high agro-potential due to their high water availability and their relatively fertile soils, specifically for rice cultivation during the rainy season because of flooded conditions. Rodenburg et al. also identified the global changes as a driver of increasing interest towards inland valleys and of their development, because of the security they can provide in agricultural production which is threatened by drier and more unreliable environments. The need to secure the agricultural production from the uncertainties of the rainfall pattern in drylands has led to research on infrastructures inside inland valleys best adapted to the hydro-morpho-characteristics and functioning of a catchment (Berton, 1988; Albergel et al., 1993; Lidon et al., 1998).

Despite the fact that inland valleys are presented as a reliable solution to climate change for agriculture, some researchers consider instead climate change as a major threat to ecosystems in wetlands in general, that will affect their hydrology. According to Erwin (2008), wetlands are expected to be affected in two ways, the decrease in the number of functioning wetlands within most ecoregions and the shift in the geographical location of certain types of wetlands. Barros et al. (2014) are more specific and consider the hydrological regime, the precipitation and evaporation pattern, and the frequency of extreme events to be affected inside wetlands. The infrastructures in place inside inland valleys are expected to be impacted as well and according to Peel and Blöschl (2011), the design and management of water infrastructures should consider uncertainties under changing conditions to the hydrology, changes induced by the natural fluctuations of the climate and from anthropogenic activities. The agro-potential of inland valleys is hence important to evaluate now and in the future in order to assess their reliability and sustainability as an adaptation solution to climate and land use changes.

1.2 Hypothesis and objectives

This study addresses the following research questions:

(i) What is the hydrological functioning of inland valleys? Inland valleys are very diverse ecosystems even though having common characteristics. The hydrology of inland valleys is of particular interest as it is a key point to assess their potential for agriculture, particularly in semi-arid and sub-humid areas in Africa, but also to evaluate their vulnerability to climate threats.

(ii) How do the agro-systems inside inland valleys perform? The performance of agricultural systems in SSA is globally low according to the literature. The valleys represent a different format with a more intensive agriculture. The diversity of valleys implies a variety in their performances, which is important to understand.

(iii) How uncertain is the climate in Dano under current and future conditions? Climate is an uncertain parameter mostly understood through statistical analyses. The uncertainties are reflected by the contradictory predictions from climate models in the literature. The dynamic of the climate at the local level is hence important to assess.

(iv) What is the potential of inland valleys to adapt to climate variability and change? As a result of a comprehensive assessment on inland valleys hydrology, agriculture and climate, the impacts of changing conditions are important to be assessed and addressed through adapted actions.

The present research aims to assess inland valleys potential as an option to cope with and to adapt to water scarcity and variability by analyzing the biophysical functioning of agricultural systems in place. For that, selected agricultural systems in inland valleys bottomlands with full and partial control of water are under the scrutiny of this research in the Dano basin.

In this respect, the following sub-objectives can be formulated:

- To estimate the water balance of selected inland valleys.
- To assess their agricultural and water performance based on appropriate indicators.
- To statistically calculate the magnitude of climate variability and change in Dano.
- To evaluate the impact of climate variability and change and elaborate adaptation options.

1.3 Description of the study area

The research is conducted in the called Dano basin located in South-West of Burkina Faso in West Africa (see Fig 1.1 to 1.5). The city of Dano belongs in the administrative division to the Ioba province and to the South-West Region. The climate pattern is Sudano-Sahelian with two distinctive seasons, dry and rainy, watered from May to October by a yearly rainfall average of 950 mm. The soils are predominantly plinthosols in the uplands and gleysols in the bottomlands. The basin covers around 580 km^2 and abounds in many inland valleys, of which four have been selected to represent the type of infrastructures and water management already existing in the area. The majority of the inland valleys have basic infrastructures consisting of bunds and canals, used to either reduce the speed of water or to drain the excess of water. The development of reservoirs with irrigated schemes inside inland valleys requires more investment and brings on the other hand more control on the management of the scheme. The selection of the four agricultural schemes in the Dano basin were motivated by the need to understand the potential of inland valleys under different sittings in terms of infrastructures and also management.

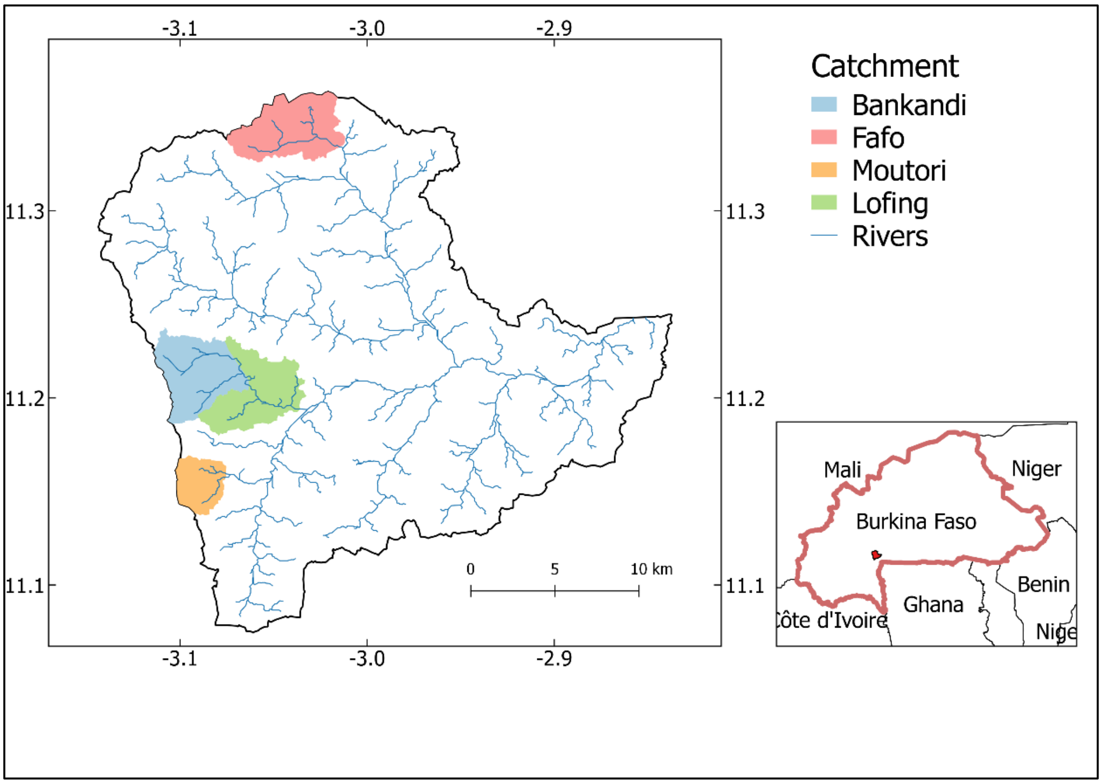


Figure 1.1: Dano basin and selected catchments

Moutori:

Figure 1.2: Irrigation scheme in Moutori

The site is at the coordinates (longitude: -3°07' W; latitude: 11°16' N), it's the closest site to the city of Dano which has around 50 000 inhabitants. The site includes a small dam with an irrigation scheme built in 2000 and 2001. The dam was designed to store a maximum volume of 720 000 m^3 and the contributing catchment has an area of 8 km^2. The irrigation scheme has an area of 20 ha with lined primary, secondary and tertiary canals. The scheme is divided into 90 parcels divided into 3 blocks and the average parcel size covers an area of 0.25 ha. A centralized lateral canal drains the excess of water from the fields. During the rainy season from June to October, rice constitutes the main crop while during the dry season from December to May, many crops are cultivated, mostly vegetables.

Bankandi:

Figure 1.3: Improved inland valley with contour lines in Bankandi

Close to the village of Bankandi, an agriculture scheme with the coordinates (longitude: -3°07' W; latitude: 11°21' N) has been built in 2006. The site is designed with contour lines for rainfed rice for an area of 28 ha. The contributing catchment has a size of 18 km². The site is limited in its downstream part by a national road allowing the drained water to pass through 4 culverts.

Lofing:

Figure 1.4: Improved inland valley with drainage canals in Lofing

The site in Lofing is at the downstream part of the one in Bankandi situated at longitude -3°4' W and latitude 11°19' N. It's the most recent site designed in 2012 with an exploited surface extending every year, with an area of 17 ha in 2014. The contributing catchment is 36 km² in size. Because of the important amount of water during the rainy season, the design has consisted of drainage canals around blocks of parcels for rainfed rice. The drainage canals are interconnected without a centralized canal and end up in a flooded plain.

Fafo:

Figure 1.5: Irrigation scheme in Fafo

The site is located at longitude -03°01' W and latitude: 11°33'N with a dam and an irrigation scheme built in 1987-1988. The dam has a maximum volume of 870 000 m^3 with a contributing catchment of 19 km² and the scheme a size of 7 ha divided into 11 blocks. Every block has an outlet canal connected to the main stream on which the dam was built.

1.4 Outline of the thesis

The thesis starts with the problem statement, the objectives and the presentation of the study area in **Chapter 1**. **Chapter 2** is on the understanding of the functioning of inland valleys agrosystems. The objective of this chapter is to assess adequately the allocation and the use of water in a selected catchment based on measurements and simulations. Field measurements on different components of the water balance such as precipitation, runoff, irrigation, drainage, reservoir water level and groundwater level, are complemented with simulations of the evapotranspiration at the field level with AquaCrop. Analyses presented in **Chapter 3** aim to understand the current management of the inland valleys. It is important to point out the constraints confronted by farmers inside inland valleys agricultural systems. Four group of indicators have been so far identified which allow cross systems analyses on different agricultural systems. The indicators are on the availability of water, the productivity and the impacts. Having observed an abrupt change in the precipitation in 2014 and 2015, enables to analyze how the climate variability impacts the availability of water in the selected schemes. In **Chapter 4**, a look at the current weather uncertainties is taken together with climate predictions, based on historical data and climate predictions. In **Chapter 5,** the impacts of climate variability and change on the inland valleys rainfed rice are analysed through the climate component within AquaCrop and the alternatives to the current management considered. The final conclusions and the recommendations from the study for future research are drawn in **Chapter 6**.

2 Balancing the Dynamics of Water in an Inland Valley Agrosystem Equipped with a Reservoir in Dano, Burkina Faso

Abstract

Small-scale irrigation systems represent a hope for the growth of African agriculture in a context of highly variable rainfalls and increasingly degraded lands. The benefits are high in terms of socio-economic impacts on a largely rural population depending heavily on agriculture. Inland valleys bottomlands represent a promising opportunity to this end thanks to their relative humid environment and fertile soils compared to the uplands. Yet, the attractiveness for the construction of small reservoirs inside the inland valleys in West Africa is questionned by their low performances, requiring to better understand their management. This study intends to comprehend the water functioning inside a reservoir-based agrosystem located in Dano in Southwestern Burkina Faso with the application of a conventional water balance equation on the reservoir and the irrigated scheme. The site has been equipped and monitored during two hydrological years from June 2014 to May 2016 in context with the WASCAL initiative. The results reveal a relatively abundant rainy season allowing the cultivation of rice and a water scarce dry season not covering the demand for the whole scheme. The losses in the reservoir by evaporation and infiltration represent together around 70% while the use for irrigation represents around 30% of the available water. Inside the scheme, around 20% of the precipitations is drained downstream during the two rainy seasons. The estimates of the water fluxes highlight the particularity of inland valleys bottomlands which delay the seasonal exposure to precipitation variability during the rainy season to the dry season with the use of reservoirs. The study positions the exercise of balancing the water as a key step to improve the management of water inside inland valleys.

2.1 Introduction

Inland valleys bottomlands are attracting investments for agriculture in West Africa, particularly the construction of small reservoirs, which allows the development of small-scale irrigation projects. For Rodenburg (2013), many factors can help to explain this situation such as the unreliability of precipitations in semi-arid areas exacerbated by climate change, the increasing pressure on resources due to population growth and also the economic driver of rice consumption. In Burkina Faso, the droughts in the 70s and 80s have entailed the rapid growth in the construction of small reservoirs. Nine out of ten reservoirs have a volume inferior to 1Mm^3 (Cecchi et al., 2008). The attractiveness of small reservoirs is however reversed by challenges on their performance, their governance and their sustainability requiring technical improvements and recurrent need of rehabilitation (Venot et al., 2012; Acheampong et al., 2014; Poussin et al., 2015), all of which demand a better understanding of their design and management.

Inland valleys are varied ecosystems with complex hydrology. Their attractiveness for agriculture investments has entailed many studies to a better understanding of their hydrological functioning. Andriesse et al. (1994) in a characterization of inland valleys in West Africa differentiate two distinct areas, the uplands, and the bottomlands. Many studies on the uplands in the 80s and 90s focused on the hydrology of inland valleys in order to propose the best adapted infrastructure to their development (Albergel, 1988; Windmeijer and Andriesse, 1993; Albergel et al., 1993; Andriesse et al., 1994; Lidon et al., 1998). The research inside the bottomlands, on the other hand, was more on the characterization of their agro-potential, mainly on rice (Andriesse and Fresco, 1991; Giertz et al., 2012; Rodenburg et al., 2014; Danvi et al., 2016). Yet, these evaluations concern non-constructed or simply managed inland valleys.

A focus on the uplands fails to integrate the management of the bottomlands when the consideration of the bottomlands do not question the adequacy of the infrastructures influencing the upland flows. Water management tools recommend systemic and integrated approaches (Brown et al., 2015; Böhme et al., 2016; Lee et al., 2018), moreover in the context of a changing climate, where the future of inland valleys is disputed between a vulnerable ecosystems or a resilient agrosystem abounding potentialities for food security (Tooth, 2017). Yet, establishing the water balance is a technical way of understanding the hydrology of the catchment as well as the management of the agricultural scheme, and also a key step in assessing and improving the scheme performance.

This research tackles the assessment of the water dynamics of an inland catchment in Moutori, in Burkina Faso, by balancing the water fluxes inside the reservoir and the irrigated scheme.

2.2 Methodology

2.2.1 Study area

The research was conducted in an inland valley in Moutori, located in the city of Dano in the South-Western Region of Burkina Faso. The region is full of inland valleys, among which the site in Moutori, chosen for its design and its importance in the social economy of the city. Most of the inland valleys in the region are not equipped with water infrastructures for their management. These inland valleys represent an untapped potential for agriculture as important flows of water transit through them without being exploited. The site in Moutori has the advantage of storing the excess of water during the rainy season, for irrigation during the dry season. The site consists of a small dam of potentially 0.72 Mm^3 receiving runoff generated in an upstream catchment of 7.9 km^2, and an irrigation scheme of 20 ha divided into three blocks. The reservoir and the irrigation scheme were built in 2001-2002 by the former national office for dams and hydraulic infrastructures ONBAH. The reservoir has never spilled to date and the irrigation scheme comprehends 90 parcels of approximately 0.25 ha per farmer, watered under gravity by a network composed of primary, secondary and tertiary concrete canals and drained by a principal canal alongside the whole scheme. The soils inside the irrigated area are principally constituted of gleysol, a characteristic of wetlands hydric soils, while the upper catchment is predominantly composed of plinthosol. The climate is characterized by a rainy season from May to October with an annual rainfall of around 950 mm, during which the scheme is rainfed under rice production. An irrigation campaign is conducted from December to late April for the production of vegetables such as tomatoes and onions. Fig. 2.1 shows the location and the monitoring equipment installed inside the catchment and the irrigation scheme. The upland catchment is equipped with two discharge stations for the understanding of the flow generating process within two sub-catchments. Unfortunately, due to technical issues, the data could not be utilized. The reservoir is equipped with a water level sensor to record the fluctuation of the reservoir at a 3-hour time frequency. Inside the irrigation scheme, two discharge stations were installed, one at the entry to record the irrigation water level, and the other at the outlet of the main drainage canal, to record the drainage water, at a 5-min time frequency. Nine piezometers were drilled to monitor the shallow groundwater fluctuation, together with five already existing wells. Three to five parcels were selected inside the scheme, to monitor the field water management for the main crops.

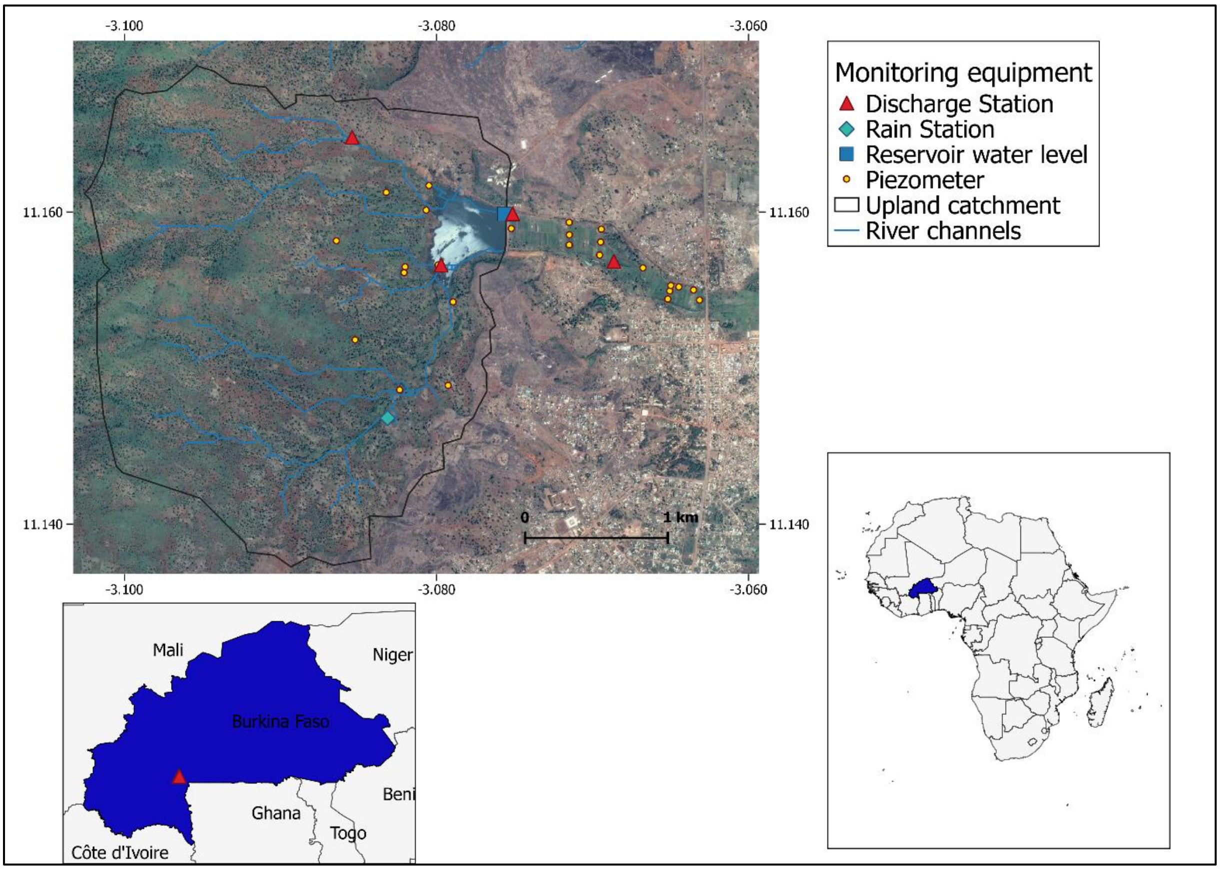


Figure 2.1: Equipment and monitoring locations in the reservoir-based scheme in Moutori.

2.2.2 Scheme water balance

The question of boundaries is important to consider in the balancing of flows and stock of water. For this study, the top soil and the ground of the aquifer are chosen as vertical boundaries because of the shallowness of the groundwater whilst the limit of the schemes are taken for the horizontal boundaries. The periods June-October 2014 and 2015 and December-April 2015 and 2016, corresponding respectively to the rainy and dry campaigns were considered for the time period. The equation of the balance can be expressed as:

$$\Delta Stock_{scheme} = (Precipitation + Irrigation + Inflows)_j - (Evapotranspiration + Drainage + Outflows)_j \quad [2.1]$$

Based on the assumption that lateral contributions to the groundwater (Inflows and Outflows terms) are equal and annul each other, the simplified equation is then:

$$\Delta Stock_{scheme} = (Precipitation + Irrigation)_j - (Evapotranspiration + Drainage)_j \quad [2.2]$$

The records from two rain gauges close to the scheme were used for estimating the daily precipitation.

For the irrigation water, a current meter was used to establish a stage-discharge relation at the entry canal by the velocity-area method. The monitoring of water levels and duration for every irrigation event allows estimating the daily amount and depth. An efficiency of 90% is considered in the volumes effectively reaching the field, to take into account losses.

Reference evapotranspiration is calculated with the FAO Penman-Monteith formula (Smith, Pereira, Raes, & Smith, 1998) using climate data. Based on that, crop-specific potential evapotranspiration is determined with AquaCrop and applying crop coefficients. The Penman-Monteith equation is attested to be one of the most precise method for the estimation of evapotranspiration in semi-arid environments (DehghaniSanij et al., 2004; López-Urrea et al., 2006; Benli et al., 2010).

The drainage has been estimated with the use of a weir at the outlet of the two first blocks of parcels representing more than two third of the scheme area, and then upscaled to the whole by the area ratio method. The use of a triangular thin-plate (so-called Thomson) weir was preferred because more precise in the estimation of low flows and the measured water levels were converted to discharges with the Kindsvarter-Shen equation (Shen, 1981), given by the formula:

$$Q = 8/15 \, . \, Ce \, . \, (2g)^{0.5} \, . \, tg\,(\alpha/2) \, . \, (h + kh)^{5/2} \quad [2.3]$$

With Ce a coefficient of discharge taken as 0.578, h the head of water above the notch, α the notch angle which is 90° in our case and kh a compensation factor representing the surface tension effects, taken as 0.85 mm.

The uncertainties in the estimation of the water balance components are manifold and can be grouped according to Winter (1981) to measurements and regionalization errors. The errors due to measurements are related to the imperfections of the instruments, to sampling design and to the collection of data, while regionalization errors are caused by the use of point-data to represent a time-space continuum. For this study, the errors related to the instruments are estimated. For the precipitation, a tipping bucket rain gauge was used, with a precision of generally 2% to 3%. The tipping bucket gauge has been compared with other rainfall measurement instruments by (Nystuen et al., 1996) and found to have a high correlation with other more precise instruments, however, the instrument underestimates the intensity of extreme rainfalls. The use of a sensor and the manual readings of the water level for the irrigation and drainage terms are attributed a precision of 0.5 cm. In addition, the use of a formula (rating curve for the irrigation and Kindsvarter-Shen equation for the drainage) is imposed a derivation in order to assess the sensitivity to the instruments errors (Bos, 1976):

$$dQ = f'(h).dh \quad [2.4]$$

With dQ the errors in the discharge, dh the water level reading errors and f(h) the stage-discharge formula used. As for the ETP, the errors in the estimation of the evapotranspiration are high considering the different parameters entering in the estimation and the spatial and temporal scaling up (Beven, 1979; Hupet and Vanclooster, 2001), in addition to the different soil water management inside the 90 fields. Yet, a relative value of 20% is chosen to represent these errors.

2.2.3 Reservoir water balance

The balancing of the reservoir is important to further evaluate the availability of water regarding the crop water demands during the dry season. The top soil and the surface water level inside the reservoir are considered for the vertical boundaries and the limits of the surface water level for the horizontal boundaries. The two periods July 14 to May 15 and June 15 to May 16 are taken for the time periods. The equation on the balance of inflows and outflows can be expressed in meter as followed:

$$\Delta H_{reservoir} = (Precipitation + Inflow + Groundwater)_j - (Evaporation + Irrigation + Infiltration + Spillway)_j \quad [2.5]$$

The contribution from the Groundwater has been neglected and the spillway flows are null as the dam has never spilled. The equation can then be simplified to:

$$\Delta H_{reservoir} = (Precipitation + Inflow) - (Evaporation + Irrigation + Infiltration) \quad [2.6]$$

Precipitation and Irrigation are the same terms as for the scheme water balance, except that the value of irrigation is not applied a loss coefficient.

The surface Inflows to the reservoir are estimated as the closing term of the equation during the rainy season:

$$\text{Inflow} = \Delta H_{\text{reservoir}} - \text{Precipitation} + \text{Evaporation} + \text{Infiltration} \qquad [2.7]$$

Potential Evaporation is calculated using the reference evapotranspiration and a multiplying coefficient for water bodies, Smith et al. (1998) recommends for the small reservoir in the tropics a coefficient value of 1.05.

Infiltration can then be estimated by correlating it to the reservoir water level (Fowe et al., 2015; Kingumbi et al., 2004). During the dry season and for the periods without irrigation, Eq. (2.8) can be simplified and the infiltration deducted from the formula:

$$\text{Infiltration} = \Delta H_{\text{reservoir}} - \text{Evaporation} \qquad [2.8]$$

The measurements of the water height are associated with an absolute error of 0.5 cm due to the precision of the sensor, hence the uncertainties in the change of the reservoir water level correspond to 2 x 0.5 cm. The errors in the estimation of the precipitation and the irrigation terms are the same as calculated previously for the scheme. A relative error of 20% is considered for the Evaporation term. The uncertainties relative to the Inflows and the Infiltration terms, taken as residual terms in Eqs. (2.9) and (2.10), can be expressed as:

$$\text{Err}_{\text{Infiltration}} = \left[\text{Err}^2_{\text{Hreservoir}} + \text{Err}^2_{\text{Evaporation}}\right]^{1/2} \qquad [2.9]$$

$$\text{Err}_{\text{Inflow}} = \left[\text{Err}^2_{\text{Hreservoir}} + \text{Err}^2_{\text{Precipitation}} + \text{Err}^2_{\text{Evaporation}} + \text{Err}^2_{\text{Infiltration}}\right]^{1/2} \qquad [2.10]$$

Lacombe (2007) estimated the noise on the infiltrations to be very high when Eq. (2.9) is considered at a daily step and recommended to consider instead longer time steps (10 days in his case) during which no inflows and outflows are recorded.

2.3 Results

2.3.1 Scheme water balance

2.3.1.1 Climate parameters

The characteristics of the climate are presented in Fig. 2.2. The rainy and the dry seasons are easy to identify with the dynamics of precipitations and are contrasted by the extreme drop of the air humidity (from 99% to 9%). The parameters have a similar pattern for the two years, except for the precipitations which show a 132 mm difference with 750 mm and 882 mm respectively during the rainy season from June to October in 2014 and 2015 respectively.

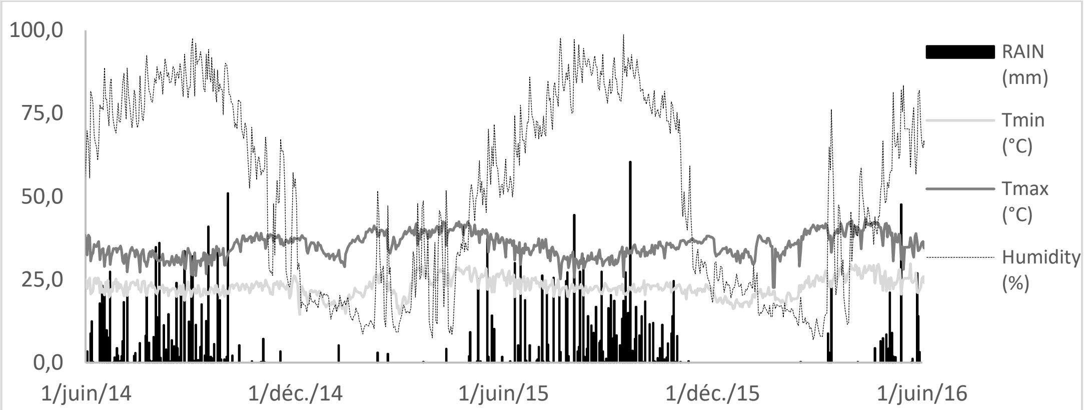


Figure 2.2: Climate parameters in Moutori.

2.3.1.2 *Irrigation:*

The scheme is irrigated only during the dry season. A rating curve has been established at the entry canal. The irrigation scheduling is very flexible and adapts to the users' needs despite a pre-defined schedule at the beginning of the season. The irrigation amounts are estimated respectively for the dry seasons of 2015 and 2016, to 776 mm and 861 mm. The relative errors are respectively 10% and 8% for the two consecutive seasons.

2.3.1.3 *Evapotranspiration:*

During the rainy season, the rice variety TS2 is the main crop inside the schemes. The potential evapotranspiration has been estimated from a parcel with the AquaCrop model, adjusted to site-specific conditions and taken as reference for the whole scheme. During every dry season, a field survey has been conducted to identify the cropping patterns presented in Table 2.1. The crop coefficients and the lengths of growing period for the different crops are summed in Table 2.2. The estimated evapotranspiration amounts are respectively 556 mm and 610 mm for the rainy seasons in 2014 and 2015, and 380 mm and 565 mm for the dry seasons of 2015 and 2016.

Table 2.1: Cropping pattern during the dry season in Moutori.

Area	Maize	Gumbo	Tomato	Onion	Cabbage	Others	Total cultivated	Total scheme
2015 in ha	3.6	1.8	1.6	0.4	0.2	1.8	9.4	20.3
2015 in %	18%	9%	8%	2%	1%	9%	47%	100%
2016 in ha	4.9	2.4	2.9	0.7	0.7	2.5	14.0	20.3
2016 in %	24%	12%	14%	3%	3%	12%	69%	100%

Table 2.2: Crop coefficients and lengths of growth phases for the cultivated crops (from FAO)

Crops	initial phase (days)	Kc - ini	development phase (days)	Kc - dev	mid-season phase (days)	Kc - mid	late-season phase (days)	Kc - late
Maize	20	0.30	35	0.75	40	1.20	30	0.48
Tomato	30	0.60	40	0.88	40	1.15	25	0.80

Onion	20	0.70	45	0.85	20	1.00	10	1.00
Cabbage	40	0.70	60	0.88	50	1.05	15	0.95
others	30	0.60	40	0.88	40	1.15	25	0.80

2.3.1.4 Drainage:

Drainage flows occur only during the rainy seasons. The measured water flows have been extrapolated from two thirds to the whole scheme and are respectively 148 mm and 171 mm in 2014 and 2015. The readings errors represent respectively 10% and 9% of the volumes. The Kindsvarter-Shen equation underestimates the flows corresponding to water levels lower than 6 cm. The measured flows under the threshold of 6 cm represent respectively 22% and 17% of the volumes during the two years.

2.3.1.5 Summary:

The different components of the scheme water balance have been measured and estimated with appreciable precision. Fig. 2.3 shows the monthly balances and Table 2.3 sums the balances for the different rainy and dry seasons.

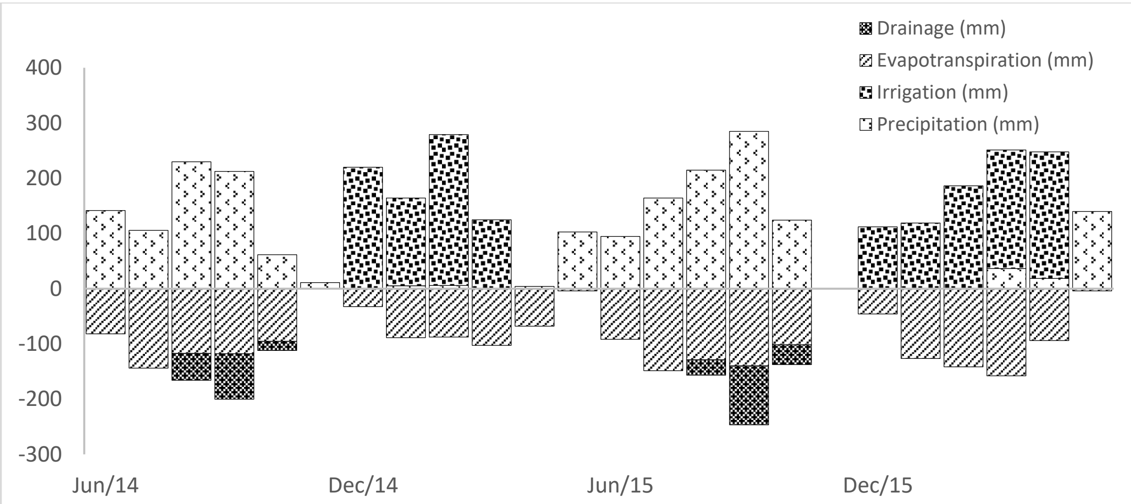


Figure 2.3: Water balance components

Table 2.3: Water balance components per season

Date	Rainy season 2014	Dry season 2015	Rainy season 2015	Dry season 2016	Relative errors
Precipitation (mm)	750	15	882	55	2%
Irrigation (mm)	0	776	0	861	11%
Evapotranspiration (mm)	556	380	610	565	20%
Drainage (mm)	148	0	171	0	10-13%

2.3.2 Reservoir water balance

2.3.2.1 Precipitation and Irrigation

The volumes are converted to height and vice-versa with the use of a volume-height curve from Schmengler (2011). The precipitation and irrigation terms, as well as their relative uncertainties, are the same as for the scheme water balance without the losses on the irrigation flows. The corresponding volumes are respectively 0.066 Mm^3 and 0.11 Mm^3 for the precipitations and 0.081 Mm^3 and 0.134 Mm^3 for the irrigation for the two periods.

2.3.2.2 Evaporation

The evaporated water corresponds to around 1900 mm and 2100 mm during the two years, equivalent to 0.162 Mm^3 and 0.271 Mm^3 in volumes. The volumes are low during the rainy seasons and high during the dry seasons.

2.3.2.3 Infiltration

As for the infiltration, the periods of receding of the water start at the end of the rainy season, usually in the beginning of October. The reservoir water balance equation has been applied to periods without rain and irrigation events from October to December. The periods of calculation and the values of infiltration and related errors are summed in Table 2.4. The values of infiltration presented in Fig. 2.4, are comprised between 0 and 4mm per day without any visible trend with the fluctuations of the reservoir water level. The average value of 1.5 mm has been considered for the daily rate for both years. The corresponding volumes are respectively 0.044 Mm^3 and 0.069 Mm^3. The relative errors equivalent to the standard deviation to the mean value are around 44% for both years.

Table 2.4: Estimation of infiltration and related errors in Moutori.

Initial date	End date	$Hres_{ini}$ (mm)	$Hres_{end}$ (mm)	ΔH (mm)	Evaporation (mm)	Infiltration (mm/day)	Err_{eva} (mm/day)	Err_{Hres} (mm/day)	Err_{inf} (mm/day)
14-Oct-14	24-Oct-14	2458	2391	68	53	1.4	0.5	1.0	1.1
25-Oct-14	1-Nov-14	2384	2330	54	38	2.3	0.5	1.4	0.8
5-Nov-14	18-Nov-14	2315	2220	95	75	1.5	0.6	0.8	0.9
19-Nov-14	10-Dec-14	2216	2060	156	118	1.8	0.6	0.5	0.6
21-Dec-14	26-Dec-14	1828	1786	42	37	1.0	0.7	2.0	2.6
31-Dec-14	5-Jan-15	1689	1636	53	37	3.1	0.7	2.0	0.9
10-Jan-15	15-Jan-15	1521	1483	38	33	1.0	0.7	2.0	2.7
4-Feb-15	9-Feb-15	1090	1042	48	36	2.5	0.7	2.0	1.1
11-Feb-15	16-Feb-15	907	870	37	31	1.2	0.6	2.0	2.2
4-Nov-15	10-Nov-15	3783	3743	40	30	1.6	0.5	1.7	1.3
11-Nov-15	14-Dec-15	3735	3490	245	218	0.8	0.7	0.3	1.2
20-Dec-15	28-Dec-15	3378	3319	59	53	0.7	0.7	1.3	2.8
1-Jan-16	11-Jan-16	3247	3169	78	69	1.0	0.7	1.0	1.8
15-Jan-16	25-Jan-16	3086	3005	81	67	1.5	0.7	1.0	1.1
29-Jan-16	8-Feb-16	2907	2814	93	79	1.4	0.8	1.0	1.2
12-Feb-16	22-Feb-16	2707	2615	92	77	1.5	0.8	1.0	1.2
15-May-16	23-May-16	1423	1353	70	44	3.3	0.5	1.3	0.5

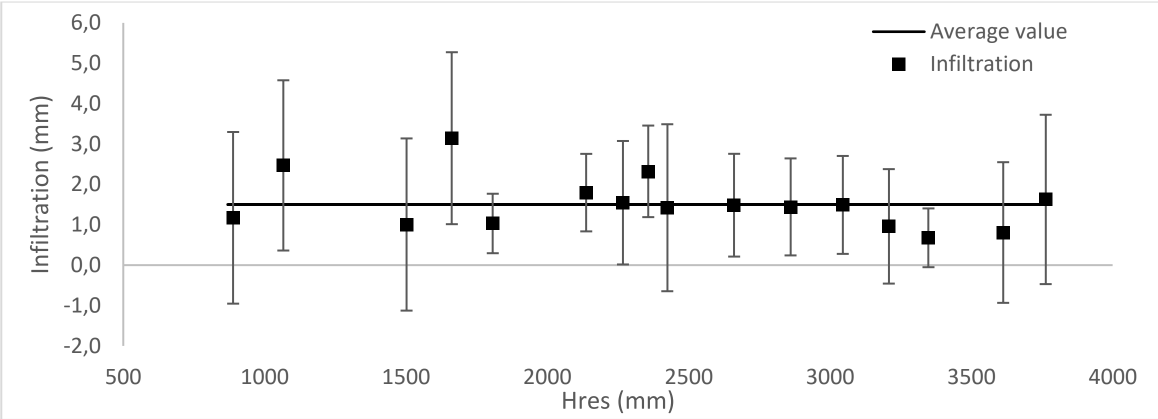


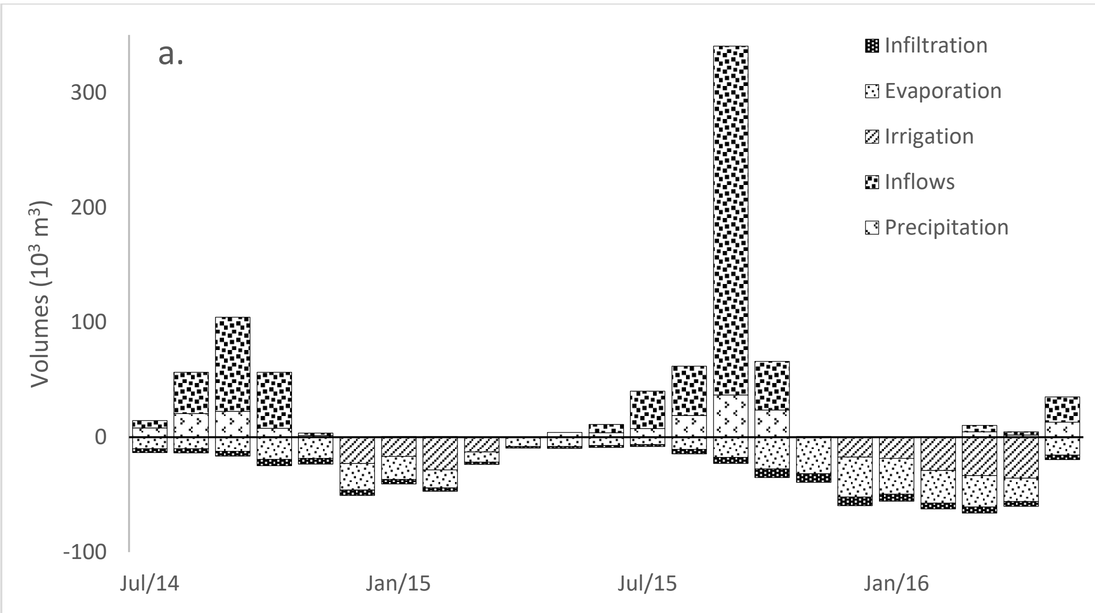
Figure 2.4: Infiltration vs reservoir water level.

2.3.2.4 Inflows

The inflows term is taken as the closing term of the reservoir balance equation during the rainy season. The estimated volumes for the two rainy seasons are respectively 0.175 Mm^3 and 0.46 Mm^3.

2.3.2.5 Summary:

Fig 2.5- a. and b. present the inflows and outflows of the reservoir on a monthly basis and the reservoir water level fluctuation and Table 2.5 presents the numerical values of the monthly inflows and outflows.



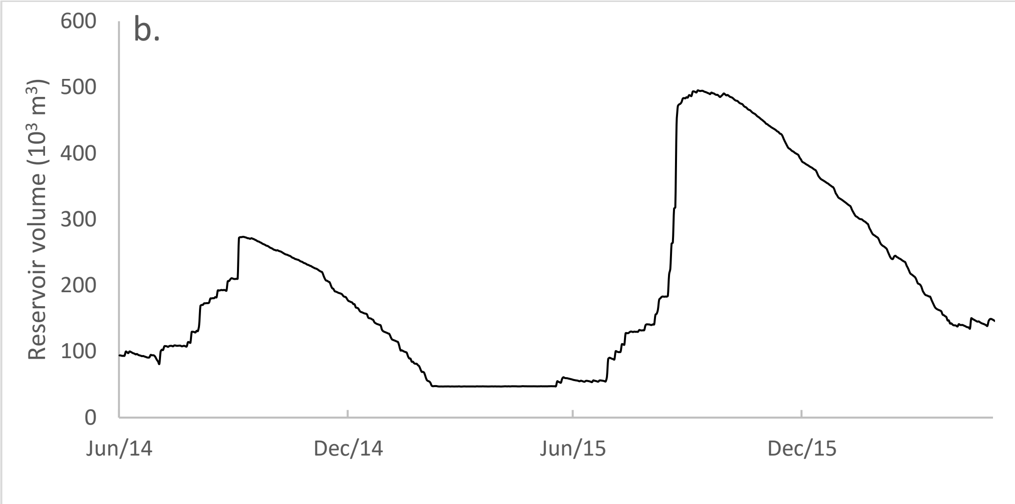


Figure 2.5: a. Components of the reservoir water balance, b. the reservoir water level dynamics.

Table 2.5: Water balance components and relative errors per year

Date	July 14 - May 15	+/-	June 15 - May 16	+/-
Precipitation (Mm^3)	0.066	3%	0.11	3%
Irrigation (Mm^3)	0.081	11%	0.134	11%
Evaporation (Mm^3)	0.162	20%	0.271	20%
Infiltration (Mm^3)	0.044	44%	0.069	44%
Inflows (Mm^3)	0.175	71%	0.459	41%

2.4 Conclusion and discussion

The construction of small reservoirs inside inland valleys is of high importance in semi-arid regions to reduce the vulnerability of agriculture to climate variability. The assessment of the water balance in both the reservoir and the irrigated scheme allows to better understand the dynamics of water storage and transfer, which makes the improvement in their use possible. In the case of Moutori, a close monitoring of the water fluxes was set in place to assess the water balance of the reservoir and the irrigated scheme with the related errors.

The scheme water balance was positive during the two rainy seasons with a higher exceeding for the second year showing the effect of the variability of the precipitations. The drainage waters represent around 20% of the inflows for both years despite the differences in the balance. The balance during the dry seasons is more influenced by the management, with the area to be cultivated, the frequency and depth of irrigation and the type of crops depending on farmers' choices. For instance, the farmers estimated the reservoir stock insufficient to cover the scheme water needs and reduced the cultivated area to 47% and 69% of the scheme surface respectively in 2015 and 2016. As for the scheduling, the frequency of the irrigation events was flexible and varied from 2 weeks to few days, an increase along the season due to hotter temperatures. These decisions resulted in a water shortage with a complete depletion of the reservoir in March 2015, causing important losses to the farmers. The absence of drainage during the dry seasons in opposition to the rainy seasons shows the influence of the shallow groundwater during the rainy seasons, depicted by flooded parcels in August and September. The management of the scheme by the farmers is informal without the use of any technical tool, although based on experience from previous years.

The results from the reservoir water balance depict the hydrological behavior of the catchment as well as the losses. The annual runoff coefficients are low, 5% and 7% for the two years. Yet, the volume of the reservoir almost doubled in the second year for a 100 mm difference in the precipitations. This is typical of semi-arid catchments (Ceballos and Schnabel, 1998; Mekki et al., 2006; Jarihani et al., 2017) and illustrates the non-linear response of the catchment, the runoff being driven by the distribution of the precipitations, the land use and the soil saturation. The assessment also reveals high losses in evaporative demand and infiltration representing together 75% and 69% of the water available during the two years. The demand for agricultural uses, although not covering the entire scheme during the two dry seasons, represent 30% and 27% of the volumes available. Fowe et al. (2015) found as well low water use ratio (less than 20%) and high evaporative losses (60%) for a small reservoir in Boura not far from the area of study. Sekyi-Annan et al. (2018) found in Northern Ghana a little higher water use ratio of around 37% in a medium-scale reservoir. The evaporative demand of around 2 m per year is a limit to the water availability for socio-economic uses that hampers the performance of small reservoirs and questions their adequacy to semi-arid environments (Liebe et al., 2007). The siltation inside the reservoir has not been considered, as the dam is relatively young. Yet, in a study on three small reservoirs around Dano including Moutori, Schmengler (2011) found a reduction of 10% to 15% of the initial volume in less than 20 years.

This study reveals the double benefits from the surface and the shallow groundwater when constructing small reservoirs inside inland valleys bottomlands. The impacts of the climate variability are more incurred during the dry season due to the catchment behavior while the rainfed cultivation benefits from the shallow groundwater. The balancings of the scheme and reservoir represent an important step in the assessment of the performance of the agrosystem in place in Moutori.

3 Water Use inside Inland Valleys Agro-Systems in the Dano Basin, Burkina Faso[1]

Abstract

The hydrological behavior of inland valleys agro-systems is investigated in the Dano basin in South-Western Burkina Faso. Four inland valleys, two with irrigation reservoirs, one with contour bunds and the last with drainage canals were monitored during two hydrological years from June 2014 to May 2016 and compared. A set of indicators on their reliability, their productivity and on the impacts on their environment were assessed. The indicators were chosen to allow spatial and seasonal comparison among the schemes. The results showed a rather abundant rainy season in the four schemes allowing the rain-fed cultivation of rice, with more available water in the simply designed schemes. The irrigation frequency inside the reservoir-based schemes is found to affect their efficiency during the dry seasons. As for the productivity, the reservoir-based schemes perform better than the rest because of a better control of the inflows and drainage system. In terms of impacts, three out of four schemes have low impacts on their downstream users with a drainage ratio over 60%, and 30% for the last one, which depicts also large amounts of unused water, especially for simple designed inland valleys. On the water quality aspects, the concentration of nitrates, nitrites, potassium, and orthophosphates in the four schemes respect the norms for drinking water, due in part to low fertilizer applications, although having a high potential for eutrophication. The study provides technical elements for comparison between different types of inland valley schemes and highlights their impacts on the water cycle.

3.1 Introduction

The economy of many African countries is impacted by the inter-annual and seasonal variability of precipitation (Brown and Lall, 2006; Barrios et al., 2010). The agriculture sector is for the most part vulnerable to dry spells and droughts, and experts agree on severe impacts of climate change in the future, particularly in the semi-arid regions (Roudier et al., 2011; Niang et al., 2014; Sultan and Gaetani, 2016). The vulnerability of agriculture is in part due to non-adapted farming systems, which are rainfed for almost 96% of the cultivated area and necessitate appropriate storage systems to compensate for the variability of the precipitations (MacCartney and Smakhtin, 2010; Delaney, 2012). The average storage capacity is around 200 m^3 per person, versus 2400 in China and 6000 in North America (Jacobsen et al., 2013).

The adoption of agriculture water management techniques is commonly presented as a resilient way to produce food and alleviate poverty in manifold projects in Africa, among which the construction of small reservoirs and the development of inland valleys (Delaney, 2012; Venot et al., 2012). Inland valleys bottomlands are flooded landscape elements during a part

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of the year. Compared to the uplands which are mostly degraded, the valley bottoms and the hydromorphic fringes provide more available water through the rather shallow groundwater and the accumulation of surface runoff and interflow, and also more fertile and suitable soil for agricultural use (Dossou-Yovo et al., 2017; Djagba et al., 2018). The development of agriculture inside inland valleys bottomlands, beforehand constrained by water-related diseases such as malaria, bilharzia, onchocerciasis, and trypanosomiasis, is becoming increasingly important under the economic driver of rice consumption in Sub Saharan Africa (Rodenburg, 2013; Balamurugan et al., 2017; Zenna et al., 2017). For Rodenburg (2013), the low performance of the farming systems hinders the potential of inland valleys, as 10% of the estimated inland valleys area can satisfy the rice consumption of the whole continent. Yet, the consequences of agriculture development inside inland valleys on the hydrology and on the water quality are over shadowed by their economic performance.

The literature on the performance of small agricultural schemes in West Africa is mainly focused on small dams, and generally depicts a poor performance due to manifold reasons: (i) low productivity characteristic of low inputs (Livingston et al., 2011; Poussin et al., 2015; Woodhouse et al. 2017), (ii) water management challenges reflecting the poor level of organization (Venot et al., 2012; Poussin et al., 2015; Mutambara et al. 2016; Sekyi-Annan et al., 2018), (iii) poor infrastructures planning, design and maintenance (Venot et al., 2012; Poussin et al., 2015; Sekyi-Annan et al., 2018; Yira et al., 2019), (iv) and transport and markets issues (Livingston et al., 2011; Hollinger and Staatz, 2015; Mutambara et al. 2016). McCartney and Smakhtin (2010) advocated the need to extend the performance assessment to other storage options such as natural wetlands, ponds, and aquifers among others, in order to understand their potential to cope with rainfall variability and to alleviate food security.

Bos et al. (2005) defined the performance assessment of any type of irrigated scheme as the "systematic observation, documentation and interpretation of activities related to irrigated agriculture with the objective of continuous improvement". Different methods exist to assess the performance of irrigation systems such as direct measurements (Bos et al., 2005; Gorantiwar and Smout, 2005), Analysis Hierarchy Process (Montazar et al., 2013; Azarnivand et al., 2015; Sun et al., 2017), Fuzzy set theory (Huang et al., 2015; Kumari and Mujumdar, 2017) and with the use of Remote Sensing (Wu et al., 2015; Basukala et al., 2017; Elnmer et al., 2018), etc. According to Elshaikh et al. (2018), there is not one agreed method for the evaluation because of differences in the objectives and in the nature of the irrigation systems. Yet, to allow comparison between different agricultural schemes, common characteristics must be found among the schemes. According to Molden et al. (1998), not all indicators allow cross-systems comparison, those on the outputs and the impacts suit more than the ones on internal processes which are site-specific. For Malano and Burton (2001), the service delivery, the productive efficiency, and the environmental performance are the domains of importance in a comparative process.

This study aims to benchmark the water use inside four inland valleys in the Dano basin, under different infrastructures and water management. Meaningful indicators on the management in the delivery system, on the generated outputs from the irrigated fields, and on the impacts on the environment are used to assess the adequacy of the schemes, the productivity of the systems, and the impacts on downstream users.

3.2 Materials and methods

3.2.1 Site description

The research has been conducted in four agricultural schemes in the Dano basin, two with a control over the irrigation system designed with reservoir and irrigation canals in Moutori and Fafo, and the two rainfed lowlands with partial control systems, one designed with contour bunds in Bankandi and the other with a drainage system in Lofing (see Fig. 3.1 and Fig. 3.2). The sites were selected to allow cross-comparison between different agricultural schemes such as reservoir-based systems with control management of water versus water harvesting schemes, and between seasonal changes such as rainy season versus dry season. The study area is part of the Sudanian agro-ecological zone with one rainy season from May to October and a dry season for the rest of the year. Rice is the main crop during the rainy season cultivated from June to October, whereas maize and vegetables are cultivated during the dry season from December to April. The soils are predominantly gleysol. Major features characterizing the schemes are provided in Table 3.1.

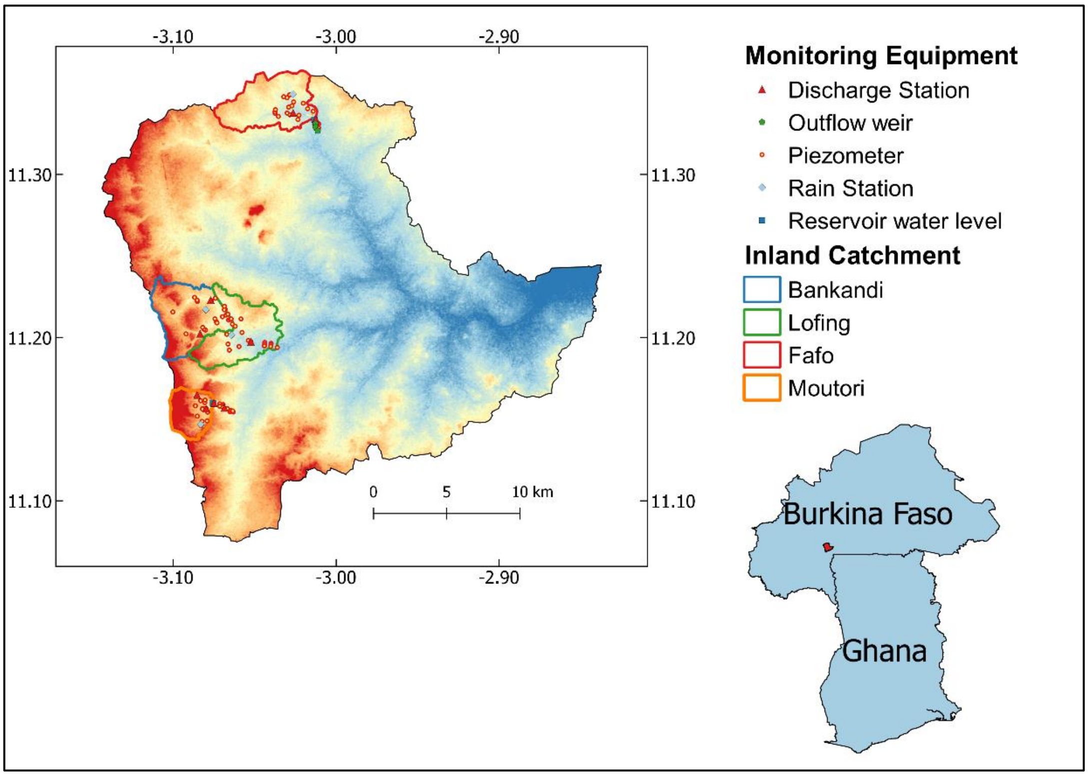


Figure 3.1: Dano basin and selected catchments with monitoring equipment

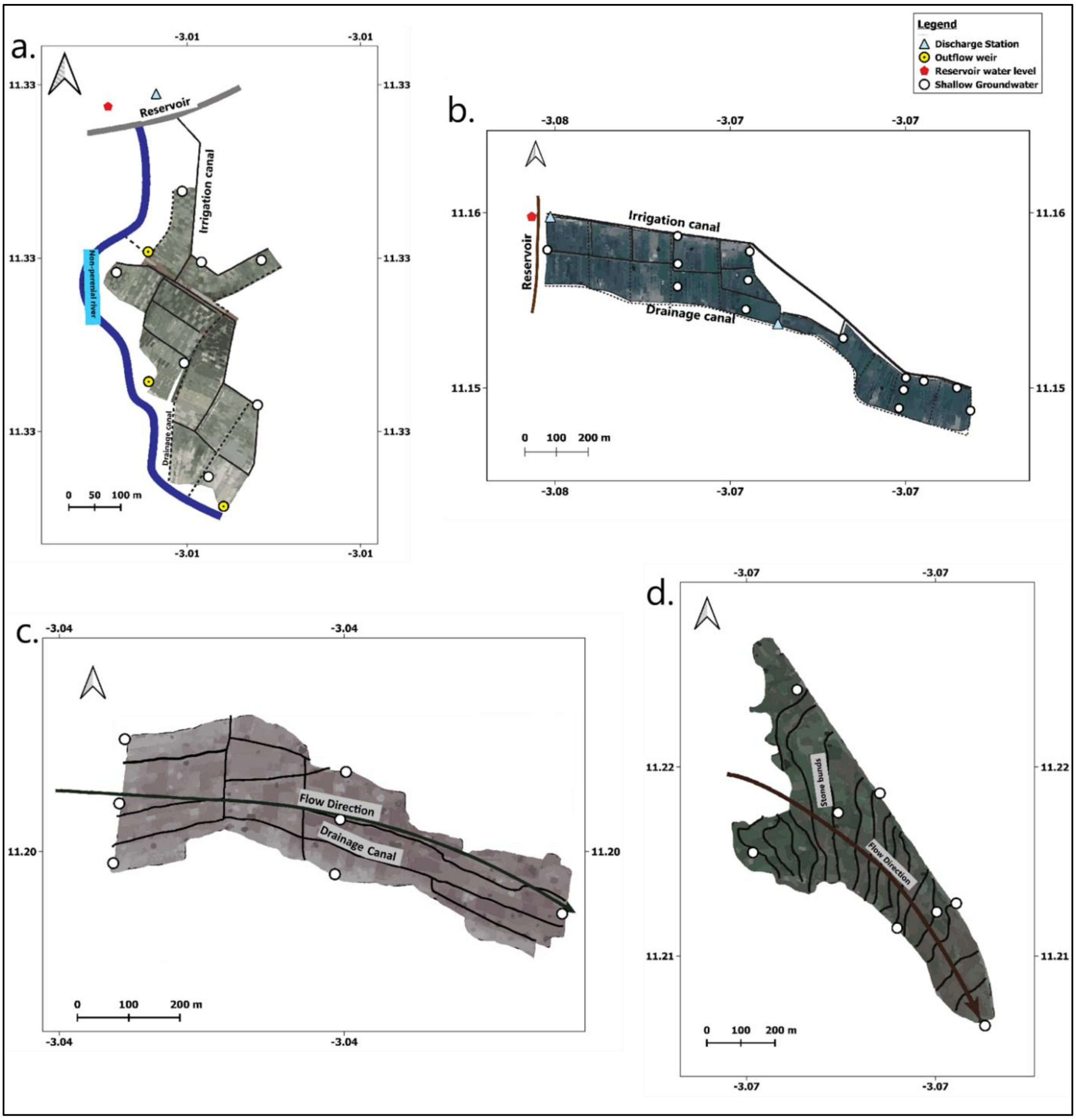


Figure 3.2: Selected schemes with: (a) Reservoir with irrigated schemes in Fafo, (b) Drainage canals in Lofing, (c) Reservoir with irrigated scheme in Moutori, and (d) Contour bunds in Bankandi

Table 3.1: Characteristics of agricultural schemes at selected sites

	Bankandi	**Fafo**	**Lofing**	**Moutori**
scheme water system	contour bunds	reservoir with irrigation canals	drainage canals	reservoir with irrigation canals
Department	Dano	Koti	Dano	Dano
latitude	11.213790°	11.329184°	11.195560°	11.158074°
longitude	-3.067576°	-3.012053°	-3.040072°	-3.069486°
Contributing catchment (km^2)	18.41	19.08	36.31	7.97
Cultivation area (ha)	27.8	6.6	16.8	20.3

cropping seasons	Rainy	Rainy and dry	Rainy	Rainy and dry
Main crop	rice	rice, maize, vegetables	rice	rice, maize, vegetables
Reservoir capacity	-	0.48 Mm^3	-	0.36 Mm^3
Date of establishment	2006	1987-1988	2012-2013	2001-2002

3.2.2 Performance indicators

A system approach was developed covering different aspects such as the farmer level, the scheme level and the supplying catchment to assess the performance of these agro-systems. This approach consisted to apprehend the factors affecting the agricultural production inside the selected inland valleys and focused on: (i) the water management at the field level which required to monitor the crop growth, (ii) the water management at the scheme level which consisted to estimate the water fluxes between the contributing catchment and the scheme, and (iii) the potential negative impact of these schemes on their surroundings. The approach was backed by the collection of technical data in the field and by information gained in discussions with farmers, farmers' associations and agricultural extension services. Analyzing this information broadens the view towards an interdisciplinary perspective in order to better understand the management practiced in the schemes and go beyond the determination of indicators, to understand the reasons for under-performance as depicted in the literature, and further to derive improvement strategies. Three sets of indicators were selected on the water availability, on the productivity, and on the impacts.

3.2.2.1 Cumulative Relative Water Supply

The RWS and the CRWS are both proven indicators of water availability (Rowshon et al., 2003; Gorantiwar and Smouth, 2005; Wellens et al., 2013). The relative Water Supply (RWS) confronts the inflows with the demands inside a scheme, and is expressed as followed:

$$RWS = (Precipitation + Inflows) / Evapotranspiration \qquad [3.1]$$

The Cumulated Relative Water Supply is aggregated based on the RWS on a daily basis:

$$CRWS = \sum t\ RWSt \qquad [3.2]$$

3.2.2.2 Productivity

The indicators on the agricultural outputs can be summed to the productivity, which is defined as a ratio between the output and the related input and many formulas exist in the literature. Bos et al. (2005) defined different indicators of productivity, of which Eq. (3.3) can be used in the four schemes:

$$Productivity\ (kg/m^3) = Yield\ (kg/ha)\ /\ Total\ water\ supplied\ (m^3/ha) \qquad [3.3]$$

3.2.2.3 Rice Equivalent Yield (REY)

The productivity indicator is inadequate when comparing different cropping systems. The Rice Equivalent Yield (REY) is commonly used to establish an equivalency between rice and other crops such as maize, gumbo, and tomato, through the prices (Biswas et al., 2006; Nayak et al., 2012; Gathala et al., 2014; Kumar et al., 2018), and defined by Eq. (3.4):

$$REY_{crop} = Yield_{crop} \text{ x } Price_{crop} / Price_{rice} \quad [3.4]$$

The prices of crops are volatile, changing from one producer to another, from the producer level to the local market, from one local market to another, and with years, depending on the demand. The prices from government reports on cereals and vegetables (MAH, 2011; MARHASA, 2015) were used instead.

3.2.2.4 System Drainage Ratio

The impacts on downstream users can be assessed through the system drainage ratio (Malano et al., 2004; Vincent et al., 2007; Bos, 2012) expressed in Eq. (3.5):

$$System\ Drainage\ Ratio = Total\ Outflows / Total\ Inflows \quad [3.5]$$

3.2.2.5 Water Quality

Studies on soil nutrients deficiency in Africa identify nitrogen (N) phosphorus (P) and potassium (K) as the required minerals for enhanced crop productivity (Kihara et al., 2016; Youl et al., 2018). Yet, the soil deficiency together with the low fertilizer application in the continent, is reversed by an excess of nutrients in water, conducting to eutrophication (Masso et al., 2017), all of which make necessary to analyze the concentrations of nitrates, nitrites, orthophosphates and potassium in surface water and groundwater around the selected scheme in Dano.

3.2.3 Data Collection

In the absence of historical data, the four catchments were equipped with climate stations, irrigation and drainage sensors, and discharge stations (Fig. 3.2).

3.2.3.1 Precipitation

The precipitations were recorded with tipping bucket rain gauges, inside three climate stations, each set at a five min interval, and interpolated in the basin by triangulation with the use of Thiessen polygons (Han and Bray, 2006). The daily precipitation values were iterated with the use of the formula:

$$Precipitation = \sum_i P_i \ . A_s \quad [3.6]$$

With Pi the recorded precipitation in a 5 min interval, and As the cultivated area.

3.2.3.2 Inflows

The irrigation water in the reservoir based schemes is estimated through the monitoring of the water level dynamics inside the irrigation canal (with a sensor and manually). As for the other schemes, the inflows were measured with two discharge stations in Bankandi and one in Lofing. A current meter was used to establish a stage-discharge relation at the entry canals by the velocity-area method (Gore and Banning, 2017). The monitoring of water levels and duration with a sensor allowed estimating the daily amounts.

$$Inflows = \sum_i f(h_i)\ .\eta \qquad [3.7]$$

With hi the mean water level inside the irrigation canal during the period Δi, f(h) the stage-discharge function, and η an efficiency coefficient corresponding to 90% in the reservoir-based schemes, and to 1 in the other schemes. The efficiency coefficient of 90% was taken to account the conveyance losses based on measurements in concrete canals by Sekyi-Annan et al. (2018).

3.2.3.3 Evapotranspiration

The crop evapotranspiration is calculated for the major crops during the different seasons. Rice is irrigated in Fafo and rainfed in the three other schemes during the rainy season, and maize and tomato are the main crops irrigated during the dry seasons in the reservoir-based schemes. The crop evapotranspiration is calculated by the following equation from the FAO guidelines (Smith et al., 1998).

$$Evapotranspiration = \sum_i \sum_j Kc_{ij}\, ETo_i A_j - \sum_i P_i\ .A_s \qquad [3.8]$$

With ETo_i the reference evapotranspiration at day i, A_j the cultivated area of crop j, and Kc_{ij} the crop growing coefficient at day i for the crop j.

3.2.3.4 Outflows

As for the outflows, the drainage water could not be measured with good precision in Bankandi, Fafo and Lofing due to floodings at the outlets. The drainage term is taken as the closing term of the water balance equation by neglecting the change in storage:

$$Total\ Outflows = Total\ inflows - Evapotranspiration \qquad [3.9]$$

3.2.3.5 Production

At the end of the cropping seasons, the weighted productions and corresponding surfaces were collected with the extension services in each scheme, except for Moutori in the dry campaigns during which the productions were approximated by samplings from three to five plots for each crop. Three fields were selected inside each scheme, and monitored twice a week to evaluate the stresses to the canopy growth.

3.2.3.6 Water Quality

The water quality was also sampled and tested for nitrates, nitrites, orthophosphates, and potassium during the rainy season of 2015 four times, the 9th and the 28th of August, the 27th of September and the 21st of October, to monitor the pollution from fertilizer input. In each site, four locations were selected: two at the inlet and outlet of the agro-systems concerned the surface water and two inside boreholes close to the agro-systems in the upstream and downstream parts. The concentrations were analyzed in situ with a spectrophotometer, with the cadmium reduction method for nitrates (Sastry et al., 2002), the diazotization method for nitrites (Sreekumar et al., 2003), and the ammonium-molybdate colorimetric method for phosphorus (Pierzynski, 2000). The concentrations of potassium was determined in a laboratory.

3.3 Results

3.3.1 Water balance

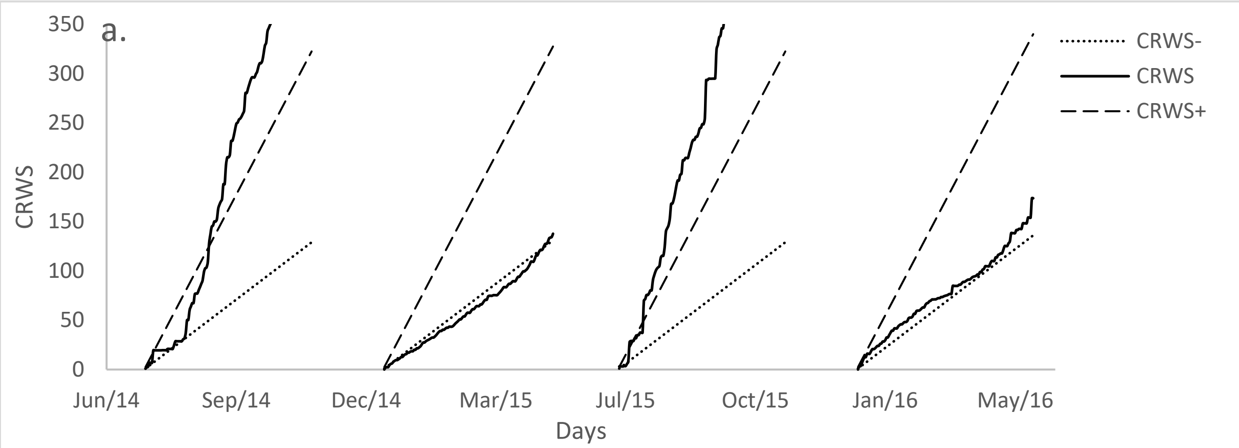
The components of the water balance are depicted in Table 3.2 for the four consecutive seasons. The balance shows an excess volume of water during the rainy seasons with more precipitation in 2015, and late beginning of the rainy season for both years according to farmers.

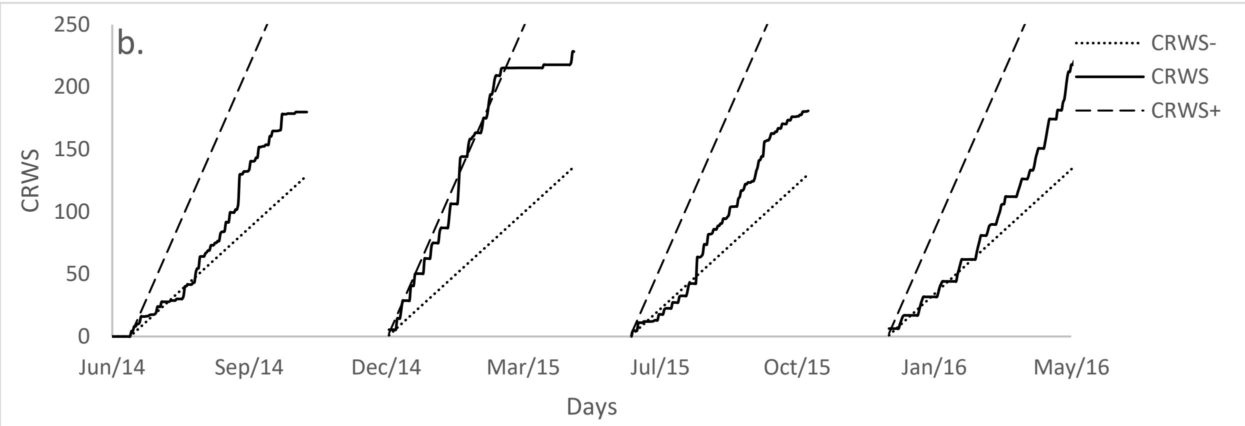
Table 3.2: Water balance components in the four schemes. The Irrigation term corresponds to reservoir-based schemes and the Inflows term to inland valleys without reservoir receiving directly the flows from the uplands.

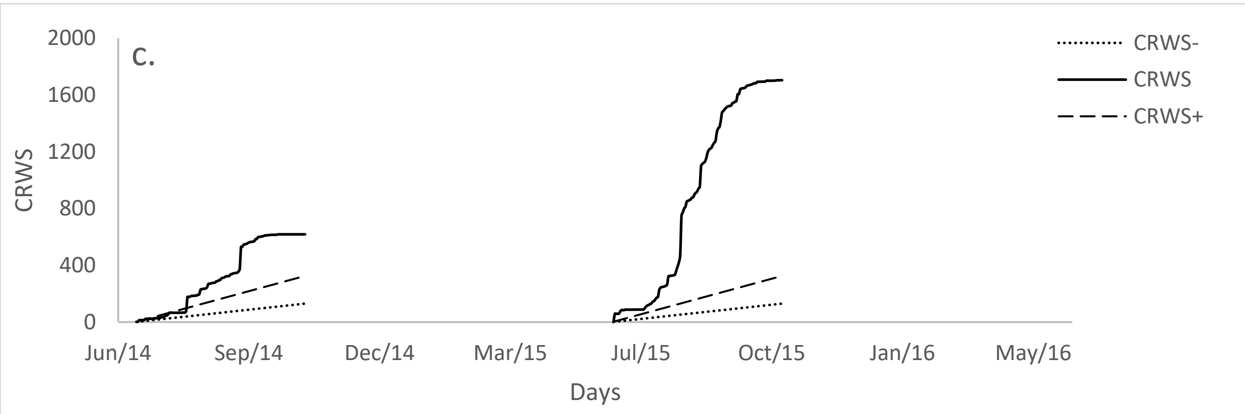
Period	**Rain (mm)**	**Irrigation / Inflows (mm)**	**Evapotranspiration (mm)**	**Drainage (mm)**
		Fafo		
Rainy season 2014	611	789	538	862
Dry season 2015	45	799	778	67
Rainy season 2015	840	560	538	862
Dry season 2016	130	645	720	55
		Moutori		
Rainy season 2014	750	0	556	195
Dry season 2015	15	760	380	396
Rainy season 2015	882	0	610	272
Dry season 2016	55	860	565	349
		Bankandi		
Rainy season 2014	646	1501	527	1620
Rainy season 2015	1110	5067	604	5573
		Lofing		
Rainy season 2014	761	9644	556	9849
Rainy season 2015	883	27083	610	27356

3.3.2 Cumulative Relative Water Supply (CRWS)

The cumulative relative water supply has been assessed in the four schemes and Fig. 3.3 shows the results for the rainy and dry seasons based on daily processing. An RWS equals to 2.5 or greater indicates excessive water supply without limiting conditions to crop production, and the lower threshold of 1 is used in this assessment as a threshold for water-scarce conditions (Ghumman et al., 2007; Chandran and Ambili, 2016). The four schemes seem to be under stress at the beginning of the rainy seasons (in June and July). The simply managed schemes (Fig 3.3-c and 3.3-d) show excessive water available during the rainy seasons and the reservoir based schemes in Fig 3.3-a and 3.3-b show curves close to water-scarce conditions during the dry seasons when well managed. In Moutori, excessive irrigation led to water shortage in the reservoir in mid of March 2014, resulting to losses.







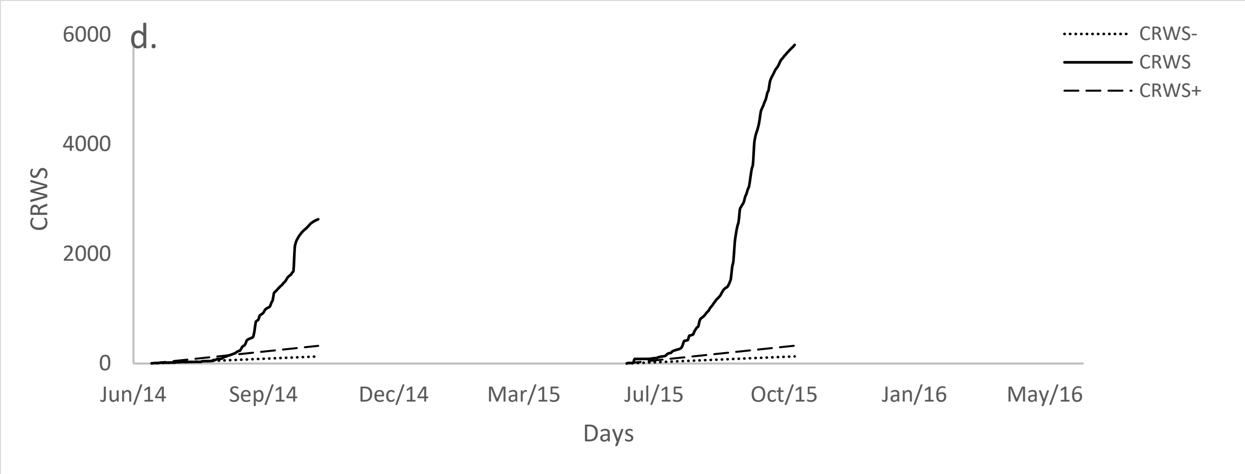


Figure 3.3: Cumulative Relative Water Supply in a. Fafo, b. Moutori, c. Bankandi and d. Lofing. The Cumulative Relative Water Supply curves CRWS+ and CRWS- correspond respectively to Relative Water Supply values of 2.5 and 1.

3.3.3 Productivity

Table 3.3 shows the yields of rice during the rainy seasons inside the four schemes and the rice equivalent yields for the dry seasons, both with their corresponding productivity values. The yields are higher in the reservoir-based schemes compared to the simply managed schemes. In Bankandi, the estimation of the productions was difficult because of the low performances in the fields. The results show as well, higher productivity values in the reservoir-based schemes in Moutori and Fafo compared to Bankandi and Lofing, and higher values during the dry seasons compared to the rainy seasons.

Table 3.3: Average yields (in ton/ha) and productivity (in kg/m3) in the different schemes during the rainy and dry seasons

	Rainy season 2014		**Dry season 2015**		**Rainy season 2015**		**Dry season 2016**	
	ton/ha	kg/m3	ton/ha	kg/m3	ton/ha	kg/m3	ton/ha	kg/m3
Fafo	4.1	0.29	5.2	0.62	4.7	0.33	2.9	0.38
Moutori	3.2	0.43	-	-	3.8	0.43	8.5	0.58
Bankandi	-	-	-	-	-	-	-	-
Lofing	2.4	0	-	-	1.8	0	-	-

3.3.4 System Drainage Ratio

The system drainage ratios are presented in Table 3.4, revealing excessive values in the schemes without reservoir in Bankandi and Lofing. Inside the reservoir-based schemes, the ratios in Fafo double the values in Moutori during the rainy seasons and are insignificant during the dry seasons.

Table 3.4: System Drainage Ratio during rainy and dry seasons

Location	Rainy 2014	Dry 2015	Rainy 2015	Dry 2016
Fafo	62%	8%	62%	7%
Moutori	26%	51%	31%	38%
Bankandi	76%	-	90%	-
Lofing	95%	-	98%	-

3.3.5 Water Quality

As for the water quality, the results are shown in Table 3.5 for the upstream and downstream parts of the surface water and groundwater. The values are low and the differences between the upstream and downstream parts are difficult to interpret as a whole. However, the concentration values of nitrates are greater in the groundwater than in the surface water for all the four schemes. In addition, the concentrations of Potassium are greater in the surface water than for groundwater in the reservoir-based schemes.

Table 3.5: K^+, NO_3^-, NO_2^- and PO_4^{3-} concentrations in Water (in mg/l)

		Surface water upstream				**Surface water downstream**				**Groundwater upstream**				**Groundwater downstream**			
		9-Aug	28-Aug	27-Sep	21-Oct	9-Aug	28-Aug	27-Sep	21-Oct	9-Aug	28-Aug	27-Sep	21-Oct	9-Aug	28-Aug	27-Sep	21-Oct
Moutori	NO_2^-	0	0.001	0.002	0.002	0.021	0.013	0.004	0.003	0.004	0.002	0.003	0.002	0.040	0.003	0.003	0.002
	NO_3^-	0	0	0	0.6	1.3	0	0.3	0.2	0.7	0.6	0.6	1	1	1.2	1.3	0.9
	PO_4^{3-}	0.3	0.5	0.3	0.1	1.6	1.3	0.8	0.1	0.6	0.7	0.5	0.3	0.5	0.3	0.2	0.3
	K^+	3.2	3.5	2.7	0	2.9	1.6	0.8	0.1	0.2	0.2	0.3	0.1	0.3	0.4	0.5	0
Fafo	NO_2^-	0	0	0.008	0.008	0	0.002	0.06	0.004	0	0	0.002	0	0.015	0.004	0.004	0.004
	NO_3^-	8.5	0	0	0	0	0	0	0	0.2	0.2	0.6	0	2.2	2.2	2.2	3.2
	PO_4^{3-}	0.4	0.7	0.3	0.5	2.2	1.2	0.3	0.5	0.9	1.1	0.6	1.0	2.0	1.2	0.5	0.6
	K^+	5.2	3.8	3.2	2.5	8.8	7.5	3.2	0.4	1.3	1.3	1.2	0.1	1.2	1.2	1.2	0
Bankandi	NO_2^-	0	0.001	0.002	0.002	0	0.002	0	0.002	0	0.003	0.005	0.005	0	0.002	0.002	0.003
	NO_3^-	0	0	0	0.2	0	0	0	0.1	0.4	0.5	1.8	1	0.6	0.5	0.4	0.3
	PO_4^{3-}	0.6	1.5	0.4	0.1	0.5	0.9	0.2	0.1	0.4	0.2	0.3	0.2	0.19	0.9	0.98	0.25
	K^+	0.3	0.2	0.4	0.1	0.9	0.7	1.9	0.1	0.8	0.9	5.2	0.1	1.14	1.135	1.243	0.1
Lofing	NO_2^-	0.005	0	0.001	0	0.001	0	0	0	0.001	0.002	0.003	0.002	0.035	0.015	0.004	0.003
	NO_3^-	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.4	4.5	4.6	4.1	4.9
	PO_4^{3-}	0.3	0.6	0.1	0.1	0.5	0.5	0.4	0.1	0.5	0.4	0.8	0.3	1.2	0.5	0.6	0.4
	K^+	0.9	0.4	0.9	0.1	0.5	0.5	0.7	0.3	0.8	0.9	0.9	0.1	1.8	1.7	3.7	0.5

3.4 Discussion

The assessment of the performance has been conducted in four schemes in Dano based on two years of measurements. The battery of indicators can be grouped into three categories on availability, on productivity and on impacts.

3.4.1 Water availability

Despite the relatively abundant volume of water available for crop production, the water RWS and CRWS indicators show the importance of a uniformly distributed rainy season and of the role of storage of water. Water stress was monitored in all the schemes at the beginning of the rainy season, a critical period for early rice plants, which depend entirely on precipitations. Crop failure at this early stage induces re-sowing and so seed wastage and additional labor (Marteau et al., 2011). In addition, water stress during the vegetative period impacts the crop growth with delayed flowering and maturity phase (Castillo et al., 2006; Zhang et al., 2016; Alou et al., 2018), a delay which can expose the crop to water stress at the end of the season in case of lesser rains or water stock. Research predicts that West Africa monsoon will be hit by climate change with more uncertainties on the onset of the season and more severe dry-spells (Jung and Kunstmann, 2007; Biasutti and Sobel, 2009; Sylla et al., 2015). Hence, the inland valleys feature a vulnerability to climate change, which can be managed by supplemental irrigation in reservoir-based schemes.

On the other hand, the excessive values of RWS and of CRWS inside the schemes without reservoir imply to have adequate drainage systems, which is not the case in Bankandi. Yira et al. (2019) investigated the hydrological functioning in Bankandi and found the poor design as responsible for the waterlogging conditions, with the contour bunds not following the contour lines, and under-sized drainage flumes. The poor design has been cited many times as one of the reasons behind the low performance of small agricultural schemes in Africa (Payen et al., 2012; Venot et al., 2012; Poussin et al., 2015).

Moreover, a close look at the CRWS in the reservoir-based schemes during the dry seasons shows the influence of the irrigation frequency. In Moutori, the water turn varies from one to two weeks, inducing irrigation water losses by deep percolation, when farmers in Fafo irrigate sparingly their fields every 2 to 3 days. According to the literature, the irrigation frequency affects the yields (Cavero et al., 2018; Vogeler et al., 2019), the nutrients leaching (Ayars et al., 2015; Gómez-Armayones et al., 2018; Vogeler et al., 2019), and the greenhouse gases emissions (Maris et al., 2016; Vogeler et al., 2019) depending on the crop type, the irrigation technique, the soil type, the time of application, etc.

3.4.2 Productivity

A comparison in the water management of the four schemes reveals an obvious advantage in the reservoir based schemes in Moutori and Fafo due to more control on the irrigation and drainage system, and to the capability of crop production during the dry season. This advantage is translated into higher yields and water productivity values. In Bankandi and Lofing, the excess of water in the rainy season is problematic for the application of fertilizers.

Inappropriate field management causes the development and competition of weed. Weed and fertilizers are among the main causes of low yields of rice in West Africa (Haefele et al., 2000; Becker et al., 2003; Niang et al., 2017). In Moutori and Fafo, the drainage system is adequate and the fertilizer amount is acceptable for some farmers, the highest yields for rice during the rainy season are comparable to those in Asia with 8.2 ton/ha monitored in Moutori in 2014. Yet, the multitude of farmers (89 in Moutori and 97 in Fafo) generates a large spectrum of practices that undermine the average yields. The water productivity of rice varies from 0.001 kg/m^3 to 0.58 kg/m^3 for the different schemes. A study by Bouman and Tuong (2001) found typical water productivity values of 0.2 – 0.4 kg/m^3 in India and 0.3 – 1.1 kg/m^3 in the Philippines. A maximum value of 1.9 kg/m^3 was reached thanks to water-saving experiments but with decreased yields. Water conservations techniques such as alternate wetting and drying, shallow water depth, aerobic rice or system of rice intensification, gave some range of values of 0.52 - 0.80 kg/m^3 in experimental fields in Japan (Sujono et al., 2011) and of 0.70 - 0.91 kg/m^3 in India (Saha et al., 2015). The water productivity is somewhat higher during the dry seasons due to more control on the supply, and to higher prices of vegetables compared to cereals.

3.4.3 Impacts

High drainage ratios can be interpreted on the one hand as inefficient schemes in the use of water, and on the other hand as leaching soils of their salinity and having low impacts on downstream users. This indicator is rarely estimated in the small schemes and values of 17% - 22% were monitored in the Aral basin, in the Indus in Pakistan, and in the Nile in Egypt (Bos, 2012). The drainage ratios are above 60% in three out of four schemes during the rainy seasons. These high drainage ratios are synonymous with the overuse of irrigation in the reservoir-based schemes, and a high potential for expansion in the schemes without reservoirs.

As for the water quality, wetlands are usually known for their water quality enhancement function (Bateganya et al., 2015; de Jong et al., 2015; Vymazal and Březinová, 2015). The water quality assessment shows a low concentration of nitrates and nitrites. According to the WHO (2011), the primary concern for water pollution by nitrates and nitrites is the methemoglobinemia which is lethal for infants. The guideline values for drinking water are 50 mg/l for nitrate and 3 mg/l for nitrite. In addition, a concentration of nitrogen above 0.1 mg/l and of phosphorus more than 0.01 mg/l can cause eutrophication. As for potassium, it is part of the essential intakes for the human nutrition and the dietary reference values go from 0.4 to 4.7 g/day from infants to adults (WHO, 2009) without any defined toxicity value. The measured values in all the sites do respect the norms for drinking water but have a high potential for eutrophication. The higher ion concentrations in the groundwater compared to surface water can be caused by ion loading induced by irrigation as experienced in manifold countries (Spalding & Exner, 1993; Pearce & Schumann, 2001; Jalali, 2009; Zhou et al., 2016). On the opposite, lower concentration values on the groundwater compared to the surface water, can be a result of a preserved groundwater, by vegetative uptake, natural denitrification, certain type of soils and tile drainage (Spalding and Exner, 1993). Because there are no liners to protect the shallow aquifer, the effect of pollution and ions accumulation in the groundwater with years through leaching is a concern to be taken seriously into consideration. Very few studies on inland valleys integrate water quality aspects. Danvi et al., (2017) investigated three inland valleys in Benin and found very low nitrate loads with concentrations less than 10 mg/l. In Nigeria, Aboyeji & Ogunkoya, (2017) explored six sites and found low concentrations of potassium (less than 2 mg/l) among other ions. Elsewhere, rice fields are tested for water quality enhancement (Tootoonchi et al., 2018; Unami et al., 2018; Uwimana et al., 2018).

3.4.4 Improvements

The assessment of the indicators on water availability, on productivity and on impacts, allows to pinpoint the issues on their management and to enhance their potential for production.

The main water management issues in the reservoir-based schemes are the low level of organization and planning and the poor technology. The reservoir-based scheme in Moutori presents water availability issues as manifested during the rainy seasons by lowest value of RWS in the beginning of the season in June, and during the dry seasons by a reduced cultivated area (respectively by 53% and 31% in the dry seasons 2015 and 2016), and by the crop failure in March 2015. The management is also at stake with the high values of RWS and drainage ratios during the dry seasons. An advanced and foresightful planning in the irrigation periods and frequencies in the beginning of the dry season can help to better manage the water availability during the dry campaigns and the beginning of the rainy seasons (Cavero et al., 2018; Vogeler et al., 2019). The irrigation scheme in Fafo is over supplied by the supplemental irrigation during the rainy seasons as revealed by the high values of CRWS above the 2.5 threshold, and the high drainage ratios above 60%. An extension of the cultivated area is possible, given the small size of the scheme (6.6 ha versus 20.3 ha) for a higher reservoir volume compared to Moutori (0.48 Mm3 versus 0.36 Mm3 at normal pool). The lack of water planning is a known problem for small reservoirs and responsible of water losses in the system (Kambou et al., 2019). For (Wisser et al., 2010), small reservoirs represent a viable solution for food security in arid environments, despite impacting the hydrological regime at the basin level (around 18%) and important losses by evaporation (around 20%). In this study, the losses inside the reservoirs were not assessed, however, a study by Fowe et al., (2015) in Boura, Burkina Faso showed a 50% loss by evaporation. A better irrigation management would imply in the reservoir-based schemes to start the dry campaign earlier in order to reduce the losses by infiltration and evaporation during the two to three months of inactivity. In addition, the adoption of micro-irrigation can help reduce the crop water consumption during the dry seasons as experienced in many studies (Kachwaya et al., 2016; Sharda et al., 2017; Fang et al., 2018; Valentín et al., 2020). Sharda et al. (2017) found drip irrigation to be more productive, and less water consuming by 40% compared to flood irrigation. Valentín et al. (2020) compared different water saving irrigation technologies on maize such as surface and subsurface drip irrigation, and sprinkler irrigation, and found a 25% difference in the water productivity for no significant difference in the yields.

As for the other schemes in Bankandi and Lofing, their design encloses their management as there is little capacity to modify their functioning. The simple managed schemes are known to have a high potential for rice production (Rodenburg, 2013; Dossou-Yovo et al., 2017; Djagba et al., 2018). The scheme in Bankandi has drainage issues and very low productivity. The drainage system is better operating in the scheme in Lofing but not optimal. An obvious improvement would be to improve the drainage inside these two schemes in order to allow better field management. The low fertilizers input is known to hamper the productivity (Livingston et al., 2011; Poussin et al., 2015; Woodhouse et al. 2017) as indicated by the low concentrations of nitrates, nitrites, phosphorous and potassium inside the four schemes. Improving the access to micro credit to farmers will permit to intensify their system of production (Tabo et al., 2007) Tamini et al., 2019).

3.5 Conclusion

The climate of semi-arid areas, characterized by a single rainy season, and a high intra and inter-seasonal variability, requires the development of irrigation projects to sustain agriculture production. The benchmarking of irrigated schemes is a good exercise to evaluate their performance and their impacts on the environment. This study revealed that inland valleys equipped with reservoirs as well as simply managed bottomlands have a relevant potential for food production. There is a room for improvement in each scheme, either by increasing the yields or by better using the water and land available. The impacts from the development of the selected inland valleys on the water quality are minor when considered alone. Further research should assess the cumulative impacts of large-scale irrigation projects on the water quality and the water cycle at the basin scale.

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4 Dynamics of the Climate in Dano

4.1 Introduction

Africa is described as one of the most vulnerable continents regarding climate change and variability according to the IPCC 5th report (Niang et al., 2014) . However, the pattern of change in the continent is not homogenous but rather geographically related. The West African region is expected to be affected one to two decades before the rest of the continent, precipitation and temperature being the most challenging parameters. The nature of the climate threat for agriculture concerns the natural variation on intra-seasonal and inter-annual variability as well as the long-term trends.

The variability of the climate in West Africa has been investigated by Norrgård (2017) over the last centuries through historical records, showing for both the Guinea Coast and the Sahel region a recurring pattern of severe droughts starting from the 16th century. Also, Shanahan et al. (2009) reconstructed for the past millennia the variability of the monsoon in West Africa based on geomorphic, geochemical and isotopic evidence on Lake Bosumtwi in Ghana. They found out that major droughts lasting over decades and centuries constitute a characteristic of the natural variation of the monsoon. The rainfall in West Africa is characterised by a North-South gradient of which the 50-100 mm mean in the Sahel region controverts the 1600-2000 mm average in the Guinea Coast. The spatial and temporal variability of the precipitation is depicted as high and sometimes erratic in the Sahelian part. Le Barbé et al. (2002) observed a 600 mm difference between two 80 km-distant stations, within the same environment in Niger. For Delaney (2012), the precipitation in the Sahel has an extreme multi-decadal fluctuation pattern manifested by a series of floods in the 50s and 60s and droughts in the 70s and 80s. On the other hand, Nguyen et al. (2011) found for the Coastal region between 1979 and 2009, a clear inter-annual variability on the onset date and the duration of the rainy seasons.

Concerning climate change, the acceptance of an increasing trend in the temperatures, both inside historical data as well as for models predictions, is reversed by the lack of consensus on the change in precipitation for this century. Yet, Monerie et al. (2013) found out for the Sahel when doing a multi-model analysis with the models from the Climate Models Intercomparison Project phase 3 (CMIP3), an increase in the precipitation in the centre and a decrease in the western part with the A1B emission scenario between the periods 1960-1999 and 2031-2070. They concluded that the Sahel region should not be taken as a homogenous block but rather different areas behaving differently under climate scenarios. Roehrig et al. (2013) reached the same conclusion for the Climate Models Intercomparison Project phase 5 (CMIP5) models, with a consensus on the sign of change with drying anomalies over the western part of the Sahel and with wetting anomalies over the eastern part for the RCP8.5 scenario.

It’s hence important for our study on inland valleys to evaluate the local anomalies induced by climate change and also to understand the climate variability in the Dano basin.

4.2 Data and methods

4.2.1 Climate Variability

Climate variability is defined by the IPCC as the variations of the climate under natural or external forcing and described by statistics such as mean state, standard deviations, extremes, etc.. According to Norrgård, precipitation is the most determining climate parameter in terms of impacts on West African lives. Daily data on precipitation from 1970 to 2013 of the city of Dano in the South Western Region in Burkina Faso, has been retrieved from the national office of meteorology (DGM) in Burkina Faso.

4.2.1.1 Precipitation frequency analysis

The question of the design of hydraulic infrastructures relies on the statistical analysis of precipitation and flood variability (Koob et al., 1999; Volpi and Fiori, 2014; Notaro et al., 2015). Under stationary conditions, the traditional statistical approach supposes that hydrological events are independently distributed and follow a stationary distribution function $f(x)$ and a cumulative distribution function $F(x)$. In case of annual precipitation, the occurrence of a given precipitation amount X_i is associated a probability of non-exceedance $P_i = P(X < X_i)$ and a return period T_i and the following equations relate the different terms:

$$F(X < X_i) = 1 - P_i \tag{4.1}$$

$$T_i = P_i^{-1} \tag{4.2}$$

The use of statistics to characterize the rainfall pattern allows the use of drought indexes such as the Standardized Precipitation Index (SPI).

4.2.1.2 The standardized precipitation index

The Standardized Precipitation Index (SPI) presented by Mckee et al. (1993) is a widely used drought indicator, computed with only the precipitations as input. The SPI identifies drought and wet periods for different cumulated months, based on the statistical distribution of the related precipitations, fitted to a gamma distribution and then standardized to normal. Different classes are defined corresponding to the values of the exceedance probability as shown in Table 4.1. The severity of droughts is assessed with the use of thresholds values (-2, -1.5, -1, 1, 1.5, 2). These thresholds correspond to return periods such as around 6 years for the SPI values 1 and -1, around 15 years for the SPI values 1.5 and -1.5 and around 44 years for the SPI values 2 and -2.

Table 4.1: SPI classification from Mckee et al. (1993)

SPI value	Exceedance Probability	Class
SPI ≥ 2	0.98 - 1	Extreme wet
1.5 < SPI ≤ 2	0.93 - 0.98	Severe wet
1 < SPI ≤ 1.5	0.84 - 0.93	Moderate wet
-1 < SPI ≤ 1	0.16 - 0.84	Near normal
-1.5 < SPI ≤ 1	0.07 - 0.16	Moderate dry

-2 < SPI ≤ -1.5	0.02 - 0.07	Severe dry
SPI ≤ -2	0 - 0.02	Extreme dry

Despite being relevant for comparison between locations and times, thanks to the standardization, the SPI classification has been criticized to be arbitrary (Singleton, 2012) and the accuracy of the index questioned for arid zones and short time scales because of errors in the distribution (Wu et al., 2006). An improved method of calculation of the SPI would hence be to apply different probabilistic distribution to a dataset in order to pick the most adapted in terms of fitness of the data series to the model distribution.

4.2.1.3 Fitting to different probabilistic distributions

For this study, the precipitations have been aggregated into monthly datasets for the rainy period and fitted to different probabilistic distributions in order to detect the magnitude and frequency of dry months. The Gamma, the Gumbel, the Log-normal, the Normal and the Weibull probability distributions are among the most commonly used in hydrology. Their functions and probability distributions are presented in Table 4.2. Goodness-of-fit criteria like the Akaike's Information Criterion (AIC) and the Bayesian Information Criterion (BIC) are widely used to identify the best distribution for a given dataset (Aho et al., 2014; Brewer et al., 2016; Ding et al., 2018).

The AIC is defined by (Akaike, 1969) with the formula:

$$\mathrm{AIC} = -2 \log \mathrm{l}(\theta) + 2\mathrm{p} \quad (4.3)$$

As for the BIC, Schwarz (1978) defined it with the equation:.

$$\mathrm{BIC} = -2 \log \mathrm{l}(\theta) + \mathrm{p} \log \mathrm{n} \quad (4.4)$$

With θ the maximum likelihood estimates of the model parameters, $log\, l(\theta)$ the log-likelihood estimates, '$2p$' and '$p\, log\, n$' corresponding to a penalty on the number of parameters p, and n the sample size.

Table 4.2: Probability models and corresponding distribution functions for a variable x

Models	**Probability Distribution Function**	**Parameters**
Gamma	$F(x;\alpha,\theta) = \frac{1}{\theta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\theta}$	α: the shape parameter Θ: the rate parameter Γ(x): the gamma function
Gumbel	$F(x;\mu,\beta) = \frac{1}{\beta} e^{(x-\mu)/\beta} e^{-e^{(x-\mu)/\beta}}$	β: the scale parameter μ: the location parameter

Log-Normal	$N(lnx;\ \mu,\alpha) = \frac{1}{\alpha\sqrt{2\pi}} e^{-(lnx-\ \mu)^2/(2\alpha^2)}$	α: the shape parameter μ: the location parameter
Normal	$F(x;\ \mu,\alpha) = \frac{1}{\alpha\sqrt{2\pi}} e^{-(x-\ \mu)^2/(2\alpha^2)}$	α: the shape parameter μ: the location parameter
Weibull	$F(x;\ \alpha,\beta,\mu) = \frac{\alpha}{\beta}\frac{(x-\mu)^{(\alpha-1)}}{\beta} e^{-((x-\mu)/\beta)^{\alpha}}$	α: the shape parameter β: the scale parameter μ: the location parameter

In order to assess the magnitude of droughts associated with the adjusted probability of non-exceedance, a coefficient of variation based on the distance to the mean as shown in Eq. 4.5, has been established:

$$\mathrm{CV_i} = \frac{(\mathrm{X_i} - \overline{\mathrm{X}})}{(\overline{\mathrm{X}} - \mathrm{X_{min}})} \quad (4.5)$$

With X_i the precipitation corresponding to the probability of non-exceedance $P(X< X_i)$, $\overline{X}$ the mean precipitation and X_{min} the minimum precipitation.

4.2.2 Climate change

Climate is defined by the IPCC as the statistical average of the weather over a period of 30 years, the weather being the state of the atmosphere characterized by elements like temperature, wind, precipitation, etc. While climate variability concerns seasonal changes, climate change goes beyond the natural variation of the weather and encloses the trend and tendencies in the long term. Climate predictions from the COordinated Regional Climate Downscaling Experiment CORDEX (www.cordex.org), emanating from the Coupled Model Intercomparison Project – Phase 5 (CIMP5), were selected for the analyses. The Representative Concentration Pathways (RCP) are the third generation of climate modelling scenarios driven under the CIMP5 Project of the World Climate Research Programme and characterized by four scenarios of greenhouse gas concentration, namely RCP2.6, RCP4.5, RCP6 and RCP8.5 (Stocker and T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, 2015). The RCP2.6 supposes a sharp decline in greenhouse gases to reach a global temperature rise less than +2°C by 2100 (van Vuuren et al., 2011). This scenario is not common in the literature on impact assessment but rather used as a radical mitigation scenario. The RCP4.5 and RCP6.0 corresponds respectively to a medium-low and a medium-high scenario with radiative forcings of 4.5 W/m² and 6.0 W/m² by 2100. While the three other RCPs are mitigation scenarios, the RCP8.5 is the business-as-usual (BAU) scenario, which supposes a continuous increase of CO_2 with concentration in 2100 three to four times the pre-industrial levels, and a radiative forcing of 8.5 W/m². For Mendelsohn (2015), the RCP8.5

doesn't represent the existing BAU scenarios and lies on the top of the range. Yet, the author reckons the RCPs not to be likely outcomes but rather selected for scientific purposes. The RCP4.5 and RCP8.5 are the most found in the literature and model database such as CORDEX, and their choices in impact assessment studies is justified as they represent the extremes of the possibilities in terms of negative impacts.

Thirteen models under RCP4.5 and RCP8.5 on the precipitations and the temperatures were considered. The temporal resolution is daily sums for the precipitations and monthly maximum for the temperatures, and the space resolution is around 50 km corresponding to a 0.44° grid resolution. The spatial discretization within CORDEX is made of nodes representing the center of the different grids, of which two nodes with coordinates (-3.08; 11.00) and (-3.08; 11.44) have been selected and averaged to cover the area of the study. Different statistical tests have been computed in order to detect anomalies in the evolution of the precipitations depths, the rainy days, and the temperatures during the rainy season. The models details are presented in Table 4.3.

Table 4.3: Climate models components

ACRONYM	INSTITUTE	Global Circulation Model	Regional Circulation Model
CCLM4_EC-EARTH	Climate Limited-area Modelling community	EC-EARTH	CCLM4
CCLM4_HadGEM2		HadGEM2	
CCLM4_MPI-ESM		MPI-ESM	
HIRHAM5_NorESM1	Danish Meteorological Institute	NorESM1	HIRHAM5
KNMI-RACMO22T_EC-EARTH	Royal Netherlands Meteorological Institute	EC-EARTH	KNMI-RACMO22T
KNMI-RACMO22T_HadGEM2		HadGEM2	
REMO2009_EC-EARTH	GERICS climate service center	EC-EARTH	REMO2009
REMO2009_MPI-ESM		MPI-ESM	
SMHI-RCA4_EC-EARTH	Swedish Meteorological and Hydrological Institute	EC-EARTH	SMHI-RCA4
SMHI-RCA4_IPSL-CM5A-MR		IPSL-CM5A-MR	
SMHI-RCA4_MIROC5		MIROC5	
SMHI-RCA4_MPI-ESM		MPI-ESM	
SMHI-RCA4_NorESM1		NorESM1	

4.2.2.1 Trend detection

The Mann-Kendall (Mann, 1945; Kendall, 1970) and the Spearman Rho tests are commonly used to detect trends in hydrological data series. Yue et al. (2002) investigated the power of these two test and found them similar and positively related with the sample size, the slope of the trend, the significance level and the distribution type of the time series. The Mann-Kendall test, which is chosen here, is a non-parametric test and the most used to detect monotonic trends. The formula of the statistic is defined as:

$$S = \sum_{\substack{1<i\leq n \\ 1\leq j<i}} \text{sign}(x_i - x_j) \tag{4.6}$$

With n the length of the data series, x_i and x_j two sequential variables and the function $sign(x) = \{1 \text{ if } x>0;\ 0 \text{ if } x = 0;\ -1 \text{ if } x < 0\}$.

The variance $Var(S)$ and the statistics Z_S are computed by approximating that S is normally distributed, with the following equations:

$$\text{Var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)\right] \tag{4.7}$$

$$Z_S = \begin{cases} \dfrac{S-1}{\sqrt{\text{Var}(S)}}, \text{if} S > 0 \\ 0, \text{if} S = 0 \\ \dfrac{S+1}{\sqrt{\text{Var}(S)}}, \text{if} S < 0 \end{cases} \tag{4.8}$$

The statistics Z_S is hence used to test the null hypothesis of no trend, which can be rejected for $|Z_S| > Z_{\alpha/2}$, with α the level of significance of the test, chosen as 5% for this study.

4.2.2.2 Magnitude of trend

The magnitude of the trend is used to estimate the anomalies and bias correct the predictions with the delta change method. Bias exist between simulation and historic data and the delta change method is the simplest way to correct the bias by considering the change instead of the values of the model. The Sen's slope (Sen, 1968) is widely used for this purpose in climate science (Gocic and Trajkovic, 2013; Sanogo et al., 2015; You et al., 2016) and can be defined as the median of the slopes of all possible lines through a pair of variables X_i and X_j, as shown by the following equation:

$$b = \text{Median}\left(\frac{Xj - Xi}{j-i}\right), \text{ for } 1 \leq i < j \leq n \tag{4.9}$$

The magnitude is hence calculated by considering the year 2006, the starting year for all the simulations, and the year 2100, the horizon of the projections:

$$\text{Percentage of change}_X = \frac{b\ (Tf - Ti)}{X_{Ti}} = \frac{b\ (2100 - 2006)}{X_{2006}} \tag{4.10}$$

$$\text{Delta change}_X = b\ (Tf - Ti) = b\ (2100 - 2006) \tag{4.11}$$

With b the slope, Tf and Ti respectively the final and initial time.

4.2.2.3 Change detection

The Pettitt's test (Pettitt, 1979) is widely used in climatic records to detect abrupt changes (Nka et al., 2015; Louvet et al., 2016; Tirogo et al., 2016). The test divides a dataset at every observation into two subseries corresponding to before and after, and compares their means in order to detect the point of significant changes. The statistic of the test is determined for a time series by the equation:

$$U_t = \sum_{\substack{1 \le i \le t \\ t < j \le n}} \mathrm{sign}(x_t - x_j) \tag{4.12}$$

With n the length of the data series, x_t and x_j two sequential variables and the function $sign(x) = \{1 \text{ if } x>0;\ 0 \text{ if } x = 0;\ -1 \text{ if } x < 0\}$.

The confidence level ρ is defined as:

$$\rho = e^{-K/(n^2+n^3)} \tag{4.13}$$

With K as the absolute maximum value of U_t and n the length of the data series.

The significance probability is then approximated by $p = 1 - \rho$.

The null hypothesis, corresponding to the absence of a break in the dataset, is rejected for a p-value inferior to a significance threshold of 5%.

4.3 Results

4.3.1 Precipitation variability

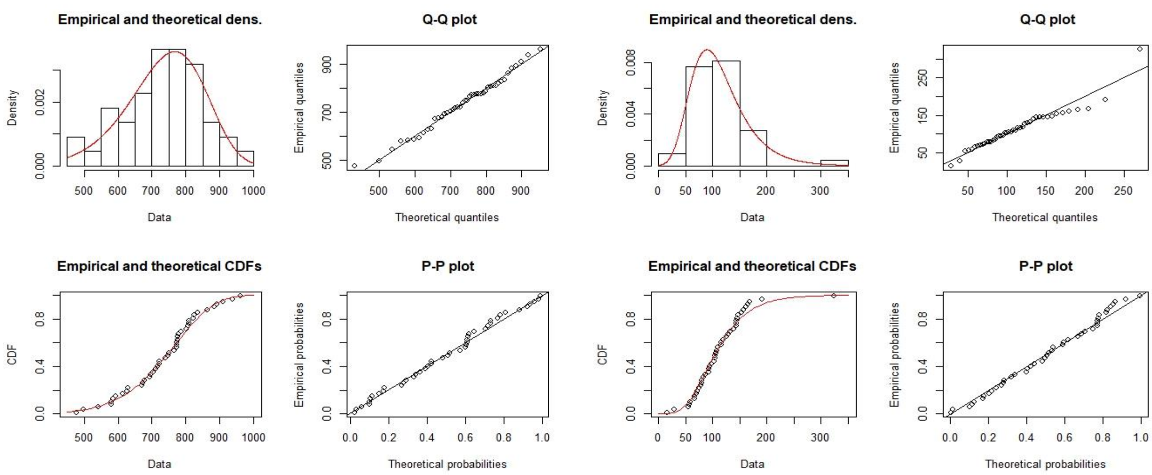
The monthly cumulative precipitation of the rainy season from June to October and their seasonal accumulation are considered separately. The Akaike's Information Criterion (AIC) and the Bayesian Information Criterion (BIC) are presented in Table 4.4. The best fit for a set of probability distributions corresponds to the lowest values of these criteria and the results from the two are concordant. Fig. 4.1 - a to f show the empirical versus the theoretical values for the density, the quantiles, the cumulative distribution functions and the probabilities of the selected probability models. The figures are important as a complement to AIC and BIC criteria in the choice of the models for the fitting in the lowest tails of the distributions, as the focus of the study is on droughts. In addition, the different datasets have passed two homogeneity tests (Pettitt and Buishand Range tests) successfully. The homogeneity tests are necessary to ensure that the dataset can be described by one probability model. Fig. 4.2 and 4.3 illustrate the relationship between the return periods and respectively the coefficients of variation defined in Eq. 4.1 and the precipitation amounts. The precipitations in June present the most severe variation with years followed by the precipitations in October. A return period of 6.5 years equivalent to a moderate drought in the SPI classification, corresponds to an 80% decrease in June and 76% decrease in October, while a severe drought (15 years of return period in the SPI classification) is related to a 100% and 91% decrease respectively in June and October. The precipitation in July and September are quite similar with respectively a 64% and 61% decrease for moderate drought and 85% and 84% decrease for severe droughts. August is the least variable month with a 39% and 60% decrease respectively every 6.5 and 15 years. The seasonal aggregation curve is comprehended within the curves of precipitations of

August, July, and September, which are the most influential months because of higher precipitation amounts compared to precipitation in June and October.

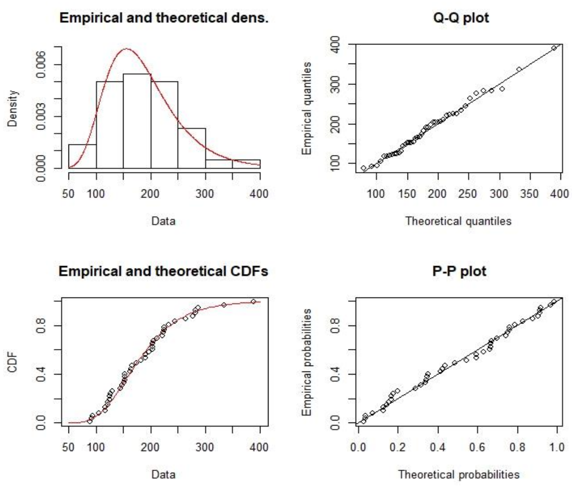
Table 4.4: Goodness-of-fit criteria of precipitation to selected probabilistic distribution

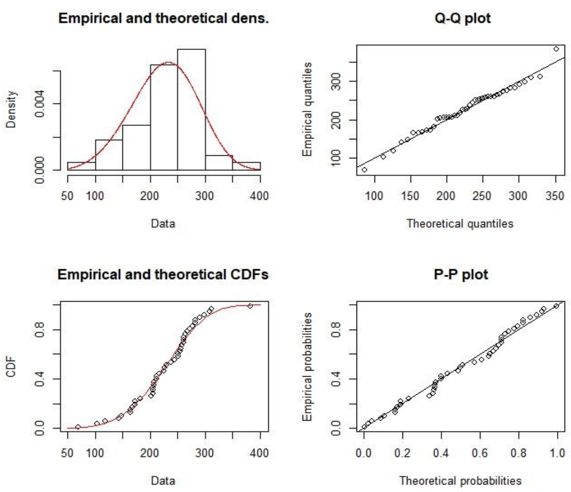
	normal	gamma	gumbel	lognormal	weibull
Akaike's Information Criterion					
Season	544.1	545.9	553.1	547.2	**543.6**
June	473.6	468.0	**466.4**	473.2	470.1
July	498.2	492.3	491.9	**491.5**	497.0
August	488.6	494.2	499.3	499.4	**488.5**
September	473.3	**470.9**	472.1	471.6	473.4
October	459.2	**433.0**	441.2	433.6	433.9
Bayesian Information Criterion					
Season	547.7	549.4	556.7	550.8	**547.2**
June	477.2	471.6	**469.9**	476.8	473.7
July	501.8	495.8	495.4	**495.1**	500.6
August	492.2	497.7	502.8	502.9	**492.1**
September	476.9	**474.5**	475.7	475.1	477.0
October	462.7	**436.6**	444.7	437.2	437.5

a. b.



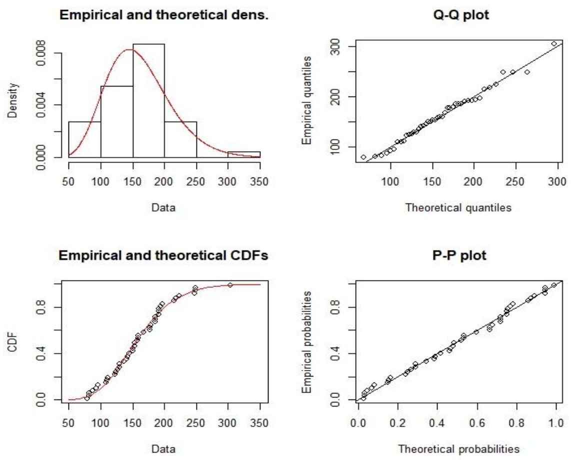
c. d.





e.

f.



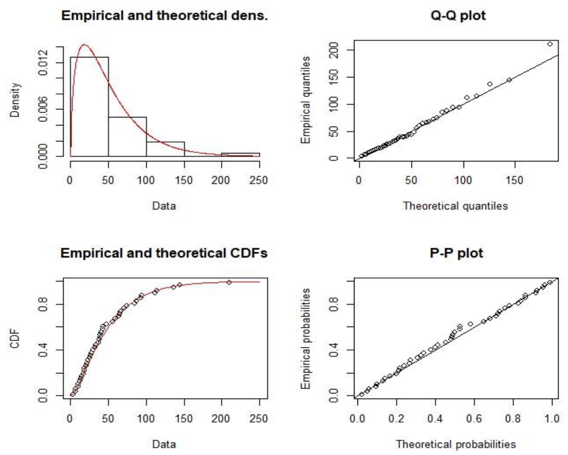


Figure 4.1: Fitting test of precipitations for a. seasonal precipitations to a Weibull distribution, b. precipitations from June to a Gumbel distribution, c. precipitations from July to a Log-Normal distribution, d. precipitations from August to a Weibull distribution, e. precipitations from September to a Gamma distribution, f. precipitations from October to a Gamma distribution

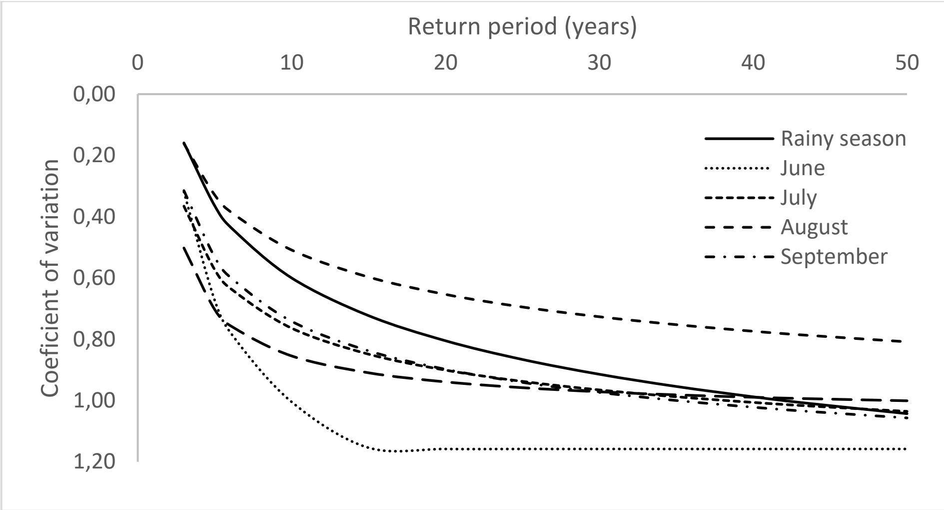


Figure 4.2: Coefficient of variation associated with the frequency of dry years

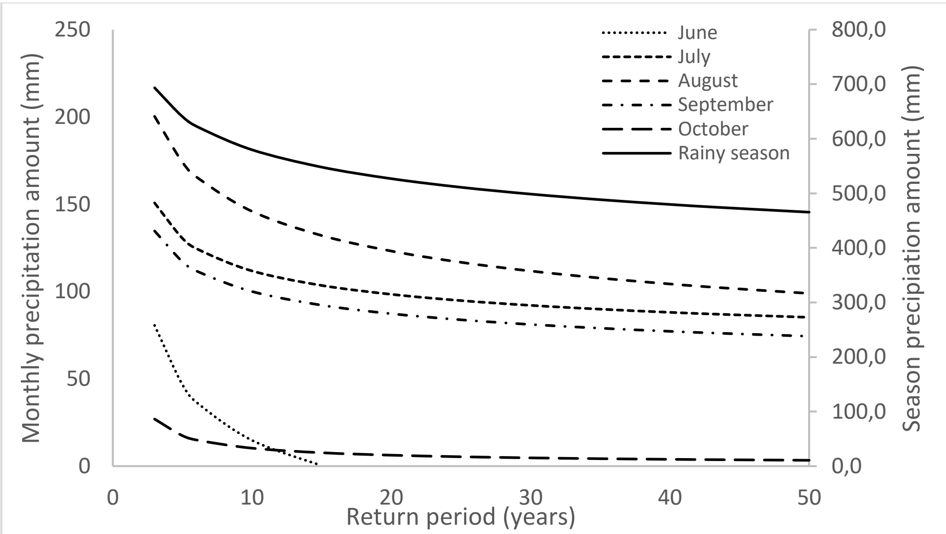


Figure 4.3: Precipitation amount in relation to the frequency of dry years

4.3.2 Climate/precipitation change

The Mann-Kendall and the Pettitt tests have been conducted together with the Sen's slope estimation, and the results are presented in Tables 4.5 and 4.6. The anomalies detected are mixed for the precipitation depth, decreasing for the precipitation events and increasing for the temperatures, with a higher effect for the scenario RCP8.5. As shown in the tables for the precipitation depths, only one of the thirteen models shows a decreasing trend for the climate scenario RCP4.5 and seven models show a trend for the RCP8.5, four increasing and three decreasing. The anomalies vary from -28% to +26% but for the majority of the models, the magnitudes of change are comprehended within the range of the inter-annual variability. Nevertheless, the decreasing trend in the number of rainy days, from -4% to -35% depicts an increase in the recurrence of dry spells with more intense rainfalls. As for the temperature, all the models show an increasing trend for the two scenarios, +1.3 to +2.9°C for the RCP4.5 and +2.9 to +7.2°C for the RCP8.5. All the models showing a significant trend with the Mann Kendall test, have also the significant presence of a break in the dataset with the Pettitt test. The dates of break are comprised between 2040 and 2089, but the majority of them are around 2050.

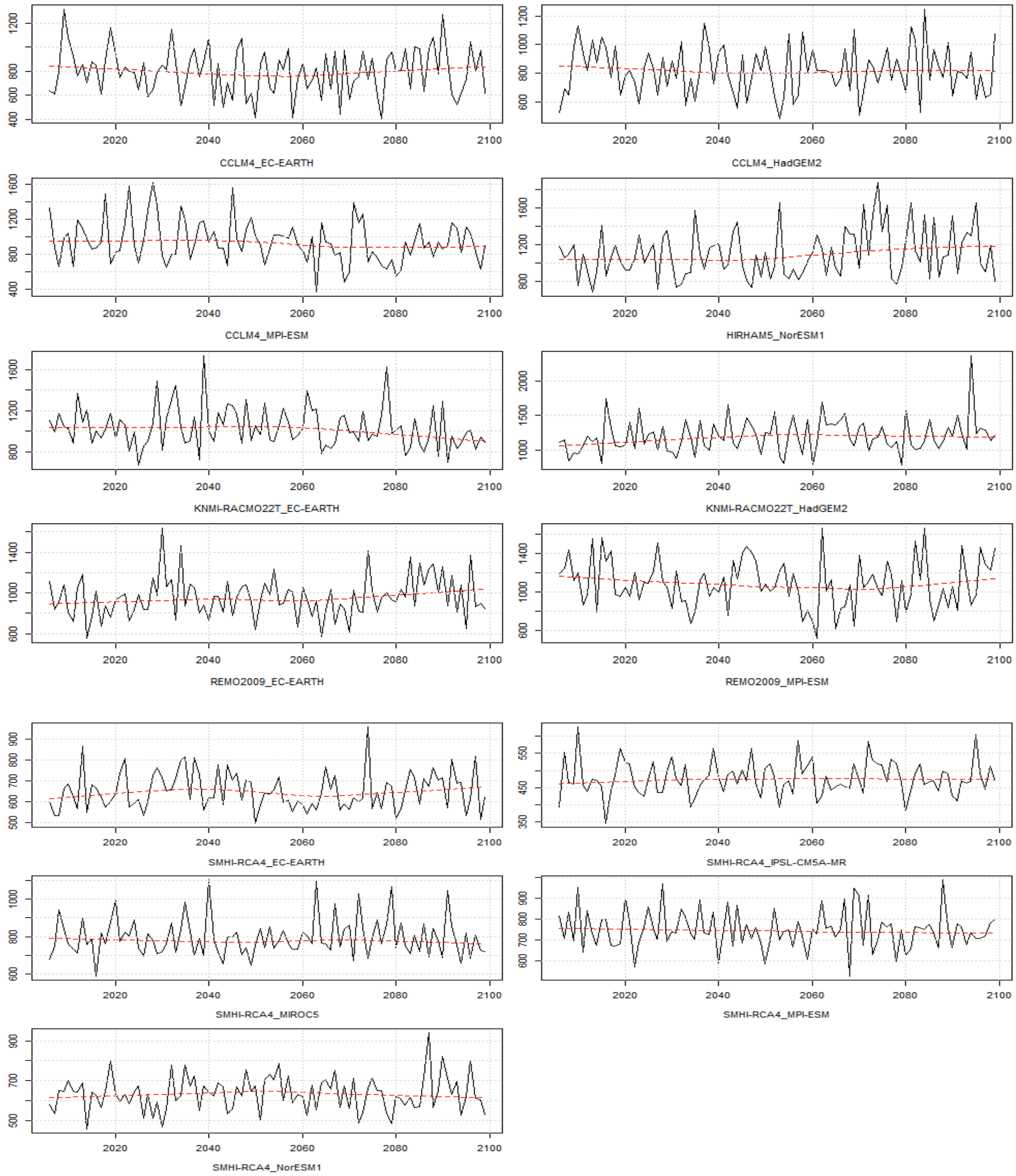


Figure 4.4: Precipitations under RCP4.5 scenario

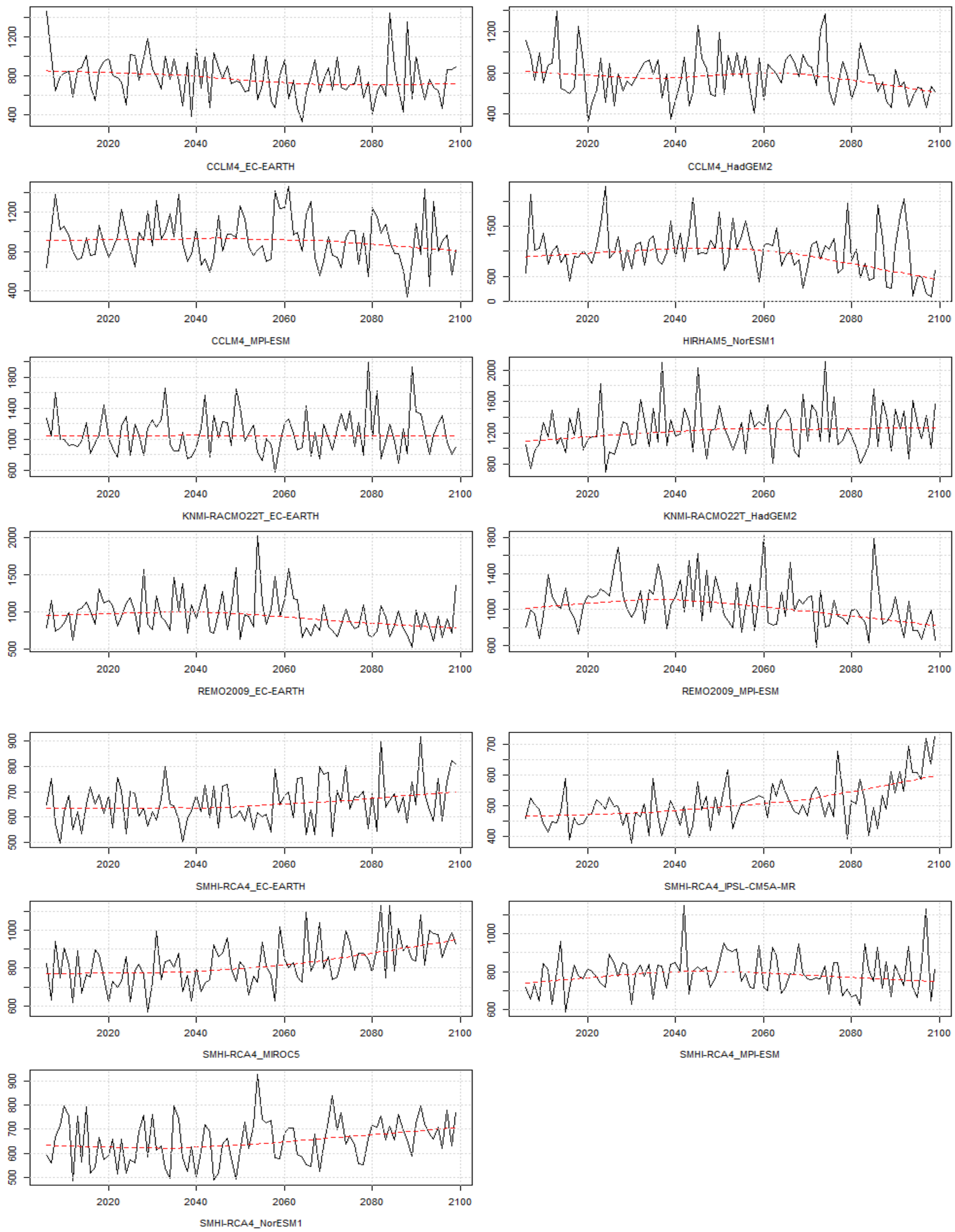


Figure 4.5: Precipitations under RCP8.5 scenario

Table 4.5: Results of different statistical tests under RCP4.5 at 5% confidence. In Grey the tests having p values inferior to 0.05 and so rejecting the null hypothesis

	Precipitation				Rainy days				Temperature			
	MK	sen's slope	pettitt		MK	sen's slope	pettitt		MK	sen's slope	pettitt	
	2-sided p.value	%	2-sided p.value	Year	2-sided p.value	%	2-sided p.value	Year	2-sided p.value	Delta	2-sided p.value	Year
CCLM4_EC-EARTH	0.98	1%	0.91	2078	0.21	-3%	0.39	2052	0.00	2.1	0.00	2043
CCLM4_HadGEM2	0.70	-5%	1.14	2019	0.01	-6%	0.00	2059	0.00	2.9	0.00	2053
CCLM4_MPI-ESM	0.08	-11%	0.09	2059	0.00	-10%	0.00	2049	0.00	2.6	0.00	2051
HIRHAM5_NorESM1	0.07	14%	0.05	2067	0.92	0%	1.24	2079	0.00	1.3	0.00	2050
KNMI-RACMO22T_EC-EARTH	0.05	-11%	0.05	2064	0.67	0%	1.55	2069	0.00	1.5	0.00	2054
KNMI-RACMO22T_HadGEM2	0.09	13%	0.19	2039	0.60	0%	0.82	2026	0.00	2.1	0.00	2053
REMO2009_EC-EARTH	0.27	8%	0.26	2074	0.70	0%	0.57	2038	0.00	1.8	0.00	2051
REMO2009_MPI-ESM	0.41	-7%	0.48	2055	0.18	-2%	0.04	2059	0.00	2.1	0.00	2049
SMHI-RCA4_EC-EARTH	0.89	1%	0.69	2050	0.97	0%	1.56	2028	0.00	1.8	0.00	2049
SMHI-RCA4_IPSL-CM5A-MR	0.63	2%	1.24	2037	0.05	-5%	0.19	2034	0.00	2.9	0.00	2078
SMHI-RCA4_MIROC5	0.92	0%	1.29	2082	0.00	-8%	0.01	2043	0.00	1.8	0.00	2042
SMHI-RCA4_MPI-ESM	0.80	-1%	1.33	2040	0.12	-4%	0.16	2049	0.00	1.9	0.00	2043
SMHI-RCA4_NorESM1	0.80	1%	0.62	2032	0.71	0%	0.93	2021	0.00	1.3	0.00	2058

Table 4.6: Results of different statistical tests under RCP8.5 at 5% confidence. In Grey the tests having p values inferior to 0.05 and so rejecting the null hypothesis

Prec	Precipitation				Rainy days				Temperature			
	MK	sen's slope	pettitt		MK	sen's slope	pettitt		MK	sen's slope	pettitt	
	2-sided p.value	%	2-sided p.value	Year	2-sided p.value	%	2-sided p.value	Year	2-sided p.value	Delta	2-sided p.value	Year
CCLM4_0.44_EC.EARTH	0.01	-12%	0.03	2048	0.00	-18%	0.00	2061	0.00	6.5	0.00	2063
CCLM4_0.44_HadGEM2	0.12	-11%	0.14	2075	0.00	-23%	0.00	2058	0.00	6.8	0.00	2055
CCLM4_0.44_MPI.ESM	0.35	-12%	0.31	2067	0.00	-22%	0.00	2068	0.00	7.2	0.00	2052
HIRHAM5_0.44_NorESM1	0.07	-57%	0.05	2064	0.00	-35%	0.00	2066	0.00	4.4	0.00	2059
KNMI.RACMO22T_0.44_EC.EARTH	0.92	1%	1.40	2072	0.88	0%	1.52	2067	0.00	3.6	0.00	2054
KNMI.RACMO22T_0.44_HadGEM2	0.13	14%	0.31	2032	0.60	0%	0.65	2049	0.00	4.9	0.00	2055
REMO2009_0.44_EC.EARTH	0.01	-25%	0.00	2064	0.01	-5%	0.05	2040	0.00	5.0	0.00	2064
REMO2009_0.44_MPI.ESM	0.01	-28%	0.01	2051	0.04	-4%	0.12	2052	0.00	6.4	0.00	2051
SMHI.RCA4_0.44_EC.EARTH	0.03	11%	0.04	2058	0.02	-5%	0.08	2080	0.00	4.3	0.00	2051
SMHI.RCA4_0.44_IPSL.CM5A.MR	0.00	26%	0.00	2045	0.56	-1%	0.01	2089	0.00	5.6	0.00	2050
SMHI.RCA4_0.44_MIROC5	0.00	23%	0.00	2065	0.32	-2%	0.49	2049	0.00	3.1	0.00	2052
SMHI.RCA4_0.44_MPI.ESM	0.95	0%	0.84	2025	0.01	-6%	0.01	2060	0.00	5.1	0.00	2053
SMHI.RCA4_0.44_NorESM1	0.01	15%	0.02	2051	0.40	2%	0.74	2022	0.00	2.9	0.00	2059

4.4 Conclusion and discussion

The understanding of climate characteristics under the form of the natural and induced variations is a key step to estimate the impacts on water and agriculture elements. This chapter used historical data as well as model predictions to unveil the recurrence of droughts, and the local anomalies under different climate scenarios in the city of Dano.

The analyses on the precipitation variability were conducted on monthly data composing the rainy season from June to October, and revealed high inter-annual variability, more pronounced at the beginning and the end of the season. The beginning and the end of the rainy season in West Africa is expected to be the most impacted by climate change (Wang and Alo, 2012; Sylla et al., 2015), but according to the statistical results, they are already the most unreliable in Dano. The analyses on climate variability are divergent, some authors accusing the droughts and floods in the past decades to be caused by already changing climate (Delaney, 2012; Sheen et al., 2017; Chamani et al., 2018), while others describe the West African monsoon to be responsible for very variable conditions since thousands of years (Shanahan et al., 2009; Norrgård, 2017; Nicholson, 2018). The difference between climate variability and climate change is in part due to the perspective for the future, the address to climate variability being more on adaptation at the moment, while for climate change different scenarios are envisaged for the future, among which mitigation scenarios. However, climate variability is, according to Ray et al. (2015), responsible for a third of observed yield variability at the global level. In the case of West Africa, the correlation was mixed depending on the country, with wet years affecting positively the yields but inducing the leaching of soils on the other hand, and the already use of adaptation strategies to the variable precipitations. Yet, the focus on climate stressors should not, however, undermine the other drivers as stated by Epule et al. (2017). The author tracked the reports in the Sahel on climate change stressors such as droughts, floods, and winds, and found that on 388 documented and peer-reviewed reports, 47% are related to non-climate drivers. The non-climatic drivers such as land degradation, and population growth, are in part responsible of the “Sahel paradox”, which is characterized by decreasing precipitations and increasing runoff with time.

As for climate change, the simulations from thirteen climate models, showed mixed results for the precipitation, and respectively decreasing and increasing trends for the rainy days and the maximum temperature, during the rainy season. Breaks in the data appear significantly for the different simulations around the year 2050, meaning that climate change is up to come in the future. The lack of consensus among the models on precipitation is not typical to Dano but common to the West African monsoon (Karambiri et al., 2011; Laprise et al., 2013; Yira et al., 2017). The reasons behind the divergence of the models output in West Africa are manifold in the literature and argued to be due to the sensitivity of the climate models to different forcings (Xue et al., 2016; Gaetani et al., 2017), to the non-integration of physical processes affecting the rainfall variability (Martin et al., 2017; Whittleston et al., 2017), etc. Yet, the decreasing trend found in rainy days even for models not showing a trend in the precipitation amounts, can be interpreted as an increase of extremes events and also more recurrent dry spells. For

Giannini et al. (2013), the recovery of the precipitation in the Sahel from the droughts in the 70s and the 80s has not reversed the reduction of the frequency of rainy days caused by the droughts, but is instead characterized by an increased intensity of rainfalls. A study by Akinsanola and Zhou (2018) on rainfall extremes, found that the West African precipitations are expected to increase in their intensity despite the decrease of the total rainfall. As for the anomalies on maximum monthly averages of temperature projections are on the other hand concordant as all the models predict an increase in temperatures for the two scenarios, with a higher increase for the RCP8.5. The increases in temperature are similar to the ones by the IPCC for West Africa, whose values range from +3°C to +6°C with RCP4.5 and RCP8.5.

5 Impact assessment and adaptation strategies for rainfed rice in inland valleys in Dano

5.1 Introduction

Rice has become a strategic crop in West Africa. The demand for rice has grown yearly at a rate of 6% since the 70s according to Maclean et al. (2013), due mainly to population growth and to the changes in food and nutrition preferences. The annual regional production growth of 4.6% implies an increasing import of rice that represents now a third of the demand. The low yields compared to the world average are a good incentive for enhancing the local production, as rice represents the strongest agricultural market in terms of potential of growth in the region (Hollinger and Staatz, 2015). Yet, the unreliable climate and the multitude of rice growing environments requires adapted understanding of the changes to come.

Among the different ecosystems in West Africa suitable to the cultivation of rice, the rainfed lowlands represent 34% of the total lands devoted to rice and 36% of the total production (Maclean et al., 2013). The potential for growth is considerable, either by expanding the cultivated land as less than 15% of the lowlands are exploited, or by enhancing the yields as the average yields are less than 2 ton/ha, versus a world average of 4.3 ton/ha and a potential 10 ton/ha in some regions. For Rodenburg et al. (2014), the constraints to rice production all over Africa are mostly due to weed competition, poor soils, and diseases. They estimated that with improved water and weed management, only 9% of total inland valleys cultivation is necessary to cover the rice demand in Africa, a good argument for the use of inland valleys for agriculture, as they are parts of the wetlands family and disposed to have their ecosystems protected.

The studies on impacts of climate change on agriculture are manifold in West Africa. Zougmoré et al. (2016) found in a literature review on impacts of climate change on crop production that most projections on West Africa’s future predict a productivity crisis. The reasons are related to the climate with the increase in temperatures and decrease in precipitations, to poor soils together with low fertilizer inputs, and the use of simple farm tools. Roudier et al. (2011) also found in a literature review on impacts of climate change on crop yields in West Africa, negative trends in the region with the northern part, the Sudano-Sahelian area, being more affected with a median decrease of 18%. The causes are a combination of higher temperature and water stresses. For Challinor et al. (2007), most studies predict a decline in yields in Africa due to climate change, yet, the magnitude of drop diverges considerably depending on the sensitivity of crop models to the variability of climate parameters.

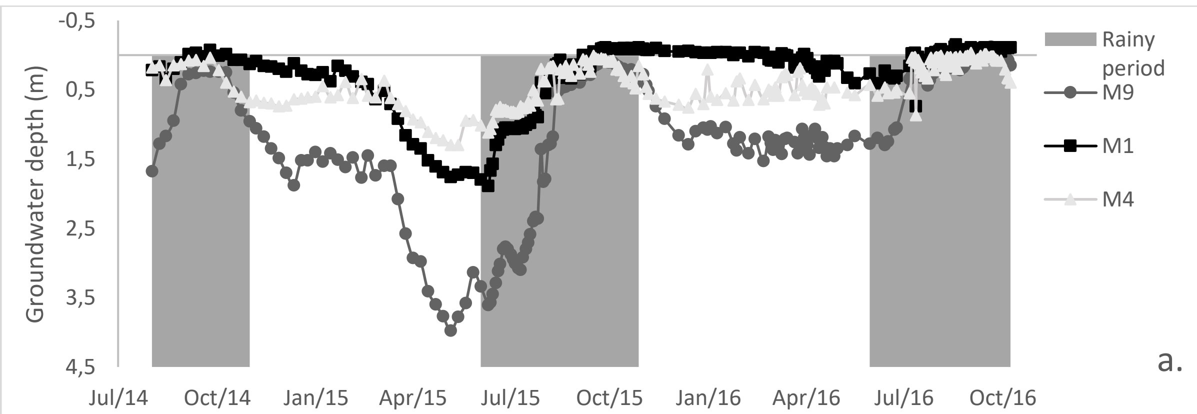
Inland valleys bottomlands are usually presented in the literature as a secure place for crop production. However, similarly to wetlands, they are expected to be impacted as well by climate change in the future. For Erwin (2008), the hydrological regimes of wetlands in general, will be altered in a profound way because of their vulnerability to changes of their water supply. They are expected to decrease in numbers in terms of functioning and the shift in the geographical location of certain types of wetlands may occur. The performance of the water infrastructures like reservoirs, although constructed to buffer the variability of precipitations, will also be affected due to uncertainties in their design (Peel and Blöschl, 2011). This questions the vulnerability of inland valleys agricultural systems to climate variability and change in West Africa, and the keys to adaptations.

5.2 Inland valleys in Dano

The study has been conducted inside four inland valleys with rainfed rice cultivation, two disposing of irrigated schemes with reservoirs in Moutori and Fafo, one with a contour bunds systems in Bankandi and the last with drainage canals in Lofing. A monitoring system has been put in place in order to follow the field and the scheme water management. Inland valleys lowlands usually comport a variable hydrology with temporal waterlogging by surface or groundwater, hydric soils and emergent plants known as helophytes.

5.2.1 Groundwater

A network of 33 piezometers completed with existing wells has been monitored to better understand the dynamics of groundwater inside the four agricultural schemes. Figures 5.1 – a to d show the fluctuation of the shallow groundwater depth to the topsoil. The rainy season corresponds to the period from June to October and the shallow water depth varies differently with to the toposequence and according to the infrastructures in place. Inside the reservoir-based schemes in Moutori and Fafo, the rise of the water level with the first rains is slow and the flooded conditions are shorter compared to the others scheme. In addition, the recharge of water due to irrigation during the dry season from December to April is visible as a sustained water depth (between 1 and 1.5 m) while in the other schemes the dry season is characterized by a decline of the water level up to 3 m.



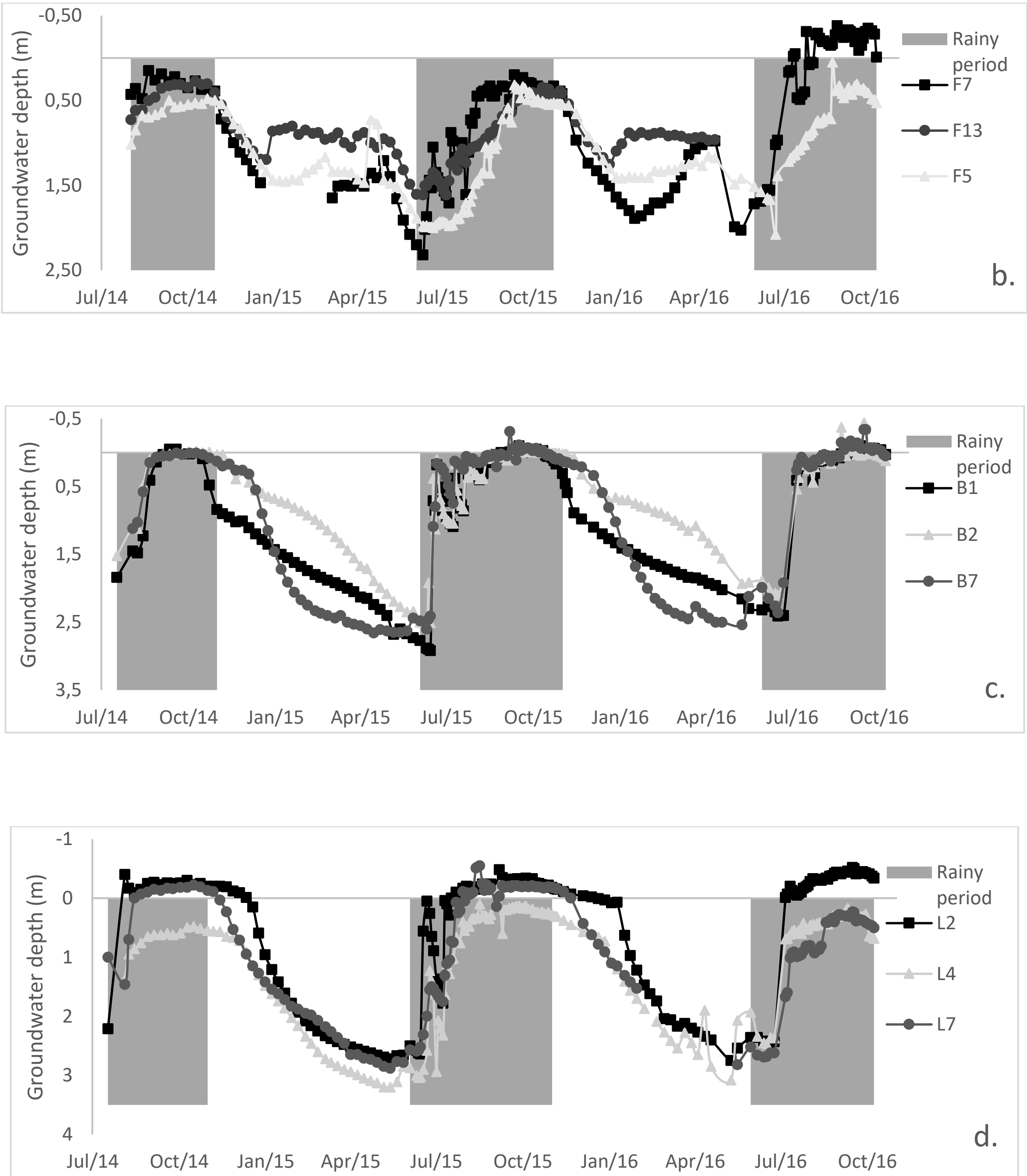


Figure 5.1: Fluctuations of the shallow groundwater in the head (M1, F13, B1 and L2), middle (M4, F5, B2 and L4) and tail (M9, F7, B7 and L7) of the scheme in (a.) Moutori, (b.) Fafo, (c.) Bankandi and (d.) Lofing

5.2.2 Soils

The soils inside inland valleys bottomlands are characterized by sediments deposits from uplands soil erosion, usually silt and clay. The fluctuation of the shallow groundwater causes the saturation of the inland soils with water and hence the oxidation of chemical elements like iron visible by the grey and brown colors typical of hydromorphic soils. Inside the inland catchments in Dano, the uplands are principally plinthosol while the bottomlands are gleysols. A soil texture survey inside selected parcels in the four schemes showed a predominant clay soil.

5.2.3 Rice

Rice is commonly cultivated inside inland valleys lowlands as it requires waterlogging conditions. Rice is cultivated under rainfed conditions in the three schemes in Bankandi, Lofing and Moutori, and supplemental irrigation in the last one in Fafo. The varieties cultivated are the African NERICA varieties FKR 19 and FKR 62, and the new variety TS 2 from Taiwan. Figures 5.2 – a and b show the annual productions and the average yields of the commercial crops in the Ioba province comprising the city of Dano. The low yields for most of the crops (less than 1.5 ton/ha) are typical of the extensive farming systems with a growth pulled by land expansion. Yet, the highest monitored yields in the selected schemes (8 ton/ha in Moutori during the rainy season 2014) are a good argument for the intensive exploitation of inland valleys.

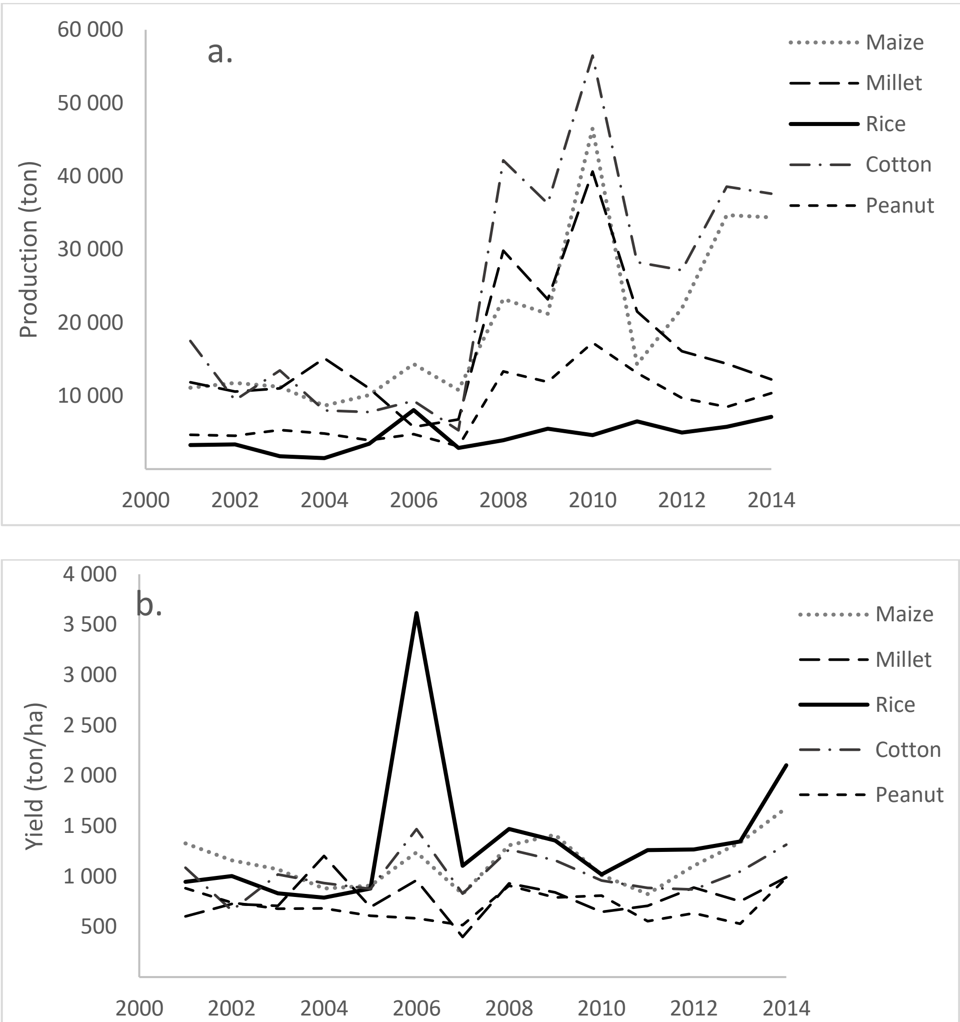


Figure 5.2: Evolution of (a.) the production and (b.) the average yield of commercial crops in the Ioba province (source: Direction régionale en charge de l'agriculture du Sud-Ouest)

5.3 Modeling with AquaCrop

5.3.1 Parameterization and evaluation

The FAO crop model AquaCrop (Vanuytrecht et al., 2014) is parametrized here to simulate the crop growth and the yields in eight parcels during the rainy season in the reservoir-based schemes of Moutori and Fafo (see Fig. 5.3 and 5.4 for the locations and Table 5.1 for the parameters).

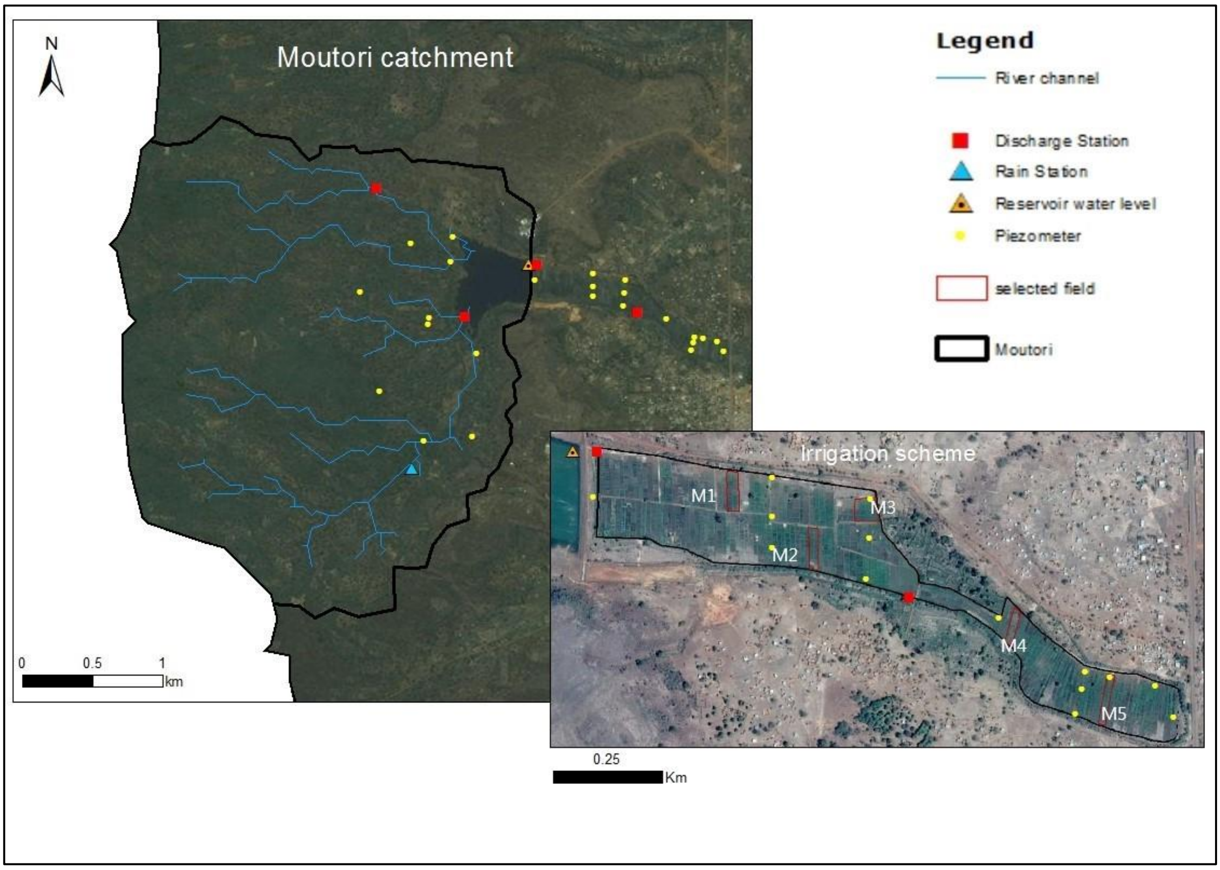


Figure 5.3: Locations of selected fields in the agricultural scheme in Moutori

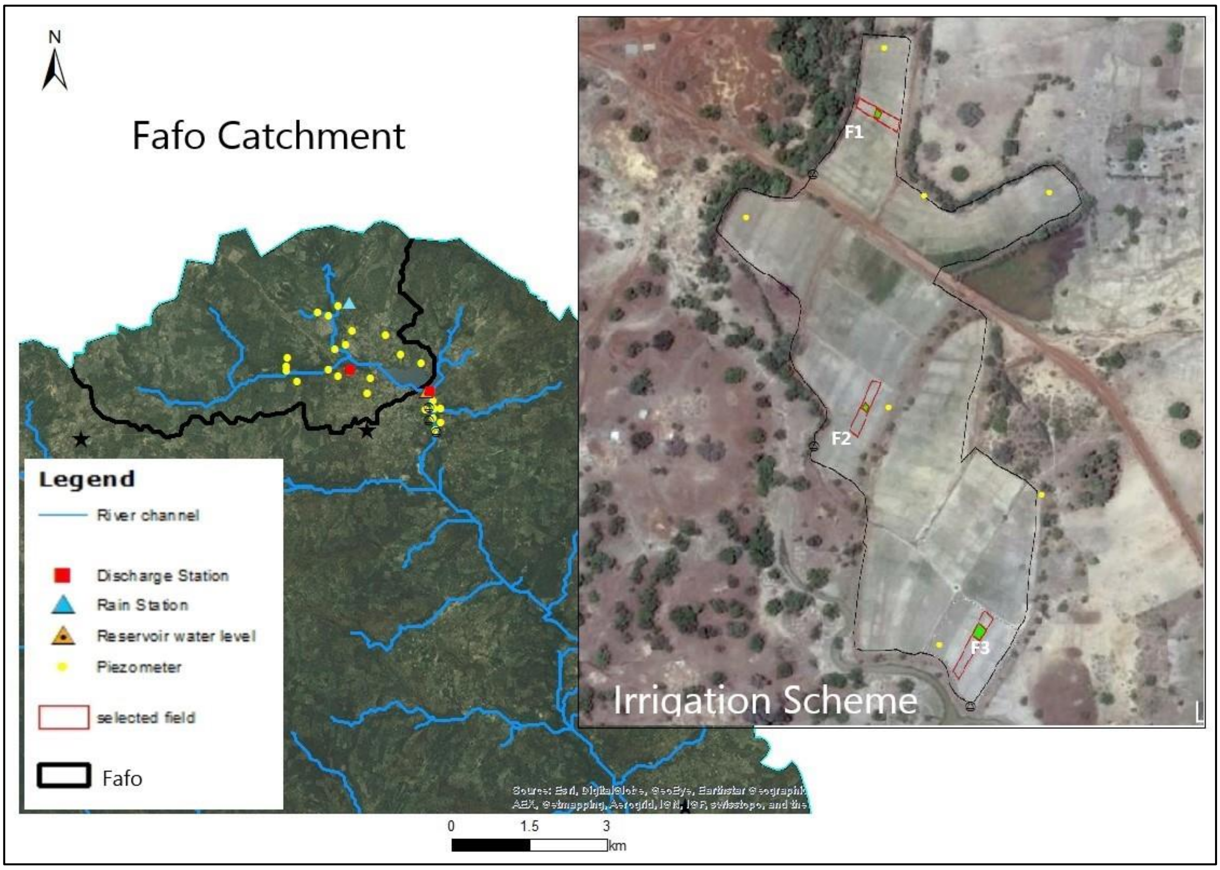


Figure 5.4: location of selected fields in the agricultural scheme in Fafo

Table 5.1: Field data in selected parcels in Moutori and Fafo

Parcel	GW depth – Min and Max (m)	Soil type	Ksat (m/day)	Growing cycle
M1	0 - 1.46	clay	0.6	23 June - 25 October
M2	0 - 1.40	sandy clay loam	0.5	19 June - 21 October
M3	0 - 1.16	clay	0.2	14 June - 20 October
M4	0 - 2.47	clay	0.0001	11 Juillet - 23 October
M5	0 - 2.47	clay loam	0.6	18 June - 20 October
F1	1.17 - 2.17	loam	50	02 August - 14 November
F2	0.32 - 1.93	silty clay loam	0.0002	01 August - 13 November
F3	0 - 1.21	clay	~ 0	07 August - 19 November

The data from the two other schemes were incomplete on the water supply and drainage aspects. The AquaCrop model has been utilized successfully for rice under different climates and water regimes (Amiri, 2016; Maniruzzaman et al., 2015; Amiri et al., 2014). The parameterization of the model requires data on crop characteristics (type, planting method, cropping period and length of growing cycle), soil profile characteristics (hydraulic characteristics, thickness), groundwater (depth and quality), climate (temperature, reference evapotranspiration, rainfall and atmospheric CO_2 concentration) and irrigation management (type, schedule and depth of application). The model has already been calibrated for rice and only the ‘soft’ parameters like the plant density and the canopy growth phases were adjusted according to field observations inside the selected fields. The AquaCrop model has shown acceptable results for the simulation of the biomass aboveground, of the canopy cover, of the unsaturated soil water content and of the yields. The comparison between the simulations and the observations are presented in Fig. 5.5 – a. to c.

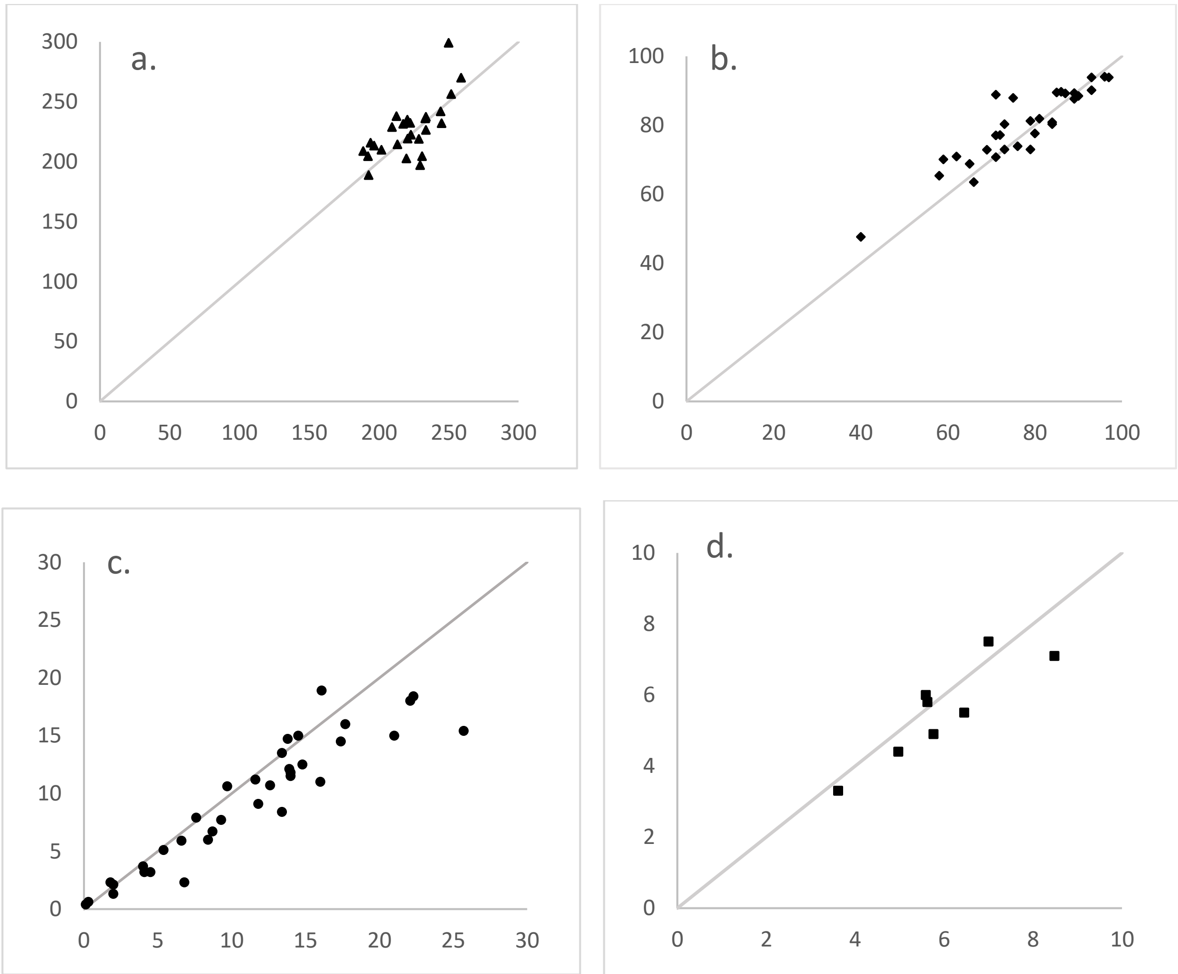


Figure 5.5: Comparison between simulations (Y-axis) and observations (X-axis) for (a.) the unsaturated soil water content (mm), (b.) the canopy cover (%), (c.) the biomass aboveground (ton/ha) and (d.) the yields (ton/ha)

The biomass aboveground was replicated with good accuracy, even though high increase rate after fertiliser application could not be reproduced. The canopy cover was not measured but instead converted from Leaf Area Index (LAI) observations by the formula:

$$CC = 1 - exp^{-k.LAI} \tag{5.1}$$

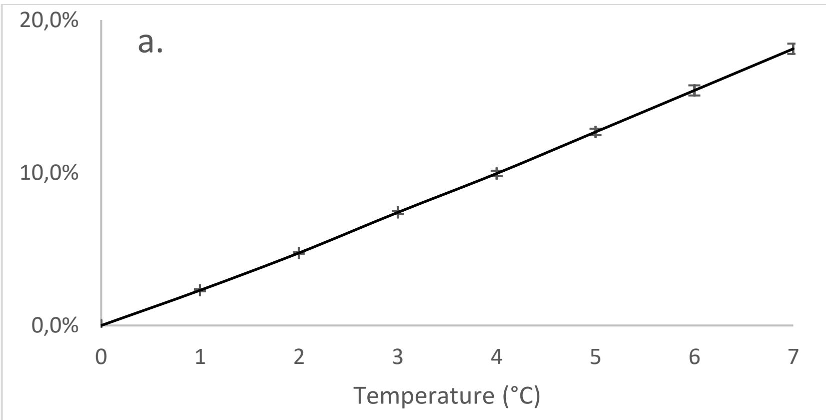
With k an extinction coefficient depending on the growth stage but also the plant density. Values of k in the literature for rice vary with the vegetative stage usually from 0.4 to 0.6 and sometimes 0.7 (Kropff et al., 1993; Casanova et al., 1998; Dingkuhn et al., 1999; Ando et al., 2002). In this study, a value of 0.7 for the growing and reproductive stage and 0.4 for the senescence was chosen to relate with high dry matter values and the high density of plants inside the fields. As for the soil water content, the soil hydraulic parameters such as the soil water content at wilting point, at field capacity and at saturation, have been adjusted in the allowed range of values to the corresponding soil textures, to replicate the observed unsaturated soil water content for each parcel.

5.3.2 Sensitivity to heat and water stresses, and CO_2 increase

The sensitivity analyses are important to understand the behavior of the model under changing circumstances such as temperature, water, and CO_2 level. For the heat stress, the minimal and maximum temperatures have been increased from +1°C to +7°C. For the water stress, the precipitations have been reduced from 10% to 50% without changing the groundwater fluctuations. The water stress is hence at the beginning of the season during the crop growth period. For the increase in CO_2, different concentrations of CO_2 have been tested from 400 ppm to 950 ppm.

5.3.2.1 Temperature stress:

An increase in temperature is interpreted by the model by a linear increase in relative evapotranspiration and a logarithmic/sigmoid decrease in harvest index and water productivity (see Fig. 5.6 – a. to c.). This is explained by the fact that the AquaCrop model considers a threshold (35°C) beyond which the pollination and hence the harvest index is impacted by the heat, on the contrary to the biomass aboveground which is resistant to high temperatures. This set-up is in accordance with the literature (Das et al., 2014) (Hatfield and Prueger, 2015), though, some varieties are more tolerant than others (X. M. Li et al., 2015) (Tanamachi et al., 2016). The pattern of temperature stress is an important parameter in the analyses of the impact on rice, such as the intensity (Huang et al., 2017) or the night temperature (Xiong et al., 2017; Jagadish et al., 2015). For this study experiment, the changes inside the different parcels are uniform despite different types of field management.



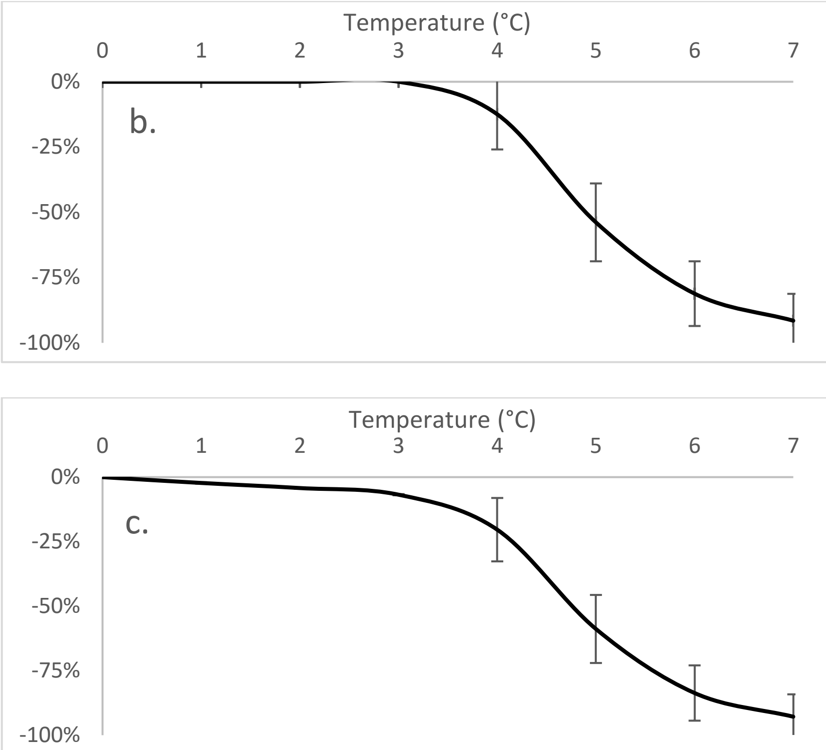


Figure 5.6: Relative change in percentage of: (a.) Evapotranspiration (ET), (b.) Harvest Index (HI) and (c.) Water Productivity (WP) with the increase in temperature in °C.

5.3.2.2 Water stress:

A reduction in the precipitations has not the same effects on the different parcels because the differences in the topography, the soils, the cropping dates and the water supply influence the water stress. In the reservoir-based scheme of Fafo, the supplemental irrigation covers entirely the crop water needs at a point that a reduction of 50% in the precipitation amounts has no impact on the plant growth. In the opposite, in Moutori, a reduction of 10% in the precipitation has a 100% crop failure for the parcel M2 due mainly to a non-saturated field condition and to low precipitation in the first days (see Fig. 5.7 and 5.8). Water stresses are impactful to the biomass growth as well as the yields (Sokoto and Muhammad, 2014) (Pandey and Shukla, 2015). The impacts of water stresses are dependent of the variety and the growth stage (Germani et al., 2016; Khan et al., 2017), yet, managed adequately, water stresses can improve drought tolerance by enforcing the root development (Zain et al., 2014; Dasgupta et al., 2015; Suralta et al., 2015)

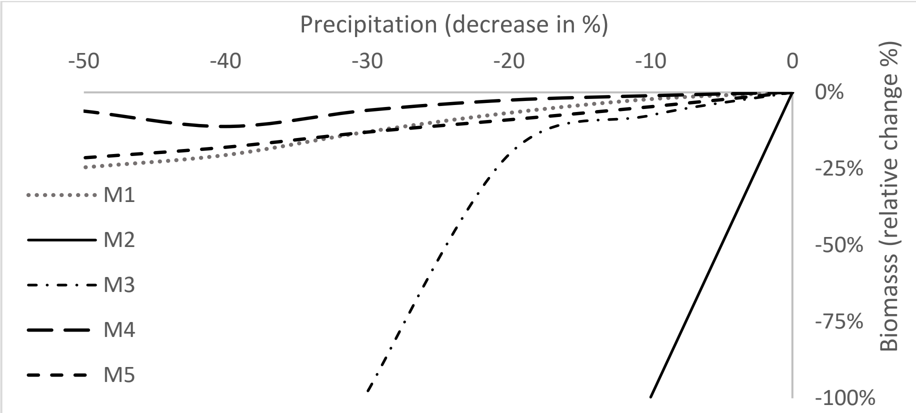


Figure 5.7: Relative change in percentage of the Biomass aboveground with the decrease in precipitation (%).

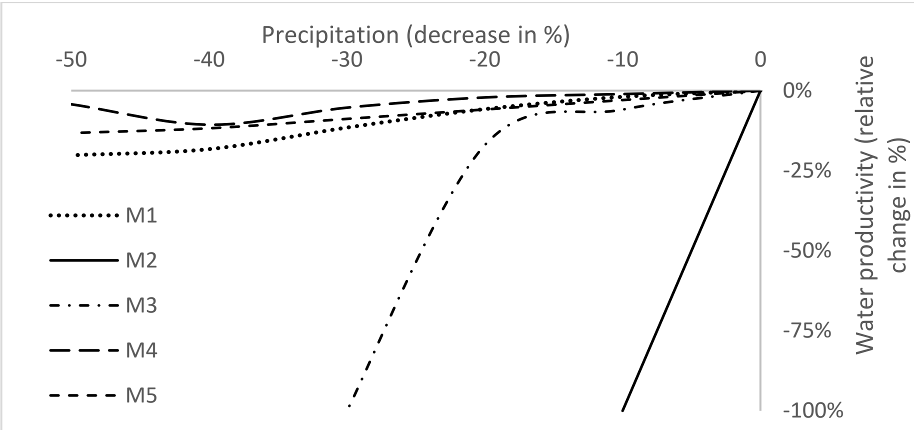


Figure 5.8: Relative change in percentage of the water productivity with the decrease in precipitation (%).

5.3.2.3 CO2 increase:

There is an opposite effect of the increase of CO_2 level on rice growth when compared with temperature rise as reflected by Fig. 5.9 and confirmed by the literature (Wang et al., 2015; Chaturvedi et al., 2017). The increase in CO_2 level is accompanied by an increase in the biomass and in the water productivity respectively of 64% and 47% for a CO_2 level of 950 ppm. As for the evapotranspiration, a reduction of 11% is noticed for a CO_2 level of 950 ppm.

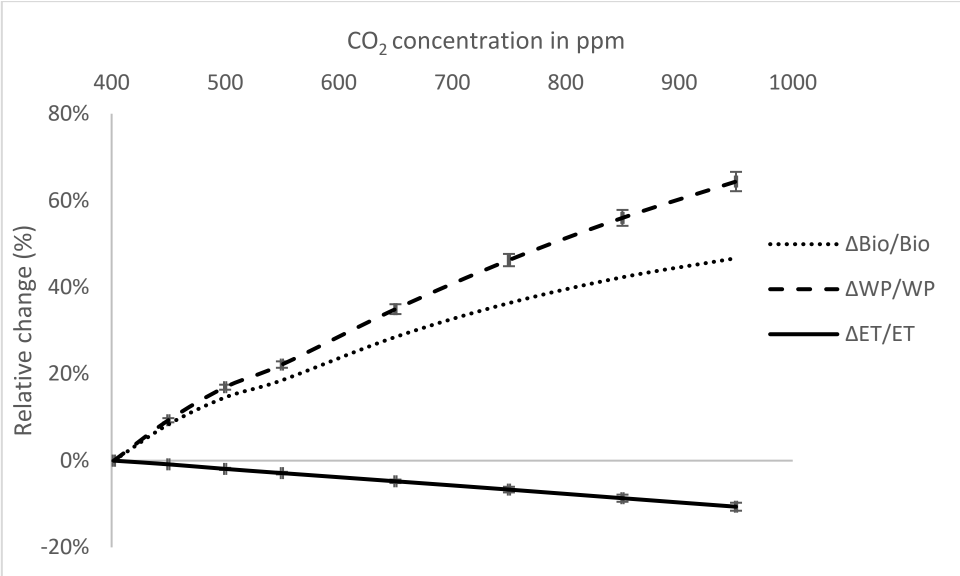


Figure 5.9: Relative change of Biomass aboveground (Bio), Evapotranspiration (ET) and Water Productivity (WP) with an increase in CO_2 level.

5.4 Climate threats

5.4.1 Precipitation variability

The variability of the precipitations in West Africa constitutes a concern for farmers as floods and droughts can have disastrous impacts on yields. A statistical analysis has been conducted on historical data to identify the variability of the precipitations for the different months composing the rainy season and Table 5.2 shows the return periods of droughts at monthly and seasonal scales. The starting months of the rainy season are the most impactful on rice due to the high variability of the precipitation in addition to low groundwater levels (see Fig. 5.2). August and September are the most stable months and the period during which the lowlands benefit most from the catchment runoff.

Table 5.2: Statistical analyses of the return periods for the precipitation in Dano

SPI Index	Return periods (Years)	Rainy season (mm)	June (mm)	July (mm)	August (mm)	September (mm)	October (mm)
mean values	**0**	**734**	**111**	**186**	**226**	**160**	**51**
	3	693	81	151	200	135	27
	5	640	47	130	174	117	17
SPI = -1	**6.3**	**619**	**35**	**123**	**164**	**111**	**15**
	10	580	15	112	146	100	10
SPI = -1.5	**14.9**	**548**	**0**	**104**	**132**	**92**	**8**
	20	527		98	123	87	6
	25	511		95	117	84	5
	30	499		92	112	81	5
	35	488		90	108	79	4
	40	480		88	104	77	4

SPI = -2	**43.5**	**474**		**87**	**102**	**76**	**4**
	50	465		85	99	74	3

5.4.2 Climate change

Thirteen climate models have been analyzed in order to identify patterns of change in the temperatures and the precipitations with the use of two scenarios: the Representative Concentration Pathway 4.5 (RCP 4.5) corresponding to a radiative forcing of 4.5 W/m² by 2100 and the RCP 8.5 for a forcing of 8.5 W/m². The results showed an increasing temperature in both scenarios from +1.3°C to +2.9°C for the RCP 4.5 and from +2.9°C to +7.2°C for the RCP 8.5 in 2100. The results for the precipitations are mixed and one out of thirteen models shows a decreasing trend for the scenario RCP 4.5 while for RCP 8.5, there are four models showing an increasing trend, four models showing a decreasing trend and three with no statistical change.

5.4.3 Scheme water balance under changing conditions

The balance of the four schemes during the rainy seasons have been assessed during the years 2014 and 2015 by a simple water balance equation as followed:

$$Inflows = ETP_{rice} + Outflows \qquad (2)$$

With *Inflows* term composed of precipitation and runoff, and *Outflows* regrouping infiltration and drainage.

Two scenarios are considered and evaluated:

- A 'Soft' change derived from the RCP 4.5 consisting of a CO_2 level of 550 ppm, an increase in temperature of +2°C and a decrease of about 20% of the inflows.
- A 'Hard' scenario inspired by the RCP 8.5 with a CO_2 level of 950 ppm, a +5°C increase in temperature and a 40% reduction in the inflows.

The results are summed in Table 5.3 and present a deficit for the scheme in Moutori while the three others are showing exceeding flows either by infiltration or by surface runoff. The soft scenario shows a positive increase in the yields due to the increase in CO_2 level. The hard scenario affects differently the yields with a variation from -56% to +11%. These differences can be explained by the influence of water stress, which affects differently the fields as explained above, and hampers the positive impacts of CO2 increase in yield enhancement.

Table 5.3: seasonal water balance in four schemes in Dano under current and water scarcity scenarios

				Soft scenario			**Hard scenario**		
Site	**Inflows (mm)**	**Rice ETP (mm)**	**Outflows (mm)**	**Inflows (mm)**	**Rice ETP (mm)**	**Outflows (mm)**	**Inflows (mm)**	**Rice ETP (mm)**	**Outflows (mm)**
2014									
Moutori	750	556	194	600	567	33	450	561	-111
Fafo	1313		757	1050		483	788		226

Bankandi	2147		1591	1718		1151	1288		727
Lofing	10405		9849	8324		7757	6243		5682
2015									
Moutori	882		272	706		83	529		-87
Fafo	1337	610	727	1070	622	447	802	616	186
Bankandi	6177		5567	4942		4319	3706		3090
Lofing	27966		27356	22373		21751	16780		16164
Potential yield	~ 8 ton/ha			+19%			-56% to +11%		

5.5 Adaptation to climate variability and change

An assessment of four inland valleys performance inside Dano under current and changing scenario brings out the question of the adaptability of each to climate variability and change.

5.5.1 Literature review

Adaptation strategies for more resilient agriculture in Africa are manifold in the literature and apprehended under different levels at the policy level and at the local or farm level.

At the policy level, the integration of climate change adaptation in the continental, regional, and national organizations' agendas assume the understanding of the stakes at the highest levels. Yet, the different policies are relatively recent, and for most funded by international funds. The National Adaptation Programme of Action (NAPA) developed in the least developed countries, for example, was under the funding of the UNFCCC, which permitted these countries to have an adaptation tool at the national level, based on their vulnerability assessment. Ford et al. (2015) consider these NAPAs to be "wish lists" that are not consistent in terms of policy and practices. The same critics have been made by Erguavoen and Wahren (2015) in Burkina Faso, who found the process of elaboration of the NAPA not inclusive in terms of local priorities and participation, and the actions 'theoretical' without government's commitment for funding. Likewise, for Niang et al. (2014), the strategies in the continent are short-termed and lack the connection between the policies at the government level and the actions taken at the local level. On the strategies to be considered, Ford et al. found in a literature review in Africa and Asia, that the majority of the reported initiatives on adaptation strategies focus on agriculture. This is due in part to the fact that agriculture is one of the most vulnerable sectors to climate change, particularly in poor countries, and to the role played in the GDP of these countries. Gebreyes et al. (2017) noted that the stresses to agricultural systems are not only climate-related and the strategies for adaptations should include these other stresses in order to be effective. The non-climate stresses to agriculture are manifold and concern the access to finance and credits, the knowledge or education, the level of participation in the value chains, etc. In other terms, adaptation strategies at the policy level should be formulated as an integrated development agenda, by taking into account the vulnerability at the local level. The case of mitigation is not usually raised in Africa, as the continent contribution to greenhouse gases is marginal at the global scale. Yet, (Mbow et al.,

2014) advocate the double contribution of agroforestry for mitigation as well as adaptation to climate change, given the numerous benefits it provides as ecosystem services.

The impacts of climate change are experienced differently at the local level, depending on the vulnerabilities of the communities. The adaptation strategies are hence diverse and the question of the most adequate strategies is a concern for policymakers. In a study across three West African countries, Douxchamps et al. (2016) found the adaptation strategies on agriculture, like crop diversity, soil and water conservation among other parameters, to be widely adopted at various degree and to have different levels of success on improving the food security of farmers. They advocate for more tailored strategies at the local level, regarding the local context. In the Sahel region, which has a long history of floods and droughts, the local communities are aware of the unreliability of the precipitations and have developed different coping and adaptive actions that are interesting to apprehend. Mertz et al. (2009) found that the traditional strategies in the Sahel to cope and to adapt to climate change at the local level relies more on social solutions like mobility, livelihood diversification, and migration. On the other hand, García de Jalón et al. (2016) found in a literature review that the Sahel region has one of the lowest likelihood to adopt 'new' adaptive strategies to climate change in Africa, and related the drivers for adoption at the farm level mainly to governance and civil rights as well as financial resources and education. The barriers to adaptive measures are manifold and Shackleton et al. (2015) qualify these socio-political and psychological barriers as hidden. In the case of Burkina Faso, the authors reported as barriers the lack of cash and access to credit, the poor access to water, the insecurity in the access of land, the lack of inputs, and the low access to information on agroforestry and crop varieties, among other parameters.

On a more technical level, the change of the rainfall pattern in West Africa with shortened seasons and more extreme rainfalls as predicted by the IPCC can be addressed with fast-growing crop species and the increase in storage, according to van de Giesen et al. (2010). They advocate for small reservoirs, which are more supportive to the local development and have less managerial issues than larger ones. Elsewhere in Europe, Iglesias and Garrote (2015) found in a literature review, that the strategies to adapt to climate change impacts such as future water scarcity for agricultural demands are on the supply side with an increase in storage and on the demand side with improved efficiency measures.

The infrastructure and the management of the schemes appear to be key points to adaptive strategies inside the schemes. Yet, behind the specificity of each inland valley, there is a need to understand the pros and cons of the infrastructures in place in addition to their management.

5.5.2 Infrastructures

The differences between the four schemes in terms of infrastructures in place can be summed to their storage capacity and their contributing catchment.

The reservoir-based schemes offer secure farming during the rainy season with the possibility to stock the water and apply supplemental irrigation while the other schemes are designed to regulate by reducing the speed of flows, like in Bankandi, or draining the excess of water like in Lofing. The design behind the choice of the different infrastructures has been proposed by Albergel et al. (1993) and Lidon et al. (1998) for valleys in West Africa, based on the hydrology, the soil, and the geometric characteristics of the valley. While the characteristics on the soil and the geometry of the valley can be measured directly in the field, the hydrology requires years of measurement and is hampered by the lack of data, the vast majority of the small catchment being ungauged. The assessment of the annual runoff is hence approximate and lies on measurement campaign in the 70s (Triboulet et al., 1996; Albergel, 1988), all of which makes difficult the choice of infrastructures inside valleys. Yet, most of the time, the finances guide the choice of the infrastructures beforehand any other criteria, the design is hence reduced to a suitability analysis of an infrastructure instead of the research for the most appropriate infrastructure for a specific site. The advantageous features of the reservoir-based schemes are offset by their high cost in terms of investment and their high water losses by infiltration and evaporation.

As for the size of the catchment, larger areas are generally related with lower runoff coefficient because of more storage or higher evapotranspiration(Cerdan et al., 2004; Chen et al., 2016). In this study, larger catchments are associated with higher runoff coefficients, which makes them more water secure and candidates for storage infrastructures. The catchments in Moutori and Bankandi have experienced runoff coefficients of 4% to 7% during the two years, while the values in the two other schemes which are larger vary from 7% to 22%. The size of the contributing catchment is important to have an idea of the runoff to the scheme, moreover is the ratio of the catchment area to the scheme area. The ratio is known as Catchment to Cultivated Area ratio or C:CA and applied in dry areas to design water harvesting systems for rainfed crops (Critchley and Siegert, 1991), however, it is usually not associated with valleys in sub-humid areas. The ratio is high for the selected valleys and can be interpreted as a coefficient of security of the scheme, the higher the ratio, the more water secure the scheme. In Dano, values of 39 and 66 are respectively found in Moutori and Bankandi, where water stress has been experienced at the beginning of the season in 2014, and values of 107 and 281 respectively for Lofing and Fafo where the schemes have higher inflows from the respective catchments.

5.5.3 Scheme management

A comparison of the supply and demand of water inside the four inland valleys does not show any stress for the seasonal amounts in three out of four schemes. Yet, the temporal and spatial distributions of the precipitations and runoff inside the scheme play an important role in the management of water. For the spatial distribution, the reservoir-based schemes have designed schemes with irrigation and drainage canals and leveled fields on the contrary of the other schemes, which are not leveled. However, the leveling inside the reservoir-based schemes does not influence the groundwater fluctuation, which plays an important role for waterlogging conditions. As for the temporal distribution, the discrepancies among the monthly precipitations are not favorable to the beginning of the season during which the schemes are not flooded. Less precipitation in the future or less rainy days will increase the hazards on rainfed rice inside inland valleys.

Manifold management solutions exist in the literature to the uncertainty at the beginning of the rainy season such as the use of supplemental irrigation based on the reservoir storage or the groundwater or farm ponds (Nangia and Oweis, 2017; Muluneh et al., 2017; Sanfo et al., 2017; Bigelow and Zhang, 2018), the use of 'wetting and drying' techniques which increase the rice productivity and mitigate the methane emission of rice fields (Meryl Richards, 2014; Lampayan et al., 2015; Nalley et al., 2015; Mazza et al., 2016; Carrijo et al., 2017), the delay in the sowing dates (Dharmarathna et al., 2014; T. Li et al., 2015; Muluneh et al., 2017; van Oort and Zwart, 2018), among others. A comparative assessment of the different techniques is challenging as each has been successfully tested in different contexts. The average yields in the different schemes are varying from 1.8 to 4.7 ton/ha are still far from the highest yields monitored in the selected parcels (8 ton/ha) and from the genetic yield potential close to 10 tons/ha. The reservoir-based schemes have higher yields due in part to the level of organization of the farmer association and to the support from the extension services. The reasons for low yields in the other schemes are related to fertilizers application and weed competition, and also to inappropriate drainage inside the fields, an issue that can be overcome with more investment inside the fields and that will compensate the loss induced by heat and water stress. However, the suitability of rice can be questioned and its replacement considered in the case of very dry conditions in the future. Among the crops tolerant to heat and water stress, millet, sorghum, and maize are already cultivated in the uplands.

5.6 Conclusion

The farming of rice has been evaluated under current and future scenarios inside inland schemes in Dano with the help of the AquaCrop model. Heat stress and change in CO_2 level have reverse and uniform effects on yields and water productivity while the impacts of water stress are difficult to predict. The inflows and outflows at the scheme level do not show important water deficit under different water stress scenarios. However, the intra-seasonal variability of the precipitation should be tackled through better storage and better water management. The low yields inside the different schemes are an opportunity for improvement and of reversing the future impacts of climate change. All of which requires more investment and research for rice cultivation in West African inland valleys.

6 General Conclusion

The future of agriculture in semi-arid areas in Africa is a concern for the whole continent, as the region produces a major part of the crops and is endangered by hotter temperatures and increasingly unreliable precipitations. The use of inland valleys as a solution to improve the resilience of farmers to climate variability and change has been assessed in this study through the prism of hydrology, crop, and climate science, in addition to the cultivation of rice, with the research questions:

- What is the hydrological functioning of inland valleys?
- How do the agro-systems inside valleys perform?
- How uncertain is the climate in Dano under current and future conditions?
- What is the potential of inland valleys to adapt to climate variability and change?

6.1 Hydrological functioning of valleys

The hydrology inside inland valleys has been described in Moutori through the water balance of the reservoir as well as the irrigated scheme during two hydrological years. The reservoir balance showed high water losses by evaporation and seepage, which represent together 75% and 69% of the water available during the two years. The irrigation water use remains low with respectively 30% and 27% for the two years. Inside the agricultural schemes, 20% of the inflows is drained during the two years.

The results of the balance raise concerns on the adequacy of small dams inside flat and semi-arid environments. The high demand for evaporation, around two meters per year, leads to a significant part of the reservoir volume lost to the atmosphere. This is supplemented by a short life cycle due to siltation as revealed by some studies in the area.

6.2 Agricultural performance

The performance inside four agricultural schemes has been assessed on the availability, the productivity and the impacts on quality and drainage. Two difficulties emerged from this assessment: the need to use common indicators to allow comparison among the schemes and from one cropping season to the other, and the necessity to overcome the contextualization of a management that can change in the future. While the first issue was easy to address, the second was in the case of reservoir-based schemes, impossible to exclude. In fact, the runoff from the catchment inside simple designed inland valleys depends only on the weather while the irrigation inside reservoir-based schemes is driven by human decisions such as irrigation depths and periods. Yet, the selected indicators gave an idea of the intrinsic potential of the schemes, the potential for yield improvement through the productivity indicators, the potential for enhanced infrastructure and water management through the availability indicators, and the potential for lowering impacts on the quality and the use of the water with the impacts indicators.

The performance assessment revealed an abundant rainy season with high drainage ratio inside all the schemes and on the opposite a dry rainy season inside the reservoir-based schemes, influenced by the rainy season variability, of which depends their reservoir storage. The rainy season, however, suffers from the dry spells in the beginning during the month of June and July. Likewise, the reservoir-based schemes showed higher productivity with rice yields from 3 to 8 ton/ha. The low yields in the other schemes are mainly due to low fertilizers amount, weed competition and lack of appropriate drainage. A comparison between the two cropping seasons, rainy season with rice and dry season with vegetables, revealed a more productive dry season in the reservoir-based schemes, the cultivation of vegetables being more lucrative than rice. As for the water quality, low concentration of chemicals from fertilizers were monitored in the surface and ground water. This is due to the low fertilizers application, and depicts the low performance of agriculture in the country, as the valleys represent the place for intensive agriculture. There is a room for improvement inside the four schemes towards a more professionalized and performing agriculture: (i) on the soil and field management to enhance the fertility and reduce the competition with weed, (ii) and on the water management to improve the water storage and productivity.

6.3 Climate variability and change

The climate uncertainties have been tested with statistical tools to assess the historical variability of the monsoon and the future trends for the precipitation amounts and events, and the temperatures. For the climate variability, historical data for the city of Dano have been fit to different probabilistic distributions in order to assess the return periods and the related percentage of change. As for the climate change, thirteen models from the CMIP5 project have been selected and statistically tested for the trend, the magnitude of change and the break points, under the RCP4.5 and the RCP8.5 scenarios.

The assessments resulted in two major findings. Alike the West African region, the precipitations in Dano are characterized by a high variability, mostly in the beginning and the end of the rainy season. A moderate drought in the SPI configuration equivalent to a return period of 6.5 years, corresponds to a decrease in the precipitation of June and October of respectively 80% and 76%, and for the seasonal amount to a decrease of 45%. Climate models, on the other hand, revealed mixed results for the seasonal precipitation amount. One out of 13 models showed a decreasing trend of -11% for the RCP4.5 and 7 out of 13 models showed a trend for the RCP8.5, of which 4 positively and 3 negatively, the values varying from -28% to +26%. The number of rainy days shows a decreasing trend for 3 models with variation from -6% to -10% for the RCP4.5, and for 8 models varying from -4% to -35% under the RCP8.5 scenario. As for the temperatures, all the 13 models revealed an increasing trend for the two scenarios, with a variation from +1.3°C to 2.9°C for the RCP4.5, and +3.1°C to +6.8°C for the RCP8.5. The predicted temperatures are above the IPCC projections for West Africa.

6.4 Rainfed rice inside valleys and climate change

Inland valleys are defined as the stronghold of rainfed rice cultivation in semi-arid Africa. The sensitivity of the crop under water and heat stresses, and increase in CO_2 level, has been assessed with the AquaCrop model. The results show uniform effects for the increase of temperature and CO_2 level on crops, with respectively negative and positive impacts on yield and biomass, while the effects of water stress are variable and influenced by the soil types and the shallow groundwater levels. The use of two scenarios based on the RCP4.5 and RCP8.5 scenarios, showed, reduced amounts of water available as direct runoff or precipitation still superior to the crop evapotranspiration in three out of four schemes. Yet, rice is vulnerable to dry spells, particularly at the beginning of the season, when the scheme is not flooded and the shallow groundwater not accessible to crops.

Based on the impact assessment, the adaptation strategies to climate change have been considered inside the selected schemes, by analyzing the elements bringing security to the variability of the climate. The strategies are on the infrastructures and the management of the scheme. Concerning the design of infrastructures inside ungauged catchment, the variability of the precipitations is not used in an optimal way. The usual design is based upon the dry years to allow a full functioning of the scheme during water-scarce years, without considering the use of the excess water during the wet years. This lack of flexibility in the cultivated area is encountered in the simple-designed inland valleys which use a very low share of the waters entering the scheme, as well as in the reservoir-based schemes, where the excess water is spilled downstream. In addition, the design of infrastructures is based on experimental gauging stations from the 70s and necessitates an update. The Catchment to Cultivated Area ratio, mostly used in arid areas for water harvesting systems, can be a good indicator of water availability for production, particularly in West Africa with the increasing demand of cultivated land and the climate becoming more arid. On the management, the adaptation strategies are manifold and concern techniques on field management, on irrigation management, on crop management, etc.

6.5 Recommendations for future research

This study contributes to a better understanding of the biophysical functioning of valleys agrosystems. Yet, the study is limited to the experiments conducted in the field and open the gate to further research.

The choice of the sites is limited to the area around the city of Dano in South-Western Burkina, which is not exhaustive on the types of infrastructures, the soils characteristics, the species of crops adaptable to inland valleys agro-ecological zones or semi-arid areas in Africa. The assessment of the water balance has revealed relatively high uncertainties in the estimation of the term of the balance that requires to think of more suited techniques of estimation or more precise instruments in the collection of data in similar studies. Likewise, the use of thirteen climate models does not represent the entire climate model simulations and similar research with other models may lead to different results.

This study focused on the agricultural schemes and did not integrate the modeling of the shallow groundwater inside the schemes and of the hydrology in the uplands. The groundwater level has been monitored inside the schemes and the uplands, but not modeled to assess the possible trends in the fluctuation. The shallow groundwater is a core of inland valleys hydrology as it influences the runoffs and the soil behavior, and affects the crop growth. The uplands, on the other hand, have been equipped with gauging stations, but not modeled to assess the influence of precipitation and land use changes on the inflows. A complete hydrological assessment is possible by aggregating this research to others on different parts of the valleys into an integrated assessment.

In addition, the economic aspects such as the agricultural market, the credits for farmers, the subvention of public organizations among other parameters, are known to influence the performance and the functioning of the agricultural farms and even the land degradation. Social contexts and political and reforms are also important drivers of agriculture in general that are important to include in future research to better apprehend agriculture inside inland valleys. An integrated strategy assessment to adapt to climate and land use change is possible with integrated environment tools.

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