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Climate impacts in the Senegal River Basin: a spatial vulnerability assessment

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OMVS
ORGANISATION POUR LA MISE EN VALEUR DU FLEUVE SÉNÉGAL

Climate impacts in the Senegal River Basin: a spatial vulnerability assessment

A&W-rapport 2253

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Content

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Summary

The Senegal River is the lifeline for local communities and the rural economy in the basin of the river in Mauritania, Senegal, Mali and Guinea. A large part of the basin is located in the Sahel, where annual rainfall is varying and unpredictable. Therefore, climate changes have a major impact on the water availability and land use in this region.

Climate changes are recognized by the OMVS as in important challenge for the near future, and thorough knowledge of the impacts of (future) climate change is needed. Therefore, in 2017 OMVS set up the component "Planning for Resilience of the Basin to Climate Change" within the PGIRE II program (PGIRE: *Projet de Gestion Intégré des Ressources en Eau et de Développement des Usages multiples du Bassin du Fleuve Sénéga*l). In that framework, more knowledge is needed on the vulnerability of the basin to climate change. The present study addresses this challenge using a spatial approach. Based on spatial analyses of water availability, land use and ecosystem services, this study assesses the vulnerability of the middle valley of the Senegal River Basin to climate change and proposes options for adaptation.

Climate change in the Senegal Basin

Worldwide, climate change has grown into one of the largest challenges in the near future. In this study the current knowledge and the uncertainties about expected climate change in the Senegal Basin are summarized, based on the most recent models and outcomes available. From this study three main conclusions can be drawn (Chapter 3):

1) Temperature change projections in West-Africa for the end of the 21st century are between +3°C and +6°C compared to the end of the 20th century. This increase in temperature will irrevocably lead to a higher degree of local evaporation, which makes the Senegal Basin a sensitive area to climate change.

2) In the Senegal River Basin, there is no consensus for an average increase or decrease in rainfall for any term or scenario. There will, however, be more variation between the years, intensification of rain events, and changes in the timing and duration of the rainy period.

3) In the Guinean highlands (upstream) there will probably be a decrease in precipitation. These highlands are the source area of the Senegal river, and a decrease in rainfall in this area will most likely have an effect on the discharge rates of the Senegal river.

Options for climate adaptation

Based on an spatial analysis of water management (Chapter 4), land use (Chapter 5) and of the mechanisms of climate change relevant to the Senegal Basin (Chapter 6), we identified several options for climate adaptation, differing in scale of both space and time. For example, important hydrological measures can be taken at the level of the river basin that affect the entire valley. Additionally, there are several relevant adaptation options at the regional and local level, by which a lot can be gained in particular for agriculture and animal husbandry.

The options are summarized here. These may form an important input to a dialogue with the local communities and stakeholders:

- Annual flooding in the valley during the wet season is necessary to guarantee the crucial ecosystem services of the river, particularly for the areas not directly connected to the river bed;
- Annual flooding is crucial to keep groundwater levels high, and to prevent drought-related problems in the long term;
- For flood-recession cultures, grazing grounds and biodiversity, an artificial flood regime is highly beneficial for the direct availability of water and nutrient-rich sediments the river;
- Allowing water levels of at least >3.5 meters in the middle valley during the flooding season is recommended from the point of view of climate adaptation.

On the basis of this study and discussion during the study with stakeholders, local farmers and experts from the OMVS, we come to the following recommendations

- To quantify the impact of climate change a hydro-dynamic model, in which current and future climate scenarios are included, is recommended. Such a model can be used to develop adaptive water management strategies for the middle valley;
- Flooding during the wet season is necessary to guarantee both provisioning and regulating services of the river. For flood-recession cultures, grazing grounds and biodiversity, an artificial flood regime that mimics the natural floods is recommended;
- Gain more insight into the spatial distribution of flood recession cultures, irrigated cultures and flood forests in the entire middle valley. This study provided an initial insight, but there is a need for spatial information at a higher level of detail;
- Increasing temperatures will threaten crop yields and transformational changes are needed. We recommend the initiation of research programs focused on drought resistant crops, changes in planting and sowing dates in the agricultural calendar and agroforestry. Pilots could be carried out in the form of experimental test farms, similar to the concept of Integrated Agricultural Community Farms (FACI).

1 Introduction

The Senegal River is the lifeline for local communities and the rural economy in the basin of the river in Mauritania, Senegal, Mali and Guinea. A large part of the Senegal basin is located in the Sahel, where annual rainfall is varying and unpredictable. Therefore, climate changes have a major impact on the water availability in this region. Based on spatial analyses of water availability and land use, this study assesses the vulnerability of the middle valley of the Senegal River Basin to climate change and proposes options for adaptation.

1.1 Framework

A balanced water management of the Senegal River is essential in view of the limited water resources in the Sahel. This important task is performed by the *Organisation pour la mise en valeur du fleuve Sénégal* (OMVS). The OMVS represents the interests of the four member states (Mauritania, Senegal, Mali and Guinea) and conducts the water management of the Senegal River as formulated in the 'Schéma Directeur d'Aménagement et de Gestion des Eaux du Fleuve Sénégal' (SDAGE, horizon 2025). This scheme provides an overall vision and framework for the development and water management in the basin. The OMVS ensures that water is distributed across the various sectors and serves the economic growth and political stability in the region. Climate changes are recognized by the OMVS as in important challenge for the near future, and thorough knowledge of the impacts of (future) climate changes is needed.

In the framework of the Dutch-Senegalese cooperation a program for integrated water management was set up in 2007 (PGIRE: Projet de Gestion Intégré des Ressources en Eau et de Développement des Usages multiples du Bassin du Fleuve Sénégal). The first phase (PGIRE I) ran from 2007-2013 and subsequently the second phase started over the period 2014-2020 (PGIRE II)[1]. The objectives of PGIRE II are twofold:

- Support the development of water uses in the Senegal River Basin in a concerted manner among the OMVS member countries;
- Strengthen the capacity of OMVS to take into account climate change in concerted development and management of water resources in the Senegal River Basin.

Within PGIRE II, OMVS set up the component "Planning for Resilience of the Basin to Climate Change" in 2017. A first study in this context was carried out by Artelia (2018), concerning an assessment of the vulnerability of the Senegal River Basin to climate change and a plan to adjust and strengthen the resilience of the basin. A next step in the assessment of the vulnerability of the basin to climate change is to provide insight in the spatial consequences for land use and ecosystem services. The present study addresses this challenge using a spatial approach. We focus on the spatial changes in water availability and land use, in particular in the middle valley, as a result of the anticipated climate changes. The combined knowledge of the two studies – Artelia (2018) and the present study - can be used to formulate measures for the Investment Plan for the coming years.

[1] PGIRE II is supported by Trust Fund III, which is managed by the World Bank. The fund has been set up to support the institutional capacity of the OMVS and to improve environmental conditions and water quality in the Senegal River Basin. The Dutch 'Waterschap Rivierenland' (Water Board) has an advisory function.

Figure 1.1. The main river and tributaries of the Senegal River Basin and its catchment area, covering parts of Guinea, Mali, Mauritania and Senegal. In addition, the existing and planned dams are indicated and the middle valley is indicated with a red outline.

1.2 Scope and objectives of this study

Geographical scope

The characterization of the impacts of climate change will be carried out on the whole of the Senegal River basin. The core of the study is located however in the middle valley, where the state and production of natural resources depends strongly on the availability of water. The climate impact in the Fouta Djalon massifs (Guinea) and the Manantali area (Mali) are taken into account in this study on a global level.

The field work in the framework of this study has been carried out in the middle valley between Richard-Toll and Matam. We define the middle valley as the vast alluvial plain between the Senegal delta in the west and Bakel in the east. This area is roughly 400 km long and up to 25 km wide.

Objectives

The overall objective of this study is to characterize the impacts of climate change on the environment and natural resources of the Senegal River Basin, and in particular the middle valley. More specifically, the objectives of this study were to:

1. Define the possible effects of climate change on precipitation and river dynamics;
2. Translate the consequences of changes in water availability in potential changes in natural resources (water, land use, ecosystems, biodiversity) and other ecosystem services;
3. Provide an overview of different climate adaptation options, in order to ensure river water-related ecosystem services in the Senegal River Basin in the future.

As a follow up of the study conducted by Artelia (2018), including a water modeling exercise in combination with an economic analysis, this study takes a spatial approach to investigate the potential influence of climate-related changes. The present study involves a spatial analysis, including remote sensing techniques, to gain more insight into the spatial availability of water in relation to climate change. With the help of water maps, associated with certain water levels, and maps of land use and terrain types, very valuable additional information was obtained. This study provides a practical approach, specifying the significance of possible climate change for stakeholders, water management, natural resources and river functions.

Simultaneously with the conducted research, a successful formation was organized in the Netherlands, in which OMVS employees have learned valuable skills in the field of GIS analysis and remote sensing.

Study approach and set-up of this report

In this report, we start by providing a concise overview of the characteristics of the Senegal river basin, in particular the middle valley, and the ecosystem services that are provided by the river (Chapter 2). We use ecosystem services as a tool to specify and quantify the importance of natural resources for local communities

Next, we discuss existing knowledge on climate change in the region of te Senegal Basin and the developments that are expected based on climate models. Also descriptions of plausible future scenarios within the delta system of the Senegal river are given as well as information on the uncertainty in these predictions (Chapter 3). The climate study is based on the most recent available knowledge and specifically for this study provided by the Potsdam Institute for Climate Adaptation.

In order to be able to interpret future climate-induced changes in (spatial) water availability as a result of changes in rainfall and river discharge, we undertook a spatial study in the relationship between river discharge and flooding in the middle valley. In Chapter 4 the results are presented. This concerns an overview of the current and historical river dynamics and the recurrent annual water availability, both quantitative and spatially by using remote sensing techniques.

To understand how and in which way land use and ecosystem services might be affected by climate change through a temperature rise and a change in water availability, it is necessary to have a proper picture of these services in the study area. On the basis of two field missions and an in depth remote sensing analysis, we produced an overview of terrain types and land use types in the middle valley, including a produced land use map. This part of the study was performed in narrow conjunction with the Institute for Biodiversity and Ecosystem Dynamics of the University of Amsterdam. The results are presented in Chapter 5.

The ultimate importance and implications of spatial river dynamics in relation to ecosystem services, especially in the light of climate change, are analyzed and discussed in Chapter 6. In addition, different practical options and approaches for adaptation are discussed in Chapter 7, based on the results of the previous chapters. A synthesis of the study and its most important outcomes is presented in Chapter 8. In this Chapter also gaps in knowledge are indentified.

2 Study area

As an introduction into the study area, this Chapter provides a short characterization of the Senegal River basin, the middle valley as study area, the water resources and important developments. In addition, we succinctly describe the water management and ecosystem services in the study area and the link with climate change.

2.1 Senegal River Basin

The Senegal River is one of the largest rivers in West-Africa. The river is 1800 km long and drains a catchment of on average 34300 km^2, flowing through Guinea, Mali, Mauritania and Senegal (Figure 1.1). The river passes through different climatic zones and ecosystems. The main branch of the Senegal River is the Bafing, originating in the Fouta Djalon mountains of central Guinea, where annual rainfall exceeds 2.000 mm. Nearly half of the discharge of the Senegal River depends on the Bafing (Zwarts et al., 2009). The other tributary, The Bakoye river, originates on the Manding Plateau in West Mali, about 250 km to the east. The Bakoye contributes nearly a quarter of the entire river flow.

The Senegal river flows through dry woodland savannas in Mali and through the arid landscapes of the Sahel, where annual rainfall does not exceed 300 mm. About half of the basin is situated in Mauritania, where rainfall is very limited. The river accumulates the flow of several other smaller tributaries, such as the Gorgol, Karakoro, Kolimbine, Falémé and Ferlo rivers. The Senegal river reaches the Atlantic Ocean at St. Louis, Senegal.

From July to October the Senegal river is characterized by high water levels. The low water season stretches from December to June. Monsoon rains in the upper basin in the wet season are the main driver behind these major fluctuations in water levels and flow rates. Downstream Bakel, the river enters the middle valley. From there, the river flows over a length of circa 800 kilometers to its mouth, with a very slight slope angle of about 0.0015% (Bader & Albergel 2015). Every year, the natural flood cycle inundates vast areas of the floodplains. In the valley, these annual inundations may cover a major bed of 10 to 20 kilometers wide, which can be considered as an inland delta. These floods provide precious ecosystem services, benefiting the riparian communities. Consequently, land use activities depending on water resources are strongly driven by the major variations in river dynamics. The water of the Senegal River is essential for the drinking water supply of the major cities of Dakar and Nouakchott, and forms the basis of important sectors such as agriculture, animal husbandry, fishing and energy production. In addition, various ecosystem services are strongly dependent on the availability of water.

2.2 Study area : Senegal River Valley

The characterization of the impacts of climate change are relevant to the whole of the Senegal River basin. This study focuses however on the river bed in the middle valley (Fig. 2.1.), where natural resources, ecosystems and land use depend strongly on the availability of water. The middle and lower valley as treated in this study roughly encompasses the river bed between Bakel (upstream) and Richard-Toll (downstream). It includes two tributaries, the Falémé and the Karakoro. The area comprises the regions Tambacounda, Matam, Saint-Louis in Senegal, Guidimakha, Gorgol, Brakna and Trarza in Mauritania and Kayes in Mali.

The middle valley comprises the river bed with a width of 2-3 km at Bakel up to 15-22 km in the direction of Podor (Figure 1.1). The maximum width of the river bed is about 26 km. A large part of the river bed is inundated in the flooding season, depending on the river flow and local rainfall (Chapter 4). Important villages near the river bed are (upstream to downstream) Ballou (south of Bakel), Matam, Kaédi, Podor and Dagana. On the left bank (Senegal) the river valley is accessed by a main route (Kidira – Richard Toll), and on the right bank (Mauritania) there is a main route from Kaédi to Boghé. In the general the river bed is bordered, on the Senegalese as well as the Mauritanian side, by higher situated, sandy levees. The river bed itself is partly inundated during the flooding season.

The middle valley is a rural area, where the Senegal River and river bed playing a central role for the provision of water, agriculture, fishing and other economic activities. The population density varies between regions (Figure 2.1). The region is in vivid development with expanding agglomerations around large rural villages: roads and markets, but also water and electricity infrastructure, schools and health structures (GRDR 2014).

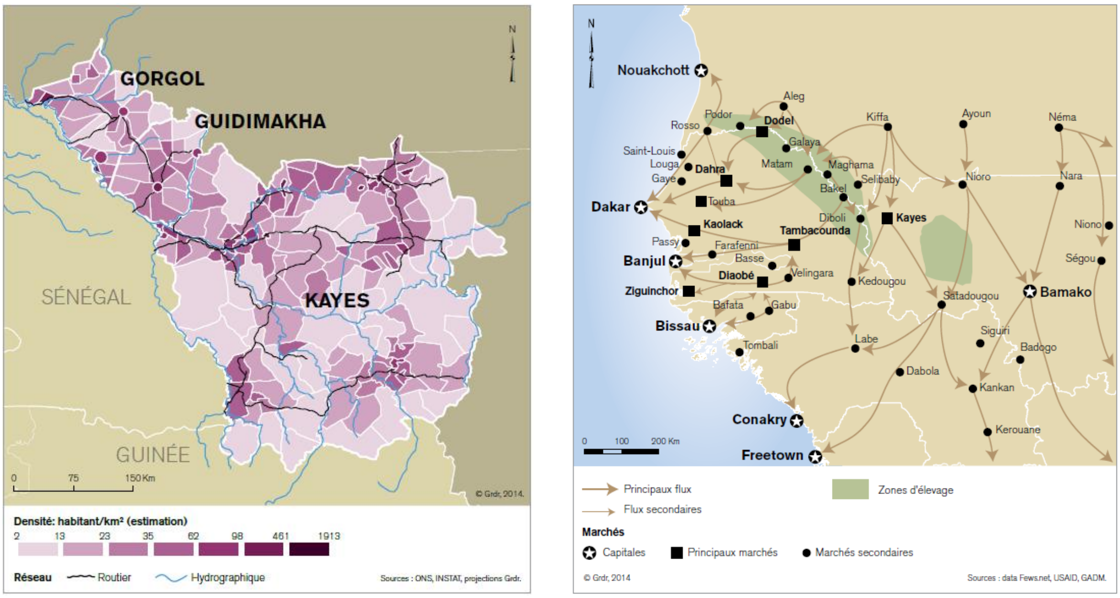


Fig. 2.1. Population density in three regions in the middle valley (left) and an overview of the principal zones for livestock and movements of livestock in the region. Source: GRDR (2014).

Agriculture and livestock raising are important drivers of the rural economy (GRDR, 2014). Livestock raising is very important in the region, especially in the Ferlo (NE Senegal) and the areas north of the Senegal River, in Mauritania. Flooded pastures near the river are essential for local pastoralists, to herd their cattle in the dry season. Along the Senegal river, and throughout the Sahel, nomadic pastoralists disperse with their livestock away from the basin during the rainy season, and return to the floodplains in the dry season (DeGeorges & Reilly, 2006). Over time, the grazing intensity increased tremendously, especially with the introduction of boreholes, leading to overexploitation and landscape changes (Zwarts et al. 2018).

2.3 Rainfall

Rainfall in the Senegal Basin shows a distinct north-south gradient. At the source of the river in the Guinean highlands, precipitation rates within the Senegal Basin exceed 1400 mm per year. Where the Bafing and Bakoye rivers flow out of Guinea and through southern Mali, rainfall rates remain over 850 mm per year. Shortly after their merge to form the Senegal River, north of the Manantali Reservoir, rainfall decreases to less than 500 mm per year, a level at which rainfed agriculture becomes difficult. About half of the Senegal Basin is situated in Mauritania, where rainfall is even lower. In the region of the Gorgol, Karakoro and Kolimbine tributaries in Mauritania, average annual rainfall is below 140 mm per year (Fig. 2.2).

Rainfall in the Sahel is highly variable seasonally, annually and over decades. During the major droughts of the 1970s and 1980s however, this rainfall distribution pattern shifted southward. After the long-lasting droughts in the '70s and '80s, rainfall seems to be recovering in the last two decades, with 2010 being the wettest year since 1958 (Sanogo et al., 2015; Zwarts et al., 2018; Fig. 2.3). The recovery of rainfall seems to be primarily due to increased intensity of rainfall rather than an increase in the number of rainy days (Giannini et al., 2013). In recent years a shortening of the rainy season was observed, in combination with increased variation of rainfall. In the few months when it rains, the precipitation rates are higher than before (Artelia 2018). Observations from the last century indicate a decrease in rainfall by 10-15 mm per decade and a shortening of the rainy period (USAID, 2018).

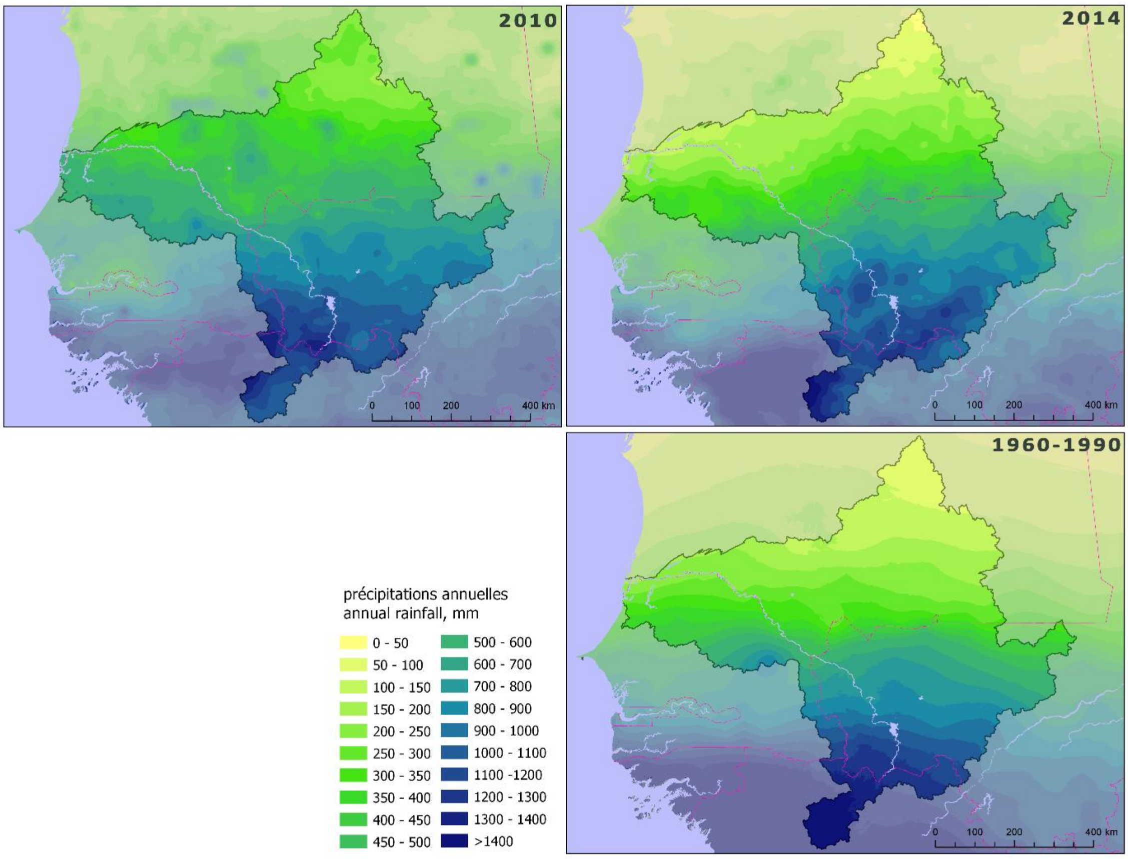


Fig. 2.2. Satellite-derived annual rainfall estimates (FEWS) in a wet year (2010) and a dry year (2014) and the average rainfall calculated for a period of 30 years (ground measurements in 1960-1990) within the Senegal Basin.

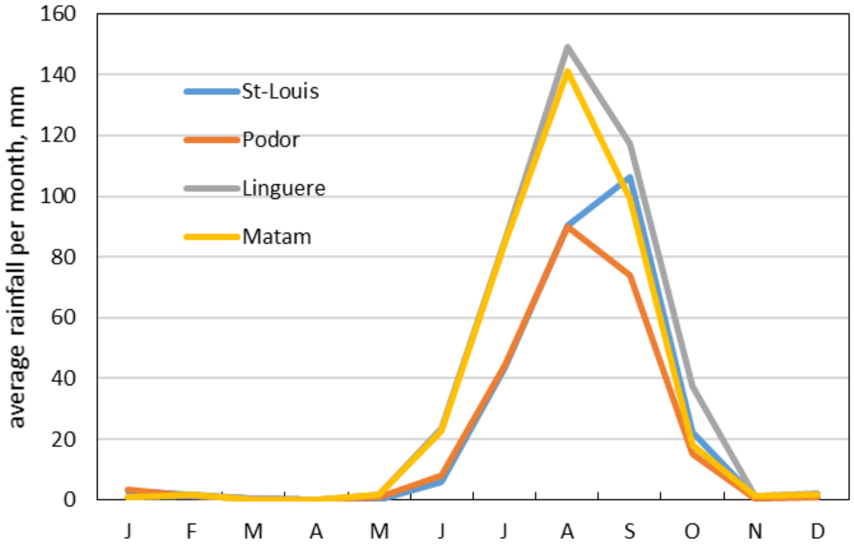


Fig. 2.3. The average monthly rainfall at 4 meteorological stations: Linguère, Matam Podor and Saint-Louis. Average values are calculated for a period of 60 years (1956-2016).

2.4 Water management

Periods of severe droughts in the 1970s and 1980s ('La Grande Sécheresse') created a need for active water management within the basin. The construction of two dams, i.e. the Diama dam in northern Senegal (completed in 1986) and the Manantali dam in western Mali (completed in 1988) have caused major changes in the hydrological dynamics of the Senegal River. Before construction of the dams, water levels followed the flood pulse generated by precipitation in the catchment area. There could be huge variations in size, height and duration of floods (Zwarts et al. 2009). Before the construction of the dams an average area of 459.000 ha was flooded every year on both sides of the bank (DeGeorges & Reilly 2006, Zwarts et al. 2009), of which between 15.000 and 150.000 ha could be used for flood recession crops, depending on the floods (National Research Council, 2003).

After the construction of the Diama (downstream) and the Manantali dam (upstream), water levels are more stable throughout the year. The current management guarantees an artificial flood pulse, realized by the releases at Manantali. Both dams were constructed primarily to facilitate irrigation during the dry season in order to maximise self-sufficiency in permanent rice production (Venema et al., 1997). The Diama dam prevents the intrusion of salt water from the Delta into the upstream areas. The Manantali dam provides in generation of hydropower. With a holding capacity reservoir of 12 km^3 on the Bafing (Bader & Albergel, 2015), and a generating capacity of 800 GwH per year (Mietton et al., 2007), the dam is designed to supply energy to three of the member states of the OMVS (Senegal, Mali and Mauritania).

The framework for the water management of OMVS for the Senegal River is provided by the 'Schéma Directeur d'Aménagement et de Gestion des Eaux du Fleuve Sénégal' (SDAGE, horizon 2025). The SDAGE is based on the strategic ambition of the four member states to ensure water availability to the stakeholders, whilst adhering to the principles of the IWRM. For implementation of the SDAGE, improvement of knowledge on future development in the basin

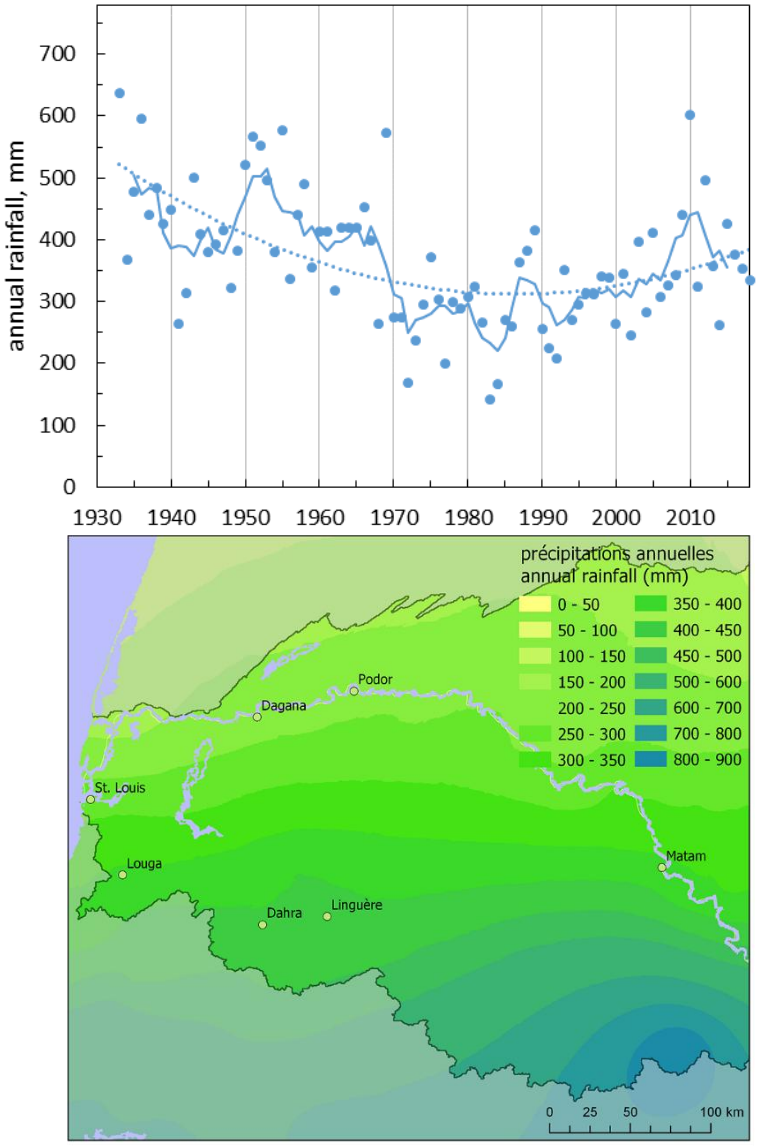


Fig. 2.4. The average annual rainfall in Northern Senegal, calculated for 7 meteorological stations: Dagana, Dahra, Linguère, Louga, Matam Podor and Saint-Louis (1933-2018). Corrected, satellite-derived monthly rainfall estimates were substituted for lacking data in recent years. Solid line: running mean calculated over a period of 5 years; dashed line: second degree polynomial. The map shows the seven stations with the average rainfall within the Senegal basin in 1960-1990.

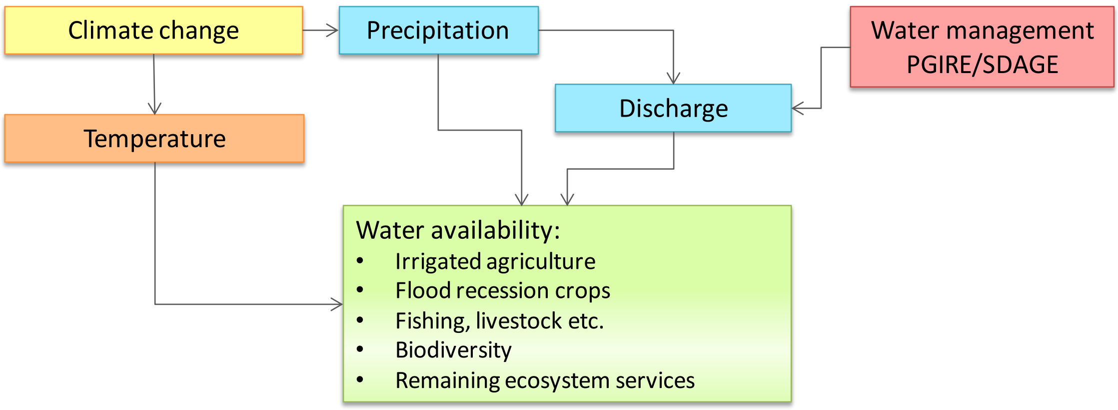


Fig. 2.5. Schematic overview of the factors determining water availability in the middle valley.

is essential. The OMVS is well aware that the basin is facing major challenges to meet increasing demands for food, water and energy by a growing population. At the same time natural resources and ecosystem services are at stake. Climate change has a major additional and interfering impact (Figure 2.5), exacerbating the problems associated with human pressure (Artelia 2018).

2.5 Ecosystem services

The water of the Senegal River is of pivotal importance to millions of people. The river is an important resource for the majority of the rural population because it feeds the pastoral, agricultural and piscicultural lifestyles. 2.7 million of the Malian population 1.9 million of the Mauritanian population, and 1.5 million of the Senegalese population live in the basin. Since time immemorial, the livelihoods of communities in the basin depend partly or largely on the river's resources (e.g. Varis & Lahtela, 2002).

Particularly in the arid parts of the basin, where precipitation patterns show a large variation within and between years, the river is the only secure source of water. The river is a direct key resource for development in terms of water supply, production of fish, grains, fruits and energy. These provisioning values are directly beneficial to people from rural and peri-rural communities. The Senegal river and the wetlands in the basin however provide a wider spectrum of *ecosystem services*. (Fig. 2.6). This not only accounts for provisioning services such as food production and drinking water, but also regulating services such as biodiversity, sustainability, resilience to communities during hazards, and mitigation of future challenges such as climate change (e.g. Finlayson *et al*., 2018). In this study, we focus primarily on provisioning and supporting services. It should be stressed however, that for the riparian and rural communities also the other services – regulating and cultural – are of high value.

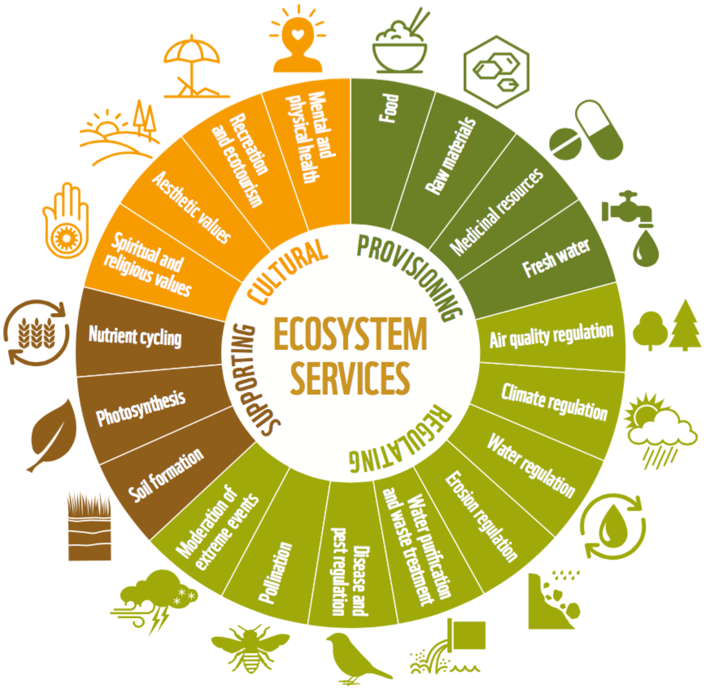


Fig. 2.6. Well functioning ecosystems provide a range of provisioning, regulating, supporting and cultural services. Provisioning services are the products obtained from ecosystems, regulating services are the benefits obtained from the regulation of ecosystem processes, cultural services are the non-material benefits people obtain from ecosystems and supporting services are those services that are necessary for the production of all other ecosystem services. Source WWF (2016), Adapted from the Millennium Ecosystem Assessment (2005).

BOX 1. The air circulation system in West Africa as driver of the seasons

Weather patterns in West Africa are driven by the Intertropical Convergence Zone (ITCZ), a belt of low pressure hugging the equator. On the scale of the African continent, this results in characteristic rainfall pattern, with very humid conditions around the equator and gradually diminishing rainfall to the north and south.

In West Africa this ***rainfall gradient*** *extends over a remarkable short distance, including the Upper Niger Basin and Inner Niger Delta. The air circulation around the equator is the main driver of the annual rainfall sequence in Africa. Ascending warm and moist air immediately north and south of the equator is sucked into the itcz and transported at altitudes of 10-15 km further north and south of the equator. To compensate for the rising air in the convergence zone, the northern flow descends in the desert zone, normally centred between 20° and 30°N. Descending air heats up as the pressure increases, becoming under saturated with water vapour and leading to the typical clear skies and general aridity of the Sahara.*

This ***air circulation system****, known as the Hadley cell, ensures that the prevailing wind over the Sahara, the* Harmattan*, always blows from the northeast and not from the north. The* Harmattan*, a well-known phenomenon in West Africa, brings dry, dusty air to the Sahel and further south. When, during the northern summer, the sun is overhead in the Sahara, a low pressure belt forms over the Sahel, bringing clouds, rain, frequent thunderstorms and a monsoon from the southeast.*

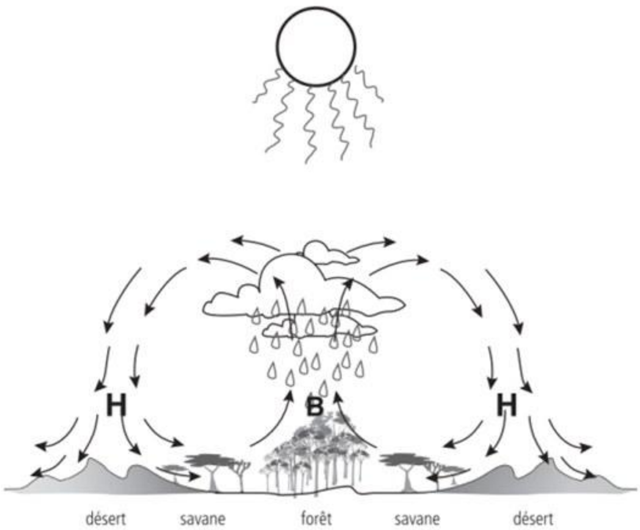


Fig 2.8. Schematic cross section of the air circulation system of the Intertropical Convergence Zone (itcz). B Low pressure zone with ascending warm and humid air, H high pressure zone with relative dry descending air, causing prevailing winds over het Sahel (Harmattan). From Beintema et al. (2007).

3 Climate change in the Senegal Basin

Worldwide, climate change has grown into one of the largest challenges in the near future. Since recently it is put high on the societal agenda. Africa, in particular the arid parts of the continent, belongs to the most vulnerable regions in the world Climate change projections for this region indicate a warming trend, frequent occurrence of extreme heat and changes in rainfall (Serdeczny et al. 2016). This Chapter summarizes the current knowledge and the uncertainties about expected climate change in the Senegal Basin, based on the most recent models and outcomes available.

3.1 Introduction

The forecast of future climate changes is a complex science that goes with many uncertainties. The Intergovernmental Panel on Climate Change (IPCC) is the leading organization which releases periodically new updates on the expected climate change. These are based on a combination of models and scenario's to show the variation of outcomes and the level of uncertainty. To gain more insight into the possible scenarios for West-Africa, and the Senegal River Basin in particular, the Potsdam Institute for Climate Impact Research (PIK) has conducted a specific analyzes for this study (Fournet, 2018). The objective was to provide plausible future scenarios for the Senegal River Basin, based on the latest scientific knowledge.

The results of the analysis for the Senegal River Basin are summarized in this Chapter, based on the technical report of PIK (Fournet, 2018). All provided data and texts are based on state-of-the-art information as reported by the Intergovernmental Panel on Climate Change (IPCC). There are four scenarios are 'pathways' which are commonly used in climate change studies based on the IPCC work; in box 2 more technical information is provided. The four scenarios or RCP's (Representative Concentration Pathways) describe different climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come. Consequently, the scenario with the lowest greenhouse gas concentration (RCP 2.6) shows minor future changes, while the scenario with the highest concentration rates (RCP 8.5) shows major future changes . The scenarios differ to what extent (global) mitigation measures have been taken into account:

RCP2.6 – very ambitious climate policy worldwide, low greenhouse gas concentration rates
RCP4.5 – many mitigation measures worldwide, modest concentration rates
RCP6.0 - limited mitigation measures worldwide, moderate concentration rates
RCP8.5 - hardly mitigation measures worldwide, high concentration rates

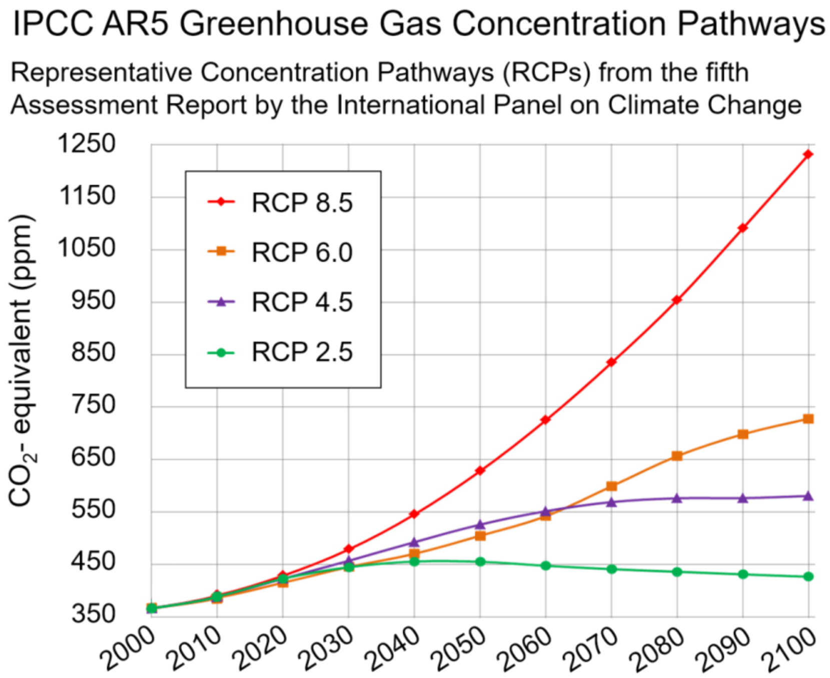
The climate change predictions focus on the evolution of temperature and the precipitation in the region of the Senegal Basin. Both have an large impact on the rural sectors and the rural live, amongst others trough a change in the climatic conditions (prolonged periods with excessive heat, changing in the timing of seasons and through a change in the availability of water (see further Chapter 7). The results presented in this Chapter build on the latest climate models but at the same time the level of uncertainty is high. These prerequisites are indicated in the text. For the analyzes by PIK, three projection periods were used: 2010-2039 (short term), 2040-2069 (medium term), 2070-2099 (long term).

BOX 2. Technical background scenario's (RCP's) for future climate change

In 2014, the IPCC finalized the Fifth Assessment Report (AR5). Researchers from around the world have analyzed model outputs to develop the results of this IPCC AR5. The Coupled Models Intercomparison Project (CMIP5) produced a state of knowledge, based on a multi-model dataset. CMIP5 includes long-term 20th century climate simulations and projections for the 21st century and beyond, for both conventional global ocean-atmosphere climate models and terrestrial system models. Any global model of CMIP5 uses a set of four different representative concentration change (RCP's – scenarios) profiles as input. This is the basis of climate models for assessing potential climate impacts, mitigation options and their associated costs.

RCP's are socio-economic emission scenarios used in climatology to provide plausible descriptions of how the future can evolve in relation to a variety of variables including socio-economic, technological, land use and energy changes and emissions of greenhouse gases and air pollutants. These RCP's are identified by their approximate total radiative forcing for the year 2100 compared to 1750. In short, radiative forcing (W/m²) or climate forcing is the difference between insolation (sunlight) absorbed by the Earth and energy radiated back to space: for RCP2.6; 4.5 W / m² for RCP4.5; 6.0 W / m² for RCP6.0; 8.5 W / m² for RCP8.5.

RCP2.6 has a decreasing profile in which the radiative forcing peaks at about 3 W/m² before 2100, then decreases to 2.6 W/m². RCP4.5 and RCP6.0 have intermediate stabilization profiles, in which the radiative forcing stabilizes after 2100. RCP8.5 has a high profile, in which the radiative forcing around 8.5 W/m² in 2100 continues to grow.



"Representative Concentration Pathways (RCPs)". IPCC. Retrieved 13 February 2019.

3.2 Results

3.2.1 General trends for the entire African continent

Temperature

Africa is one of the most vulnerable continents for climate change due to its high exposure and low adaptive capacity. In continental Africa, the IPCC attributes high confidence to evidence of global warming in response to anthropogenic climate change. Ten-year temperature analyzes strongly suggest an increase in warming trends for the next 50 and 100 years. It is likely that temperatures throughout Africa will increase faster than the global average, particularly in the most arid regions during the 21st century. Compared to the end of the 20th century, average annual temperature changes reach 2°C in the middle of the 21st century and exceed 4°C by the end of the 21st century on the continental set according to RCP8.5. The average change is less than 2°C over the two periods mentioned above in RCP2.6.

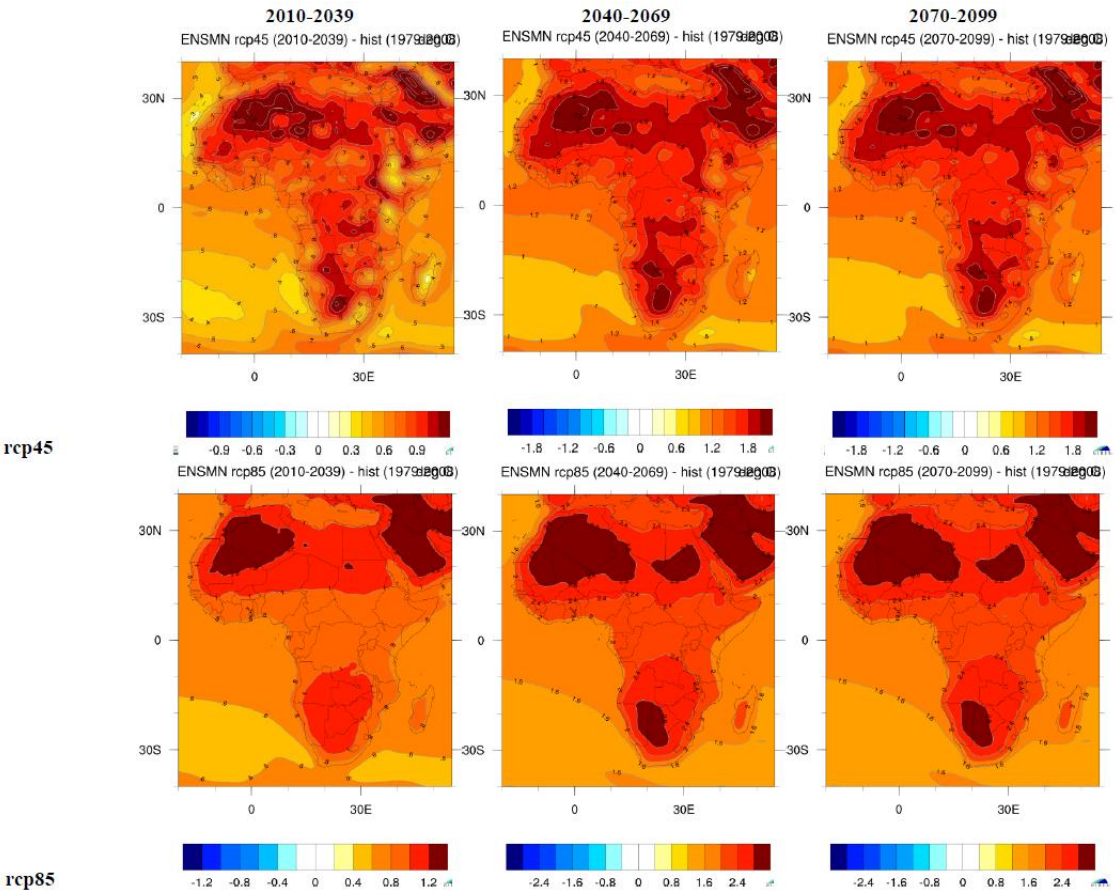


Figure 3.1. Absolute difference in average surface air temperatures (°C) on the African continent for two climate change scenarios (RCP 4.5 and RCP 8.5) for three future periods (Fournet 2018).
<u>Explanation of the maps</u>: each map shows the difference of the chosen modeled future period with the reference period (1979 – 2008). The colors indicate the level of absolute change in average air temperature (blue is colder, red is warmer).

Precipitation

Rainfall projections in Africa for the mid-to-late 21st century are more uncertain than temperature projections and exhibit greater spatial and seasonal dependence than temperature projections. All models show some comparable large-scale features, such as the drying trends in northern and southern Africa and increasing precipitation in the east.

More in detail, CMIP5 projects decreases in mean annual precipitation over the entire Mediterranean region of North Africa in the mid-to-late 21st century according to RCP8.5. The model also predicts decreases in southern Africa beginning in the middle of the 21st century according to RCP8.5, which extend substantially in the late 21st century. In contrast, CMIP5 is likely to project increases in mean annual precipitation over areas of central and eastern Africa beginning in the mid-21st century under RCP8.5. In RCP 4.5 these changes are much smaller.
Note that the indicated changes on the map are given as a change in mean average annual precipitation. On an annual basis these may seem rather small, in particular in regions with a high annual variation in rainfall in time and space.

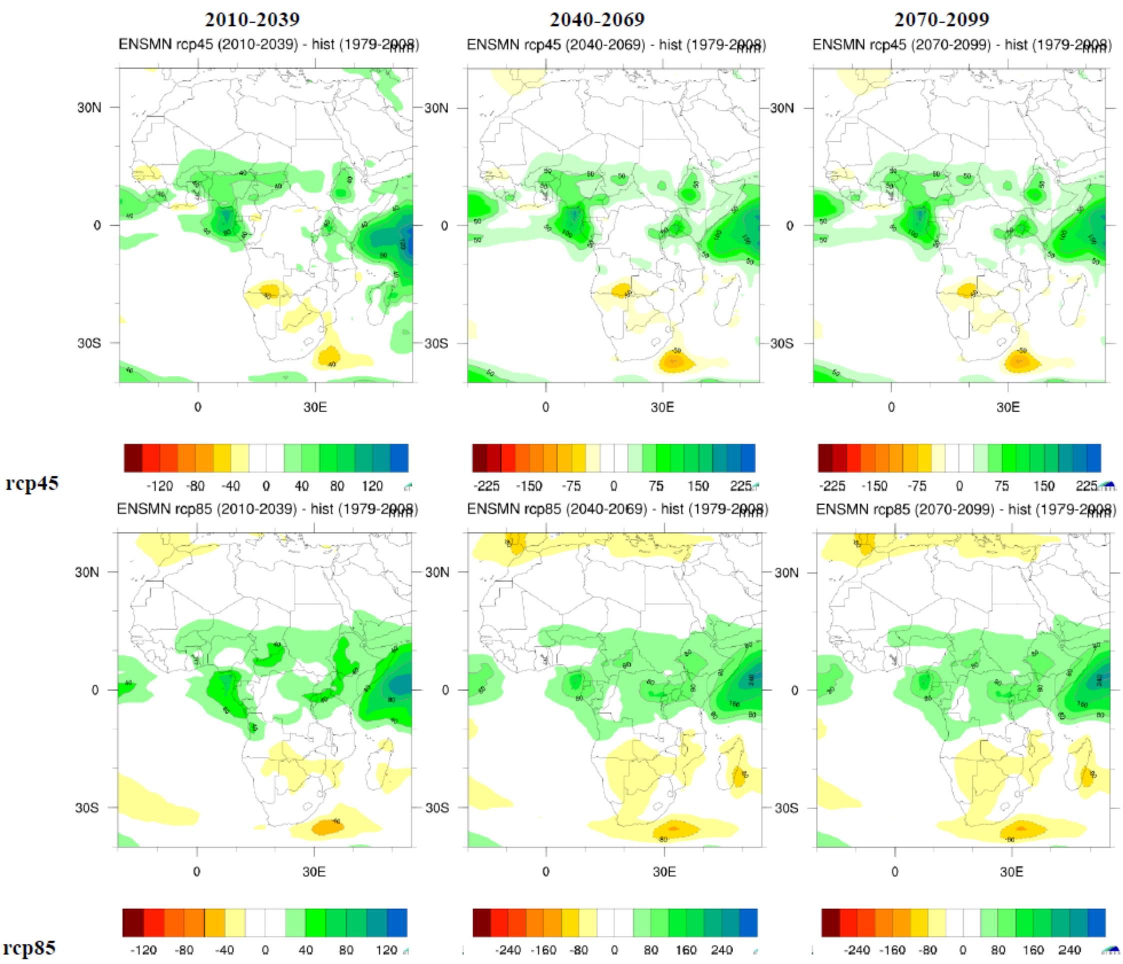


Figure 3.2 Absolute difference of mean annual precipitation (mm) for 2 emission scenarios (RCP 4.5 and RCP 8.5) between 3 future periods in mm (derived from PIK, 2018). Explanation of the maps: each map shows the difference of the chosen modeled future period with the reference period (1979 – 2008). The colors indicate the level of absolute change in average air temperature (red is less rainfall, green-blue more rainfall).

3.2.2 Focus on Senegal and the river basin

Temperature

In West-African and Sahelian regions, surface temperatures have increased over the last 50 years. The number of cold days and nights has decreased and the number of hot days and nights has increased between 1961 and 2000. Most of these trends are statistically tangible at 90% and similar trends are observed for extreme temperature indices. Collins (2011) statistically shows a significant warming between 0.5°C and 0.8°C between 1979 and 2010 on the regional set.

As for projections, there is a clear consensus for an average increase in temperatures in the Senegal River Basin. An increase in temperatures of 0.8 to 1 °C in the short term (2010-2019), 1.1 to 2.5°C in the medium term (2040-2069) and 1.1 to 4.2°C in the long term (2060-2099) is projected according to the different scenarios taken into account. As expected, there is a clear difference between the different scenario's. For the current situation RCP 4.5 and RCP 6.0 can be considered as a realistic scenario's.

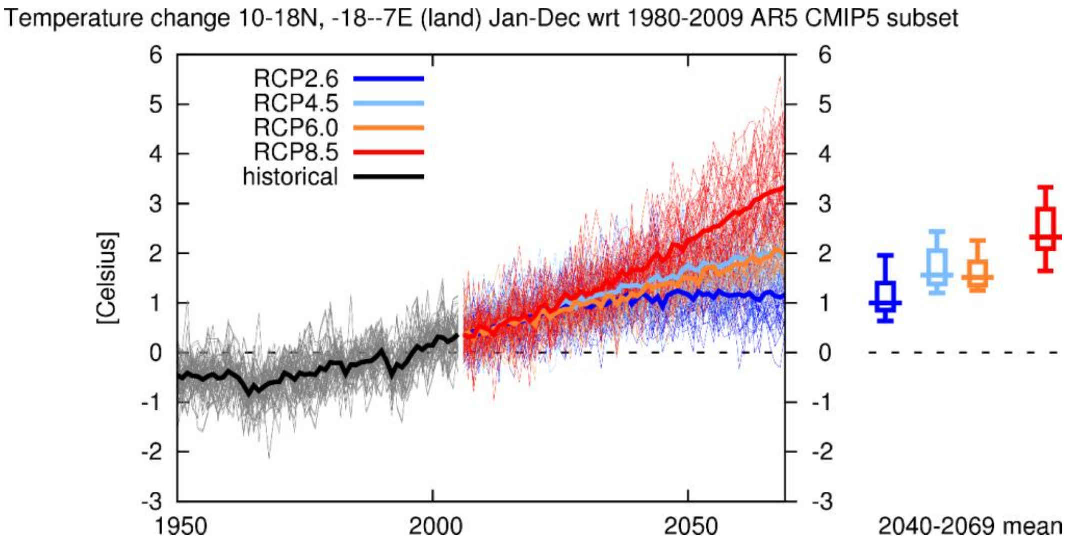


Figure 3.3 Absolute difference of mean air surface temperature (°C) for four scenarios in the Senegal Basin region, compared to the historical reference period. Explanation of the graph: thin lines show the individual model simulations, thick lines the ensemble mean. The boxplot on the right side of the graph indicate the median (-), the 25-75% variation tile (□) and the 5% and 95% tiles. Colors refer to the different scenarios.

For spatial disparity, the increase in average temperatures is for any term and emission scenario much more pronounced in the north-east of the region and much less pronounced in the south-west of the region with concentric radiation having a north-east / south-west gradient (Figure 3.4). Near the coast of West-Africa the impact of climate change in terms of temperature rise is less pronounced, but still there is a clear consensus about a rise in temperature.

The results presented here show a clear consistency in temperature rise, so there is a high level of certainty. For the spatial maps it is important to realize, that these are global projections and present an average pattern.

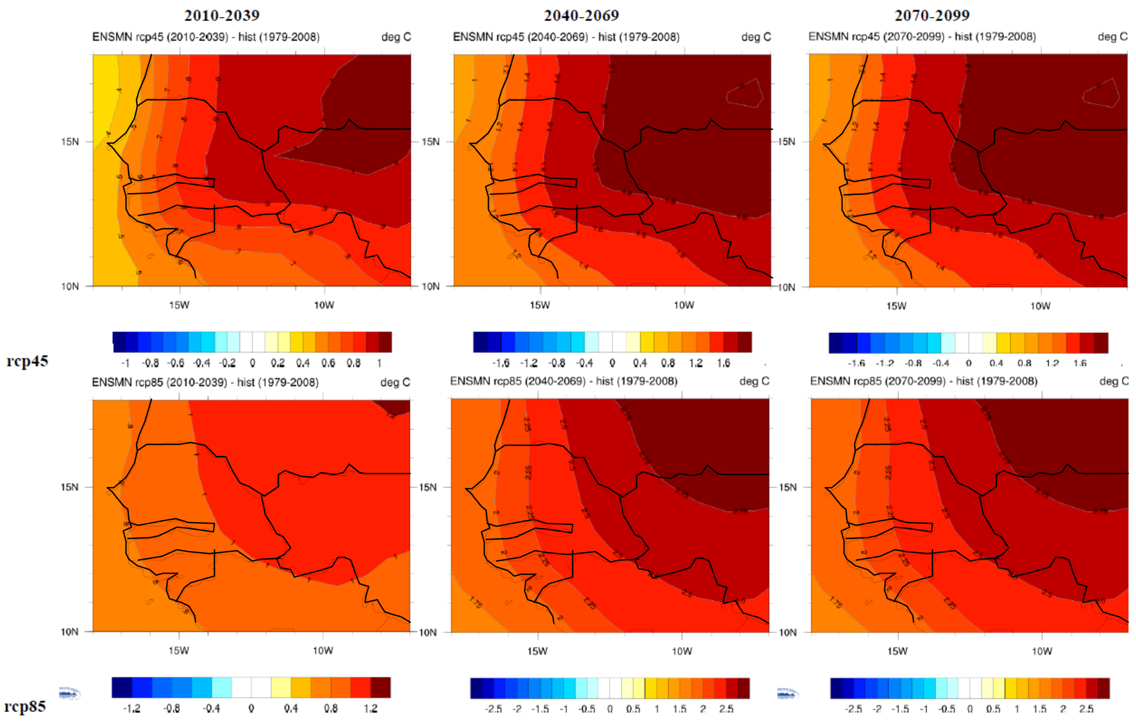


Figure 3.4 Absolute difference of mean air surface temperature (˚C) in the region of the Senegal Basin for two climate change scenarios (RCP4.5 and RCP 8.5) between three future periods (derived from PIK, 2018). Explanation of the maps: each map shows the difference of the chosen modeled future period with the reference period (1979 – 2008). The colors indicate the level of absolute change in average air temperature (blue is colder, red is warmer).

Precipitation

As previously noted, a low degree of confidence is associated with precipitation projections in the tropical part of West Africa and its monsoon system. It is likely that natural fluctuations in the multi-decadal Atlantic Oscillation – the periodical shifts in the Intertropical Convergence Zone (ITCZ, Box 1) - will influence regional climates at least as much as human-induced changes, which would affect the West-African monsoon.

Studies based on regional models suggest an increase in the number of days of extreme precipitation over West Africa and the Sahel during May and July, and more intense and frequent recurrences of extreme rainfall on the Guinean highlands. The West-African rainfall projections in the CMIP5 archives show a large variation between models as well as on the amplitude and the direction of the change. This large variation and thus uncertainty is at least partially attributed to the inability of the models to solve the convective rainfall, characteristic for the region (Box 1).

Many of the CMIP5 models indicate the heart of the rainy season as wetter with a slight shift from the beginning to the end of the 21st century. A further complication is made with regional climate models that can alter the signal of change in rainfall patterns of incoming global models especially in regions with high and complex topography. In conclusion, there is low confidence in the robustness of changes in regional rainfall until a broader set of regional results are available. In the Senegal River Basin there is no consensus for an average increase or decrease in rainfall for any term or scenario (Fig. 3.5).

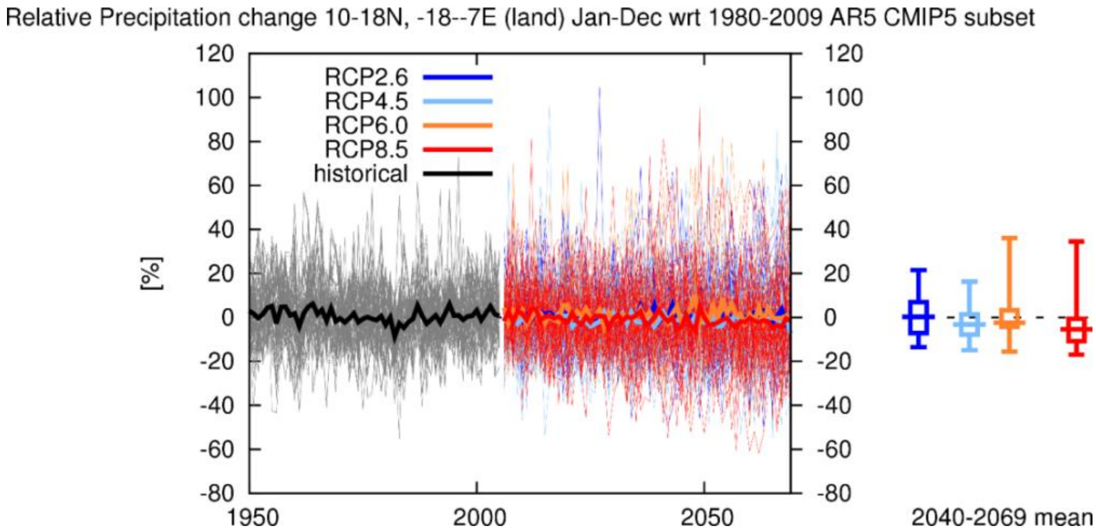


Figure 3.5 Absolute difference of mean precipitation (mm) for four Climate change scenarios in the region of the Senegal Basin, compared to the historical reference period. <u>Explanation of the graph</u>: thin lines show the individual model simulations, thick lines the ensemble mean. The boxplot on the right side of the graph indicate the median (-), the 25-75% variation tile (□) and the 5% and 95% tiles. Colors refer to the different scenarios.

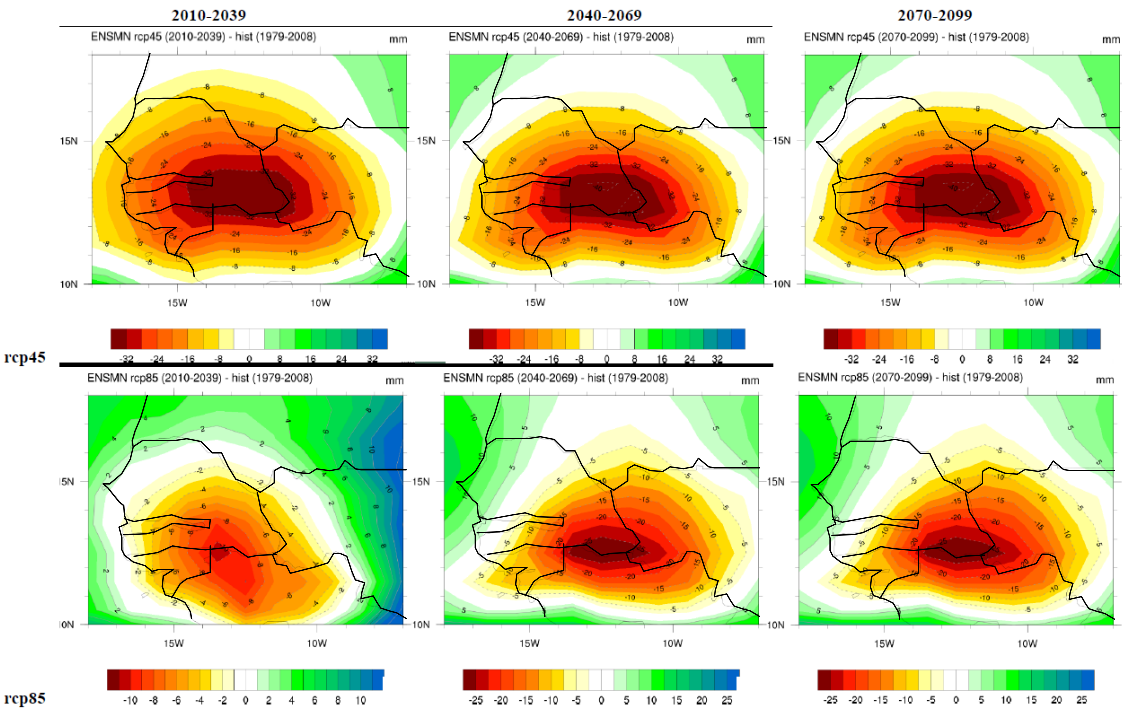


Figure 3.6. Absolute difference of mean annual precipitation (mm) for two climate change scenarios (RCP 4.5 and RCP 8.5) in three future periods. <u>Explanation of the maps</u>: each map shows the difference of the chosen modeled future period with the reference period (1979 – 2008). The colors indicate the level of absolute change in average air temperature (red is less rainfall, green-blue more rainfall).

For the spatial disparity on a larger scale, one can observe a strong concentric reduction in rainfall in the area around the border between Mali, Senegal and Guinea, thus in the southern part of the basin (Figure 3.6). This part of the Senegal Basin fringes and belongs to the Guinean highlands, the source area of the Senegal river. In general, in this region the annual rainfall amounts up to 900-1200 mm, however with a lot of annual variation (Chapter 2.3). From that perspective, the predicted changes may at first not seem very significant, but are relevant in a very large area. One has to keep in mind that the level of uncertainty of these projections is high, that there are large annual variations and the climate scenario's also predict more erratic rainfall.

A systematic decrease in rainfall in this area will most likely have an effect on the flow rates of the Senegal river, which subsequently may have a strong impact on water availability in the basin. However, to quantify the current projections from the different climate scenario's into a change in future river discharge, a hydrological model is needed in which climate changes can be incorporated (like has been done for the Upper Niger Basin and the Inner Niger Delta, Liersch *et al*. 2018).

3.3 Summarized conclusions

Based on the results of the analyzes by PIK (Fournet, 2018) of all scenarios and different projection periods, three main conclusions can be drawn:

4) Temperature change projections in West-Africa for the end of the 21st century are between +3°C and +6°C compared to the end of the 20th century. This increase in temperature will irrevocably lead to a higher degree of local evaporation, which makes the Senegal Basin a sensitive area to climate change.

5) In the Senegal River Basin, there is no consensus for an average increase or decrease in rainfall for any term or scenario. There will, however, be more variation between the years, intensification of rain events, and changes in the timing and duration of the rainy period.

6) In the Guinean highlands (upstream) there will probably be a decrease in precipitation. These highlands are the source area of the Senegal river, and a decrease in rainfall in this area will most likely have an effect on the discharge rates of the Senegal river.

All three projected developments above will have consequences with regard to ecosystem services related to water availability in the basin, as elucidated in the following chapters.

4 Dynamics and availability of water

The river and river bed are offering valuable natural resources to local communities as nutrient-rich soils for agriculture, grazing grounds and fisheries. Natural resources are the key to land use and ecosystem services. In the arid parts of the Senegal Basin, such as in the study area, the availability of water is essential in this respect. To understand the impact of water-related climate change it is therefore important to have a good and recent picture of water availability and natural resources. In this Chapter we present the results of both an analysis of water dynamics and a spatial assessment of water availability by using remote sensing techniques.

4.1 Water levels and discharge rates in the river

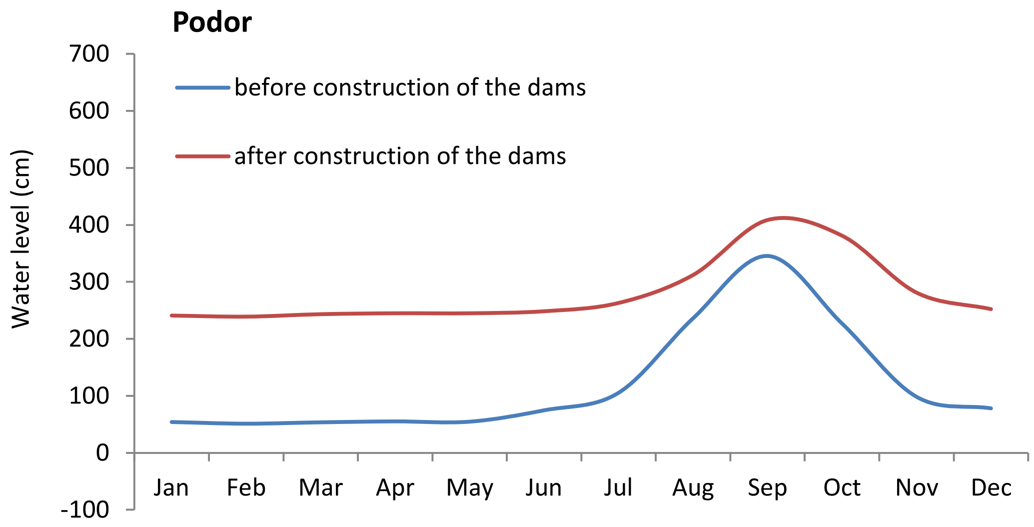
For the quantitative data of river characteristics, an extensive dataset was provided by the OMVS, with daily water levels and discharge rates from the year 1980 until present. For the spatial distribution of water at specific times and the correlation of spatial information with water levels, remote sensing techniques and statistic tools were used. The remote sensing analyses were focused on the middle valley of the Senegal river (Section 4.2).

Precipitation in the wet season is the main driver behind major fluctuations in water levels and flow rates in the Senegal river. In July, water levels start to rise and rapidly reach a peak in September, after which they drop again and reach the low dry season levels in January (Figure 4.1). Every year, the natural flood cycle inundates vast areas of the floodplains in the middle valley. In the past also vast areas in the Senegal Delta were flooded, but this changed after the major embankments in the Delta in 1960s and 1990s and the (Zwarts *et al.* 2009). Consequently, land use activities depending on water resources are strongly driven by major variations in rainfall, not only in the Senegal River Basin itself but also in areas upstream.

Before and after the construction of the dams

Before construction of the dams, the water levels in the river were determined by the flood pulse generated by precipitation in the catchment area. The severe droughts in the 1970s and 1980s (‘La Grande Sécheresse’) created a need for active water management within the basin. Since the construction of the dams, water levels in the river are more stable throughout the year, and severe lowering of the water level is prevented by accurate management of the releases at Manantali. Figure 4.1 illustrates the differences between mean maximum water levels (cm) per month in the river recorded at Podor and Matam, before (1980-1983) and after (1990-2018) the construction of the Diama dam and the Manantali dam.

Before construction of the dams, water levels during the dry season in Podor did not exceed 70 cm and showed a five-fold increase to roughly 350 cm in the wet season. In contrast, since the 1990s the water levels during the dry season are maintained at around 250 cm, increasing to 400 cm in the wet season in Podor.



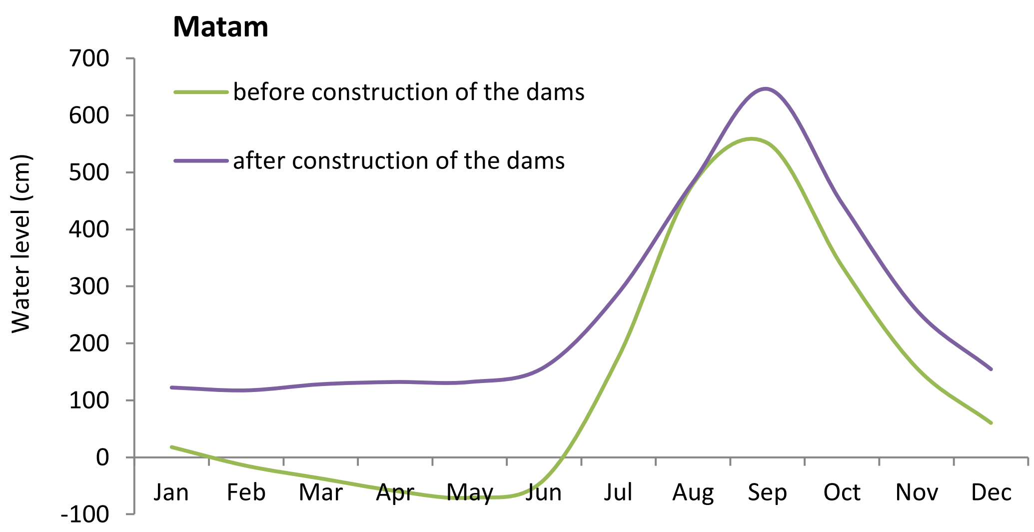


Figure 4.1 Mean water levels (cm) per month in the Senegal River recorded at measuring stations in Podor and Matam, before (1980-1983) and after (1990-2017) the construction of the Diama and the Manantali dams. The negative values for water levels recorded at Matam in the period 1980-1983 indicate the period with lowest water levels (étiage). All data was provided by the OMVS.

In Matam, located further upstream (Fig. 2.1), the difference between before and after construction of the dams is even bigger than in Podor. Before the dams were constructed, the lowering of the water level in the dry season in Podor was, to some extent, buffered by inflow of river water from the delta during the dry season. However, this water did not reach the areas more upstream, which meant that before the dams were constructed upstream parts of the basin dried out in the dry season, characteristic for rainfed rivers in the Sahel. The drop in water levels during the dry season (*étiage*) varied from year to year, depending on the remaining discharge. During the period of the Great Drought in the 1970s and 1980s the water levels were extremely low. Since the 1990s, however, the water levels are maintained above 100 cm in the dry season, increasing to over 600 cm in the wet season in Matam.

After construction of the dams the water availability in the middle valley changed in a large part of the season (November – July). These changes strongly facilitate the availability of water for irrigated agriculture, and at the same time have a strong impact on the functioning of the ecosystem (Chapter 5 and 6).

A significant part of the hydrologic properties of the drainage basin downstream Bakel are regulated by management of the Manantali dam. In addition, substantial contributions of uncontrolled tributaries are received downstream from Manantali, mainly from the tributaries Bakoye, Baoulé and Falémé, and additionally by the Karakoro and Gorgol (Figure 1.1). The water management of the Manatali dam is such that an artificial flood pulse is maintained, but the properties of the flood have changed (Fig. 4.1): during the crue the discharge and water levels are lower than in the pre-dam era, while during the dry season the water levels are higher because of the releases of the dam. The water management may change in future, as there are plans for the realization of new dams, e.g. in the Falémé tributary (at Gourbassi) and in the Senegal river itself (at Gouina).

Zwarts et al. (2009) mention that nearly half of the discharge of the Senegal River depends on the Bafing, which means that the Bafing river is the main tributary when it comes to contribution of river water for the whole Senegal river valley. Discharge data from the OMVS show, that the average discharge at Bakel – where the most important tributaries merge – over the period 2010-2018 is 608 m3/s. Over the same period the discharge of the Bafing downstream Manatali was 188 m3/s, the Falèmé at Kidira 143 m3/s and the discharge of the Bakoye at Oualia 89 m3/s. This corresponds with the statement that nearly half of the discharge of the Senegal river is provided by the Bafing.

The Manantali dam is situated in the Bafing. In addition, the Bakoye river contributes nearly a quarter of the entire river flow (Zwarts et al., 2009). The dam management at Manantali in the Bafing is therefore decisive when it comes to the possibilities of mitigating the effects of climate change through dam management in the whole valley.

4.2 Spatial availability of river water

To analyse the spatial variability of water in the middle valley we produced water maps. Water maps were produced by using remote sensing techniques. A full description of computational methodology and the used datasets is provided in paragraph 4.2.1. The produced maps show the spatial distribution of standing water in the basin, and are indicative for the extent of inundation at specific times, especially in wet periods with high water levels in the Senegal river. For these analyses many images were used, derived from multiple different satellites. Imagery from Landsat satellites was used for analyses of the situations in 1999-2018, and for recent years Sentinel-2 imagery was used.

4.2.1 Selection of input variables and pre-processing

Selection of input variables

For the situation in 1999, 2000 and 2002 we used satellite imagery from Landsat 7, for the period 2013-2018 we used Landsat 8, and additionally Sentinel-2 imagery was used for 2016 and 2017. An inevitable problem when using satellite images is the cloud cover. Particularly in the wet season with inundation, many images are covered with clouds and therefore not usable for analyses. Because of this, we were bound to a selective and rather modest amount of in total 30 suitable images from landsat satellites without clouds (Table 4.2 and 4.3).

As the flood retreats after a period with high water levels and water levels are dropping, isolated water surfaces in the former flooded areas may occur. These water bodies are no longer connected to the river, and are therefore no longer related to the water level in the river. To ensure the reliability of our correlation analyses with river water levels, it is important that the imagery of these situations is excluded. Therefore, only the imagery of dates, on which the water level showed an overall increase over a period of five days, were used for the creation of water maps.

Analysis of Sentinel data

Cloudfree multi-spectral Sentinel-2 Level 1C data covering the middle valley of the Senegal River area were downloaded from the ESA open access data hub (ESA, 2018) (Table 3.1; Figure 4.2). Pixel resolution of Sentinel-2 data is 10 m, 20 m or 60 m depending on the spectral band. The Sen2Cor processor implemented in the open source Sentinel Application toolbox (SNAP, v.6.0; ESA, 2018b) was used to apply atmospheric correction and create Level 2A surface reflectance products at 10m pixel resolution (Mueller-Wilm, 2016).

The Normalized Difference Water Index 2 (NDWI2) water index (McFeeters, 2007) was calculated using the NDWI2 Processor in SNAP based on bands 3 (green) and 8 (Near Infra Red) (Figure 4.3). A NDWI2 threshold of -0.2 was applied to delineate surface water features. NDWI thresholds vary depending on local water characteristics such as turbidity, color as well as the size of water features compared to the pixel resolution of satellite imagery (Lei Ji et al., 2009). The chosen NDWI2 threshold was based on visual inspection of Sentinel-2 images for June 2017 by applying masks for different threshold values in SNAP and comparing the result to high resolution satellite imagery (Bing maps, 2018). If the threshold is set to -0.2, most water features are extracted. If the standard threshold of 0 is used, narrow water features show considerable gaps. A known issue of the NDWI2 water index is that this method does not suppress the signal from built-up land. Therefore, built-up land may be misclassified as water (Sun et al., 2012) (Figure 4.4).

Table 4.1: Sentinel-2 data products that were used for analysis.

Productname	Acquisition Date
S2A_MSIL1C_20170617T113321_N0205_R080_T28QDD_20170617T114506	17/06/17
S2A_MSIL1C_20170614T112111_N0205_R037_T28QDD_20170614T113645	14/06/17
S2A_MSIL1C_20170614T112111_N0205_R037_T28QED_20170614T113645	14/06/17
S2A_MSIL1C_20170614T112111_N0205_R037_T28QFD_20170614T113645	14/06/17
S2A_MSIL1C_20170614T112111_N0205_R037_T28PFC_20170614T113645	14/06/17
S2A_MSIL1C_20170601T110651_N0205_R137_T28PGC_20170601T112448	01/06/17
S2A_MSIL1C_20170601T110651_N0205_R137_T28PGB_20170601T112448	01/06/17
S2B_MSIL1C_20170910T113309_N0205_R080_T28QDD_20170910T113505	10/09/17
S2B_MSIL1C_20170907T112109_N0205_R037_T28QDD_20170907T113242	07/09/17
S2B_MSIL1C_20170907T112109_N0205_R037_T28QED_20170907T113242	07/09/17
S2B_MSIL1C_20170907T112109_N0205_R037_T28QFD_20170907T113242	07/09/17
S2B_MSIL1C_20170907T112109_N0205_R037_T28PFC_20170907T113242	07/09/17
S2A_MSIL1C_20170909T110651_N0205_R137_T28PGC_20170909T112440	01/06/17
S2A_MSIL1C_20170909T110651_N0205_R137_T28PGB_20170909T112440	01/06/17
SENTINEL2A_20160927-112525-613_L2A_T28QDD_D_V1-3	27/09/16
SENTINEL2A_20160927-112525-613_L2A_T28QED_D_V1-3	24/09/16

SENTINEL2A_20160927-112525-613_L2A_T28QFD_D_V1-3	24/09/16
SENTINEL2A_20160927-112525-613_L2A_T28PFC_D_V1-3	27/09/16
S2A_OPER_PRD_MSIL1C_PDMC_20160924T195954_R137_V20160924T110802_20160924T112414.SAFE	24/09/16
SENTINEL2A_20170922-112655-804_L2A_T28QDD_D_V1-4	22/09/17
SENTINEL2A_20170922-112655-804_L2A_T28QED_D_V1-4	22/09/17
SENTINEL2A_20170922-112655-804_L2A_T28QFD_D_V1-4	22/09/17
SENTINEL2A_20170922-112655-804_L2A_T28PFC_D_V1-4	22/09/17
S2A_MSIL1C_20170919T110721_N0205_R137_T28PGB_20170919T111808	19/09/17
S2A_MSIL1C_20170919T110721_N0205_R137_T28PGC_20170919T111808	09-19-17

Figure 4.2 Sentinel-2 tile grid for the Senegal River basin between Richard-Toll and Bakel.

A vector shape file of the outline of the Senegal River basin was created based on the Sentinel true color composite for June 2017. The outline was used as mask to extract the NDWI2 data for this area. The number of pixels classified as water was multiplied by 100 (pixel size = 10 x 10 m) to calculate the area covered by water for the whole Senegal River basin between Richard-Toll and Bakel. To be able to compare the Sentinel-2 water surface areas with those calculated based on Landsat data, the Sentinel-2 water surface areas were also calculated for the part covered by the Landsat tiles for Podor and Matam.

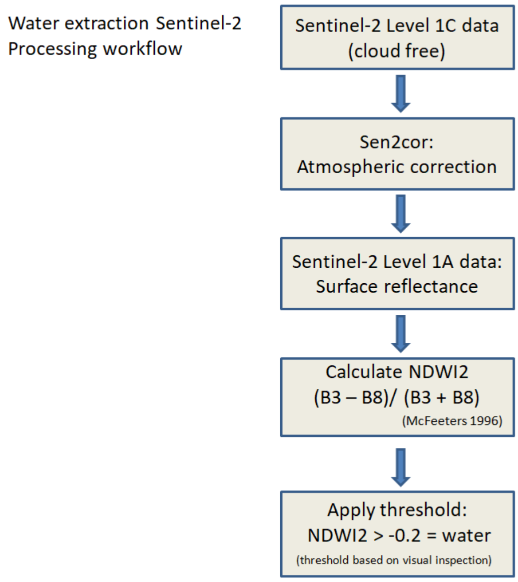
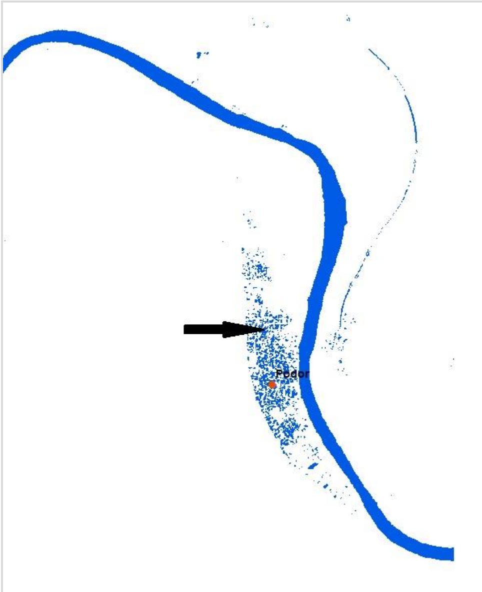


Figure 4.3 Water extraction Sentinel-2 processing workflow.



Fi

Figure 4.4 Urban pixels near Podor that are misclassified as water using the NDWI2 on Sentinel-2 data.

Analysis of Landsat data

Landsat 7 and Landsat 8 OLI/TIRS surface reflectance data products covering the Senegal River area near Podor and Matam were downloaded using the USGS earth explorer website (USGS, 2018) (Table 3.2). The NDWI2 water index was calculated by using Bands 3 (green) and 5 (Near Infra Red), according to the following formula:

NDWI2 = (reflectance band 3 – reflectance band 4) / (reflectance band 3 + reflectance band 4)

Pixel resolution of these spectral bands is 30 m. The NDWI2 images were reclassified to water (value 1) and other (value 0) using the NDWI2 threshold of –0.2. If the imagery contained clouds, these were masked using the data from the Landsat 8 pixel quality image. However, mostly cloud free Landsat data were used. The outline of the Senegal River Basin was used to extract the NDWI2 data and calculate the area covered by water. The number of pixels classified as water was calculated by multiplying by 900 (pixel size = 30 x 30 m) to calculate the area covered by water within each Landsat tile.

Table 4.2: Landsat 7 surface reflectance data products that were used for analysis.

Product name	Acquisition date
LE07204048199909260 1T1-SC20180725065109	26/09/99
LE072040491999092601T1-SC20180724045055	26/09/99
LE072030491999102101T1-SC20180723042717	21/10/99
LE072040481999111301T1-SC20180725065848	13/11/99
LE072040491999111301T1-SC20180724045107	13/11/99
LE072030492000090501T1-SC20180723042624	05/09/00
LE072030492002011401T1-SC20180724045113	14/01/02
LE072030492002070901T1-SC20180724045114	09/07/02
LE072030492002082601T1-SC20180724045101	26/08/02

Table 4.3: Landsat 8 OLI/TIRS surface reflectance data products that were used for analysis.

Product name	Acquisition date
LC08_L1TP_203049_20160808_20170322_01_T1	08/08/13
LC08_L1TP_203049_20130901_20170502_01_T1	01/09/13
LC08_L1TP_204049_20130924_20170502_01_T1	24/09/13
LC08_L1TP_203049_20140224_20170425_01_T1	24/02/14
LC08_L1TP_203049_20140718_20170421_01_T1	18/07/14
LC08_L1TP_203049_20140904_20170420_01_T1	04/09/14
LC08_L1TP_204049_20140911_20170419_01_T1	11/09/14
LC08_L1TP_204049_20140927_20170419_01_T1	27/09/14
LC08_L1TP_203049_20150619_20170407_01_T1	19/06/15
LC08_L1TP_204049_20150914_20170404_01_T1	14/09/15
LC08_L1TP_204049_20160425_20170326_01_T1	25/04/16
LC08_L1TP_203049_20160520_20170324_01_T1	20/05/16
LC08_L1TP_203049_20160707_20170323_01_T1	07/07/16
LC08_L1TP_204049_20160714_20170323_01_T1	14/07/16
LC08_L1TP_204049_20160831_20170321_01_T1	31/08/16
LC08_L1TP_203049_20160925_20170321_01_T1	25/09/16
LC08_L1TP_203049_20170523_20170526_01_T1	23/05/17
LC08_L1TP_203049_20170624_20170713_01_T1	24/06/17
LC08_L1TP_204049_20170717_20170727_01_T1	17/07/17
LC08_L1TP_203049_20170827_20170914_01_T1	27/08/17
LC08_L1TP_204049_20180125_20180206_01_T1	25/01/18

Figure 4.5 Landsat tile grid for the Senegal River Basin.

Combining Landsat and Sentinel

When combining the results from analyses with Landsat imagery and Sentinel imagery, it is important to take into account that these results are not exactly comparable. Sentinel imagery has a resolution of 10m, while Landsat imagery has a resolution of 30m. This means that from Sentinel images more detailed information can be extracted, such as additional small streams. Consequently, the calculated water surface in total will naturally be bigger from Sentinel-analyses than from Landsat-analyses for a particular situation.

4.2.2 Remote sensing results

All produced water maps can be found online in Digital Appendix C. The water maps not only show that the analysis results can be accurately and reliably determined on the basis of Landsat and Sentinel images, but also show that there are large differences in flooding surface between both seasons and individual years.

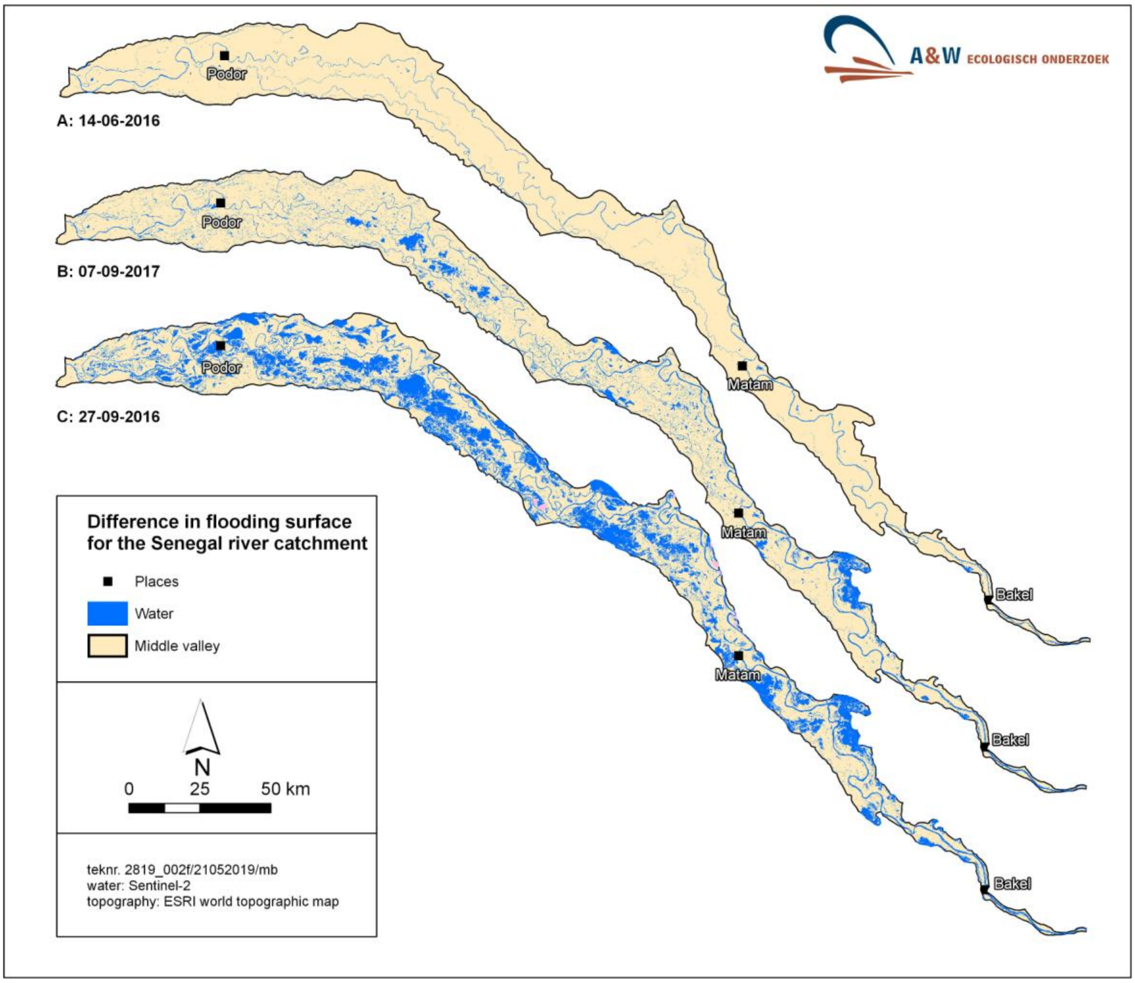


Figure 4.6 Three examples (A, B, C) of water maps in the Middle Valley (ca. 755.514 ha from Bakel to Richard Toll) at different dates.

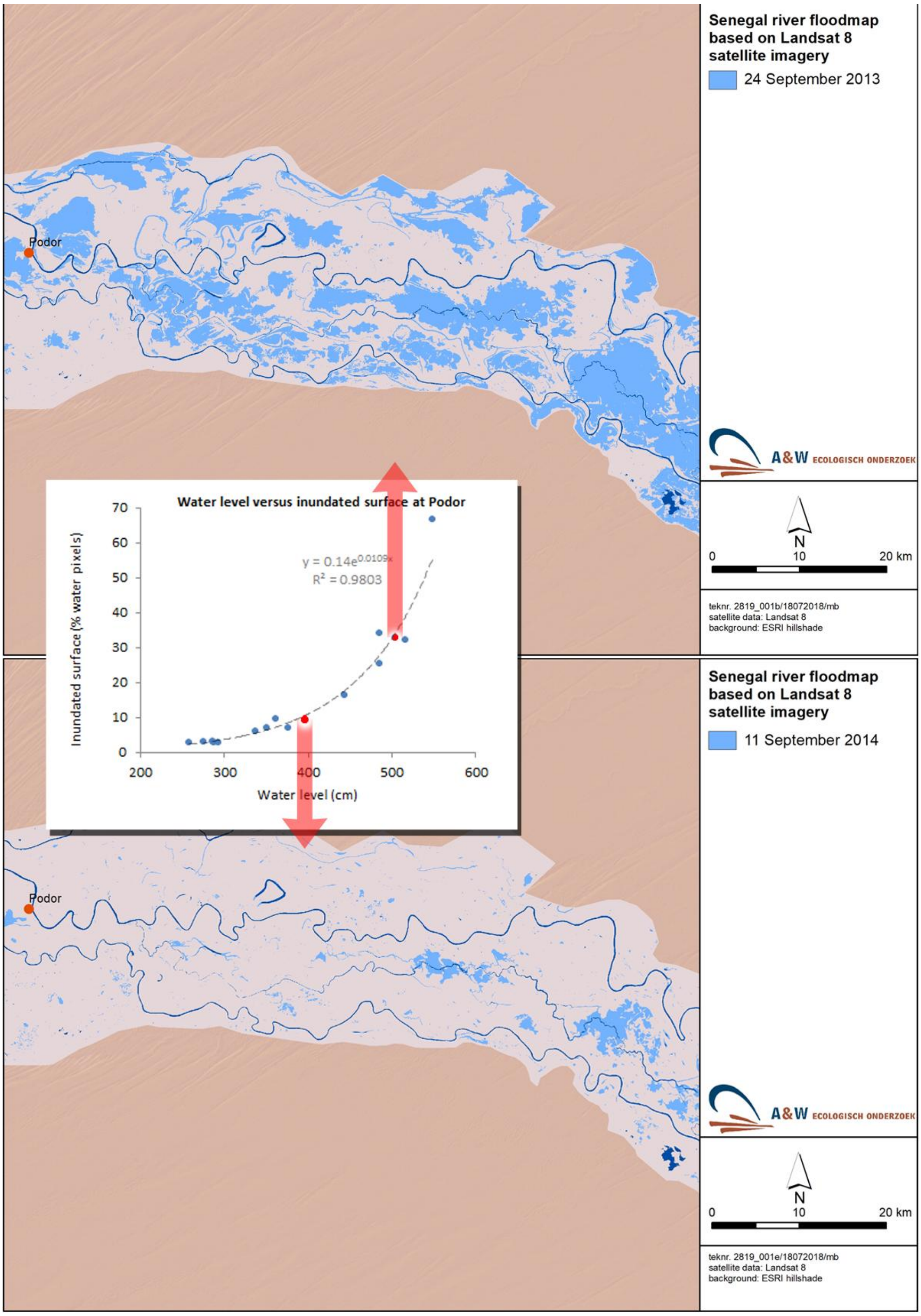


Figure 4.7 The water levels measured at Podor show strong exponential correlations with the inundated surface. The dark blue water line in both figures illustrates the water surface in the recent dry situation of July 2017, as a reference of the river. In the water map below, the inundation zone during moderate flooding is shown (end of September 2014) in light blue, and the water map above illustrates severe flooding (end of September 2013). Corresponding water levels are indicated by red arrows in the graph.

In order to be able to comprehensively compare the NDWI2 results from both Sentinel, Landsat 7 and Landsat 8 imaginary, all results of inundated surfaces have been expressed in percentage of water pixel coverage with respect to the total amount of pixels in the potential floodplain. This information was used for further analysis on correlations.

4.3 Correlations between river characteristics and inundation

The Senegal river dynamics show a strong linear correlation between water levels and discharge rates when considering the data from Matam as provided by the OMVS (Figure 4.7a). The higher the water level, the higher the discharge rates. Discharge rates also show a strong exponential correlation with the inundated surface, as calculated by NDWI2 analysis (Figure 4.7b). Unfortunately, discharge rates are not available for the other measuring stations along the river. Water levels, on the other hand, are available for multiple stations during a long period of time. Therefore, we chose to use the measured water level instead of discharge rates for further exploration of correlations.

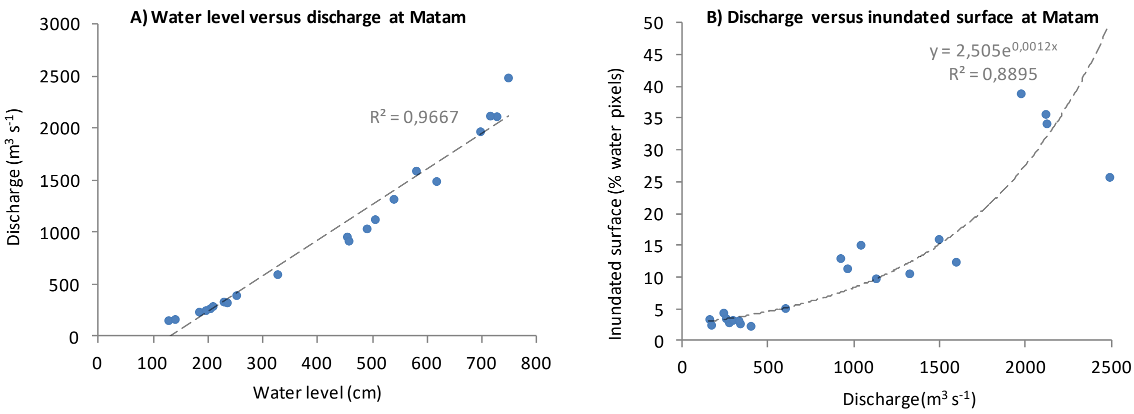


Figure 4.8 A) Water levels and discharge rates show a strong linear correlation for measuring station Matam. B) Discharge rates show a strong exponential correlation with the inundated surface around Matam.

Both Matam and Podor show strong exponential correlations between the water level and the inundated surface (Figure 4.8 and 4.9). The combined results for both locations indicate that, in situations with a river water level under 3 meters high, there is no significant flooding. However, when river water levels exceed this limit of 3 meters, the river overflows its banks and flooding occurs with exponential expansion.

Based on the strong correlations between the water levels and the inundation zone, it is possible to estimate the flooding zone in previous years. Water levels have been accurately measured from 1980 to the present by the OMVS. For each year, at the moment with a maximum water level, the corresponding inundation zone can be calculated with the formulas of the correlation analysis. The result is shown in Figure 4.10, with separate graphs for the areas around Podor and around Matam. The indicated maximum inundation areas per year are expressed as percentages of the potential floodplain surface in the tiles (Figure 4.5) as used for NDWI2 analyses for the areas around Podor and around Matam separately.

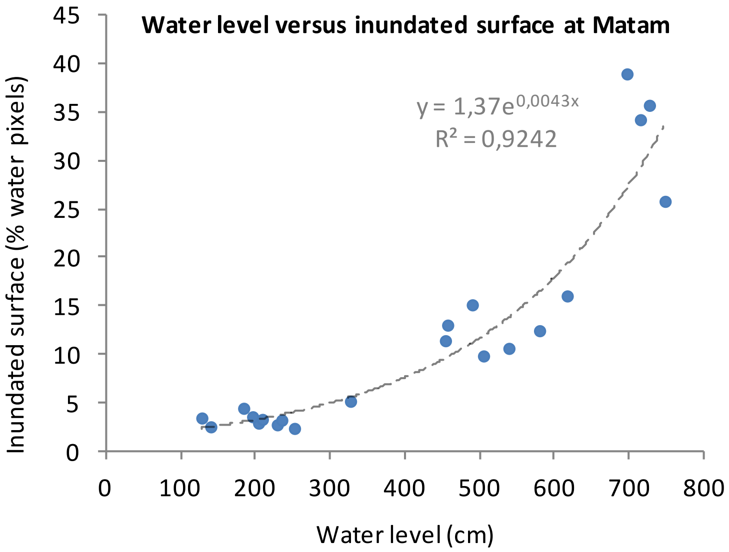


Figure 4.9 The water levels measured at Matam show strong exponential correlations with the inundated surface as detected by NDWI2 analysis.

The two tiles of the area around Podor and around Matam together form the middle valley (Figure 4.5), defined as the area from Bakel in the southeast to Richard-Toll in the northwest. The average flooding percentage of the two sub-areas can be used to estimate the maximum annual inundation zone for the entire middle valley, for both banks of the river both in Senegal and Mauritania (Figure 4.11). According to our estimates, the annual maximum inundation zone fluctuates between 50.000 and 450.000 ha in the total middle valley with an area of approximately 755.514 ha (Richard Toll - Bakel).

These estimates show an enormous variation over the years, but it is clear that the inundation zone is generally relatively small compared to the total middle valley in recent years. Before the 'Grande Sécheresse' and the construction of the dams, the inundation area used to be much larger. According to DeGeorges & Reilly (2006), an average area of 459.000 ha was flooded every year in these years.

With regard to climate change, an important question is: what is the influence of precipitation on the inundation area, and what is the influence of the water management on the water levels? Figure 4.11 does not immediately show a strong link between the annual precipitation and the estimated inundation area. In years with a high degree of inundation in the middle valley, there is not always a high precipitation rate upstream, and vice versa: rainy years with a lot of precipitation do not always show high values for inundation in the middle valley.

To analyse the relationship between the inundation surface area and rainfall in the catchment areas, scatter plots (Figure 4.12) provide more clarity. In these diagrams the estimated yearly maximum inundation area in the middle valley is plotted versus precipitation rates in the highlands of Guinea (A), upstream from Manantali (B), and downstream from Manantali (C). It is clear from these figures, that there is no strong correlation between precipitation and inundation, which means that the annual rainfall in the catchment area does not significantly determine the maximum inundation area in the same year.

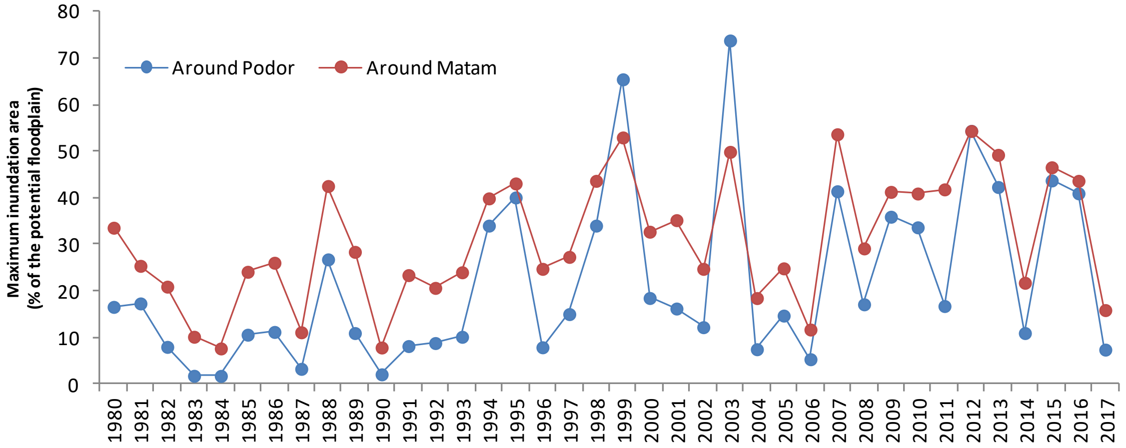


Figure 4.10 Based on the maximum water levels per year, and the results of correlation analyzes, the maximum flooding area estimated for each year from 1980 onwards for the areas around Podor and Matam (for both banks of the river both in Senegal and Mauritania).

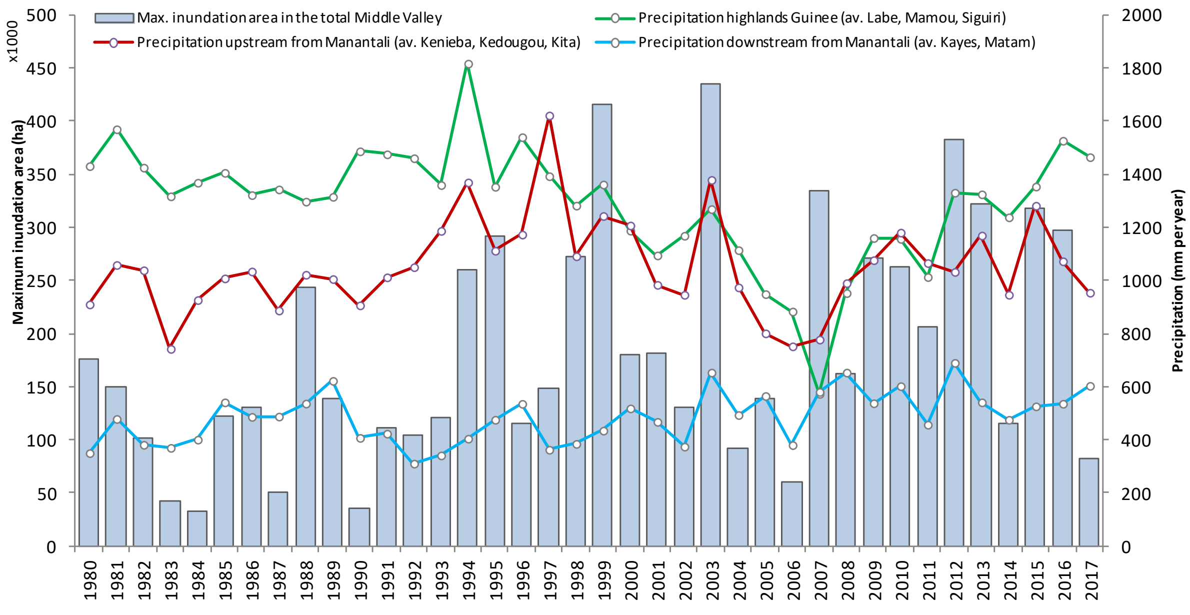


Figure 4.11 Estimations of the maximum inundation area per year in the total middle valley (ca. 755.514 ha from Bakel to Richard Toll), for both banks of the river both in Senegal and Mauritania. In addition, average precipitation rates (mm per year) are indicated for stations in the Guinean highlands (in green: Labe, Mamou and Siguiri), upstream from Manantali (in red: Kenieba, Kedougou and Kita), and downstream from Manantali (in blue: Kayes and Matam).

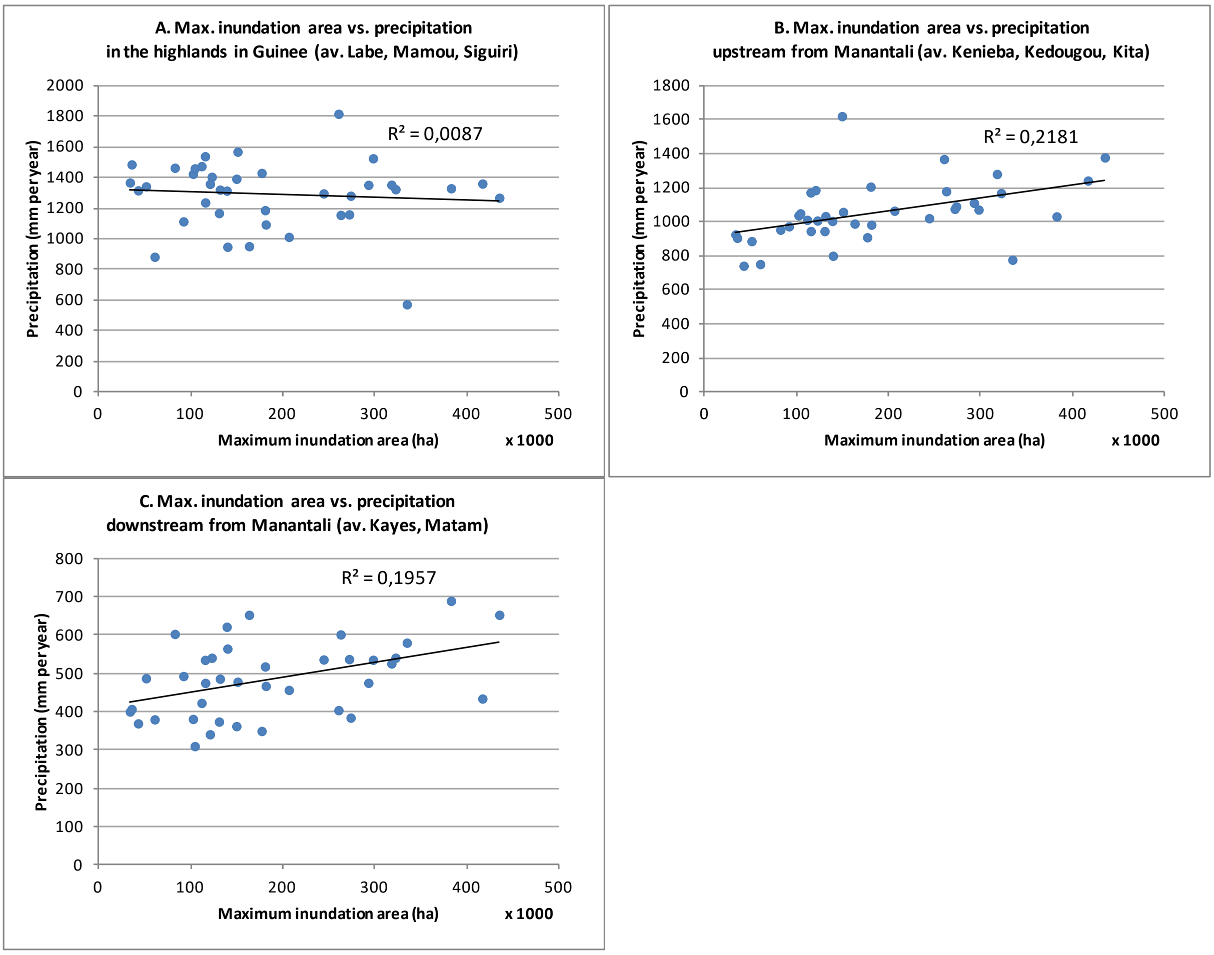


Figure 4.12 Scatterplots, showing the estimated yearly maximum inundation area in the middle valley versus precipitation rates in the highlands of Guinea (A), upstream from Manantali (B), and downstream from Manantali (C).

Since inundation is not highly correlated with rainfall in the cathment area, the variation in water level is therefore also influenced by other factors. In Sahelian river basins the interaction between discharge and groundwater levels plays an important role. After a number of dry years (hence lowered groundwater levels) a significant part of the water is 'used' for supplementing ground water resources. This means, that more rainfall in a specific year not directly translate into a higher discharge rate, and thus a large inundated surface area. The same applies vice versa: after a series of wet years, less rainfall will be needed to cause flooding, because groundwater levels are still relatively high. This phenomenon is sometimes called the 'hydrological memory' of the system, and also is known for the Inner Niger Delta (Upper Niger Basin: Zwarts et al. 2005, Zwarts et al. 2009).

Much more important is of course the water management upstream. Since the construction of the Manantali dam in the Bafing tributary (providing nearly half of the annual discharge) the water level of the Senegal river is for a large part determined by the water management of the dam (retention in the wet season, additional releases in the dry season). The discharge from the catchments of the Falèmé, Baoulé and Bakoye are still uncontrolled and show a natural pattern in discharge. This pattern will change when new dams in the Falémé tributary (at Gourbassi) and in the Senegal river itself (at Gouina) come into operation. The operational management of the current dams (Manantali, Félou) and the future dams (Gourbassi, Gouina) will be decisive in mitigating the impact of climate change in the downstream valley.

4.4 In conclusion

Based on the results of the analyzes in this Chapter the following conclusions can be drawn:

1) For the water availability in the lower middle valley the provision of water resources by the river is very important. Untill know, there is a seasonal flood pulse with extensive inundations in the period September – October.

2) Large parts of the middle valley between Bakel and Podor are inundated annually in this period, but extensive floods are certainly not occurring every year. There is a huge annual variation in the flooded surface area. The inundations are closely linked to the maximum water levels, which are on their turn a function of the river discharge.

3) Analyzes of the water levels in combination with the spatial availability of water show that there is a clear exponential correlation: generally, when river water levels exceed a limit of 3 meters, the river overflows its banks and flooding occurs with exponential expansion.

4) The variation in discharge, and thus in annual inundation, is only partly directly determined by rainfall in the catchment area. The occurrence of series of wet and dry years, also called the ‘hydrological memory’ plays a role, but much more the upstream management of water resources through dams.

5) Although the degree of inundation in the valley at present has increased since the Great droughts in the eighties, there still is a strong flood restriction as a result of water management through dams. At the same time, this may offer opportunities for water storage as adaptation measure for climate change.

5 Natural resources, land use and ecosystem services

The river and river bed offer valuable natural resources to local communities as nutrient-rich soils for agriculture, grazing grounds and fisheries. To understand the impact of a change in climate it is important to have a good and recent picture of the land use and natural resources. In this Chapter we present the results of a spatial assessment in combination with a field survey of parts of the middle valley. We use this information to analyze the impact of climate change.

5.1 General approach

Natural resources, land use and ecosystem services are closely linked. Natural resources are often exploited through different types of land use, while natural resources offer an array of provisioning or other ecosystem services (Fig. 2.6). The aim of this part of the study is to analyze the implications of river dynamics and water availability on ecosystem services. In particular the goal was to get more information on which land use types are inundated at a particular moment in time. Therefore we mapped land cover types, as a indicator for natural resources and ecosystem services.

In cooperation with students from the University of Amsterdam, remote sensing techniques were applied to create land cover maps for the two parts of the middle valley (Rentier, 2018; Bossen, 2018; Juijn, 2018). In these analyses six different land cover types were distinguished:

1. Open areas with shrubs and a low tree density (incl. porential area for 'cultures de décrues')
2. Forests (closed canopy)
3. Irrigated agriculture (mainly rice fields)
4. Barren soil
5. Water
6. Typha-fields

The land cover types are a good but rough indicator of ecosystem services in the middle valley. Table 5.1. gives a global impression of the ecosystem services which can be distinguished on the level of the land cover types which are mapped. In this study, the obtained maps are compared with the water maps from Chapter 4. This comparison provides insight into the spatial importance of temporary flooding in the middle valley, and the importance of associated water levels in terms of ecosystem services.

5.2 Mapping land cover

In the recent past, land cover has been mapped several times in Senegal, making use of the experience of Senegalese experts at the Centre Suivi d'Ecologie (CSS) and other institutes. With the growing quality and resolution of satellite imagery it became more easy to perform national land cover projects. One of the first high-quality land use assessments was done by Tappan *et al*. (2004). Next to the land use patterns per ecoregion they also analysed trends in changes in land use. Recently, this work was updated by the CILSS (2016) for West-Africa, including an assessment of land use and trends in Senegal over the years 1975, 2000 and 2013. Recently, also the Observatoire du Sahara et du Sahel produced a land use / land cover atlas with the resolution of 200m (OSS 2015). For our goals, this resolution is too low. Therefore, we performed a specific land cover map with Sentinel for this study.

Land cover maps were produced by using remote sensing techniques in conjunction with two field missions to the middle valley (February and December 2018, Appendix A&B) for collecting training sites and additional validation. These maps show the spatial distribution of different types of land use and terrains in the Senegal river basin. For these analyses satellite imagery was used.

Table 5.1. Global impression of the ecosystem services of land cover types in the middle valley of the Senegal River, based on two field visits in February and December 2018 and earlier studies by Klop et al. (2016).

Land cover type	**Landuse**	**Ecosystem services**
Overall: the whole river bed on a system level)	Various types of land and water use: Irrigated agriculture, flood recession cultures, grazing, fisheries	- Flood control (important on system level and specifically for the Senegal Delta and Saint - Louis - Water retention (important on local and regional level) - Transportation
Open areas with shrubs and a low tree density (less than 50% coverage) Frequent tree species are *Acacia seyal, Acacia nilotica, Ziziphus mauritianus, Balanites aegyptiaca, Faidherbia albida*	- Seasonal grazing grounds - Flood recession cultures along the river - Small to medium scale vegetable gardening: mainly onions, cabbage, tomatoes, chili pepper, aubergine, carrots etc. Partly flood recession, partly small-scale irrigation	- Nutrient-rich, moist soils for agriculture - Trees: timber, fruits, charcoal, medicinal use - Vegetation for grazing - Biodiversity
Moist and flooded forests with closed canopy Flood forests consist mainly of *Acacia nilotica* and to a smaller extent *Ziziphus mauritianus*	- Limited grazing	- Timber, fruits, charcoal, medicinal use - Biodiversity
Irrigated agriculture	- Rice farming - Sugar cane production	- Biodiversity (limited, specific species)
Barren soils (mainly western part of the valley)	- None / low intensity grazing	- Vegetation for grazing - Biodiversity
Open or vegetates water bodies	- Fishing	- Potable water for local communicates, and livestock - Food supply (fish) - Biodiversity
Typha infested areas / in the eastern part Scirpus fields	- Grazing ground (strongly limited)	- Biodiversity

5.2.1 Technical remote sensing methods

For the spatial analysis of land cover, detailed satellite imagery from Sentinel-2A was used. These images date from 10-05-2018, covering the middle valley from Bakel in the southeast to Richard-Toll in the northwest. The images were downloaded from the ESA open access data hub (ESA, 2018). This imagery has thirteen different spectral bands and a 10-20 meter resolution. After downloading all necessary data, the data was prepared for classification. Spectral bands B2, B3, B4 and B8 were stacked for each individual image and the colors were corrected by using the color correction tool in ERDAS Imagine 2015. After layer-stacking, all the individual tiles were mosaicked and color-balanced and clipped to create a raster file covering the entire middle valley. Next, the pre-processed raster was classified in eCognition by using Object Based Image Analysis (OBIA). When performing OBIA, pixels are grouped into objects based on their spectral resemblance, a process called 'segmentation'. In order to obtain the optimal scale parameter for this segmentation, research of Darwish et al. (2003) was used as a guideline. Automatically, eCognition adds a category 'unclassified' for the areas that could not be classified.

For classification in eCognition, training sites were used as references. These training sites were appointed to each class, and were based on the field observation points from the field mission in 20-26 February 2018 (Appendix A). By combining the coordinates of these field observations, the Sentinel-2A imagery and additional visual data from Google Earth, different classes were identified on the satellite imagery and subsequently classified for the whole potential floodplain of the middle valley. After classification, small pixels were filtered out by using the 'majority filter' tool in ArcMap.

Finally, an accuracy assessment was performed in ArcMap in order to validate the outcomes of the analysis. Randomly distributed points within each class were generated, where the number of points in each class is proportional to its relative area. According to Congalton (1991), a good rule of thumb is to collect a minimum of 50 samples for each land use category, which results in an assessment of more than 350 sampling points for the land use analysis of the middle valley. During the accuracy assessment, each sampling point was given the value 0 or 1, indicating whether the classified area was assigned to the correct class (1) or not (0). At the end of the assessment, the total accuracy, was calculated. The total accuracy is the fraction of the accurately classified points with regard to the total number of selected points.

5.2.2 Remote sensing results

Reliability of the mapping

The mapping has been done with automatic techniques and on a global scale, which means that these results cannot be used as a detailed land cover map in the field. For these purposes there are other land cover maps available, like the land use maps of CILSS (2016) and Tapan et al. (2004). For a good impression on land cover in the middle valley recently we refer to the Atlases of OSS (2015a, 2015b). Also, the analyses for the current study was done for one specific moment in time (Sentinel images of 10 May 2018). For the purpose of this study, the global level and limited number of land cover types is no restriction, as we want to analyze the combination with flooding.

The overall accuracy of the generated maps was 78% (286/366) with no class (land cover type) less than 50% accurate. According to Landis & Koch (1977) a value greater than 80% represents strong agreement, and a value in between 40-80% represents moderate agreement. The overall accuracy of 78% of the generated land cover map can therefore be characterized as quite reliable. Typha fields and water show the lowest accuracy probabilities for (respectively 50% and 56%). This is mainly a result of the color reflection that is difficult to recognize. Open areas with shrubs and flood recession crops, and irrigated agriculture show the highest accuracy rates (respectively 90 and 85%), which means that these land use types can be classified quite precise.

Distribution of land cover types

The generated map clearly show the variation and distribution of six different types of land cover and land use in the potential floodplain (Figure 5.2 and 5.3). A detailed version of this map can be found online in Digital Appendix D. Table 4.1 provides the corresponding statistics of these maps. Areas for different land cover types were calculated by extracting the number of pixels for each land cover type and multiplying by 100 (Sentinel-2 pixel size = 10x10m). The areas are calculated with respect to the total potential flood plain of the middle valley with boundaries as indicated in Figures 5.1 and 5.2.

Table 5.1 The total calculated area for each land cover type in the total potential floodplain of the middle valley.

	Land cover type	Nr. of pixels	Area (m²)	% of total potential floodplain
1	Open areas with shrubs and a low tree density (incl. potential area for flood recession crops)	37316407	3731640700	53,1
2	Forests (closed canopy)	2141367	214136700	3,1
3	Irrigated agriculture (mainly rice fields)	2531587	253158700	3,6
4	Bare soil	24935885	2493588500	35,5
5	Water	2343096	234309600	3,3
6	Typha fields	999805	99980500	1,4
	Total	70285752	7028575200	100

The results show that more than half of the potential floodplain concerns open areas with shrubs and a low density of trees. Present trees are mostly *Acacia nilotica* but also, on dryer places, *Faidherbia albida* (White acacia), *Acacia seyal* (Red acacia, mainly eastern part of the valley) and *Balanites aegyptiaca*. These parts of the river bed are potential areas for flood recession crops 'cultures de décrues' in case of large-scale flooding. Especially for the rural communities, this feasible way of agriculture was, and still is lucrative. Mainly sorghum and a variety of vegetables is being cultivated: beans, onions, tomatoes, cabbage, aubergine, chili pepper, okra, carrots, sweet potatoes etc. The extent to which this potential zone is used for recession crops depends on the degree of annual flooding. In theory, a very large area is suitable for recession crops if large-scale flooding occurs. The difference between traditional flood recession agriculture and other open areas with vegetation could not be detected with our remote sensing method, because flood recession is solely practiced in/after the rainy period. It was very hard to find recent useful imagery during this period (without clouds).

Furthermore, there is a large proportion of bare soil in the middle valley (35,5%). In these areas, drought-induced loss of vegetation cover, overgrazing, and soil erosion result in bare and unproductive land, even in the rainy season. The portion of bare soil in the area around Podor is relatively large, while the area around Matam shows instead more open areas with vegetation (Figure 5.1 and 5.2).

The proportion of irrigated agriculture is low in the total middle valley, much lower than in the delta in the west. The management regime at Manantali facilitates the year-round availability of water for irrigated agriculture, which at many locations in the basin lead to a shift from traditional flood-recession agriculture to intensive, irrigated and permanent production of mainly rice in the basin. Irrigation schemes developed rapidly, especially in the lower delta. In the middle valley, the development of irrigation agriculture took more time and on a much smaller scale than in the densely populated lower delta. Rice farming is by far the most important agricultural activity. Based on our field work, we can conclude, that irrigated agriculture was successfully detected by remote sensing applied in this study, although a small portion of these areas were not detected.

In the middle valley flood forest with a closed canopy, mainly consisting of *Acacia nilotica*, was only present on a small scale. The dry climate offers little chance for relatively dense forests, but more importantly, a large part of the extensive flood forests in the middle valley in the past, has been cleared (Tappan et al. 2004, CILSS 2016). The decline of trees in the valley through clearing in recent years is worrying, and the area of forest with closed canopy will probably become even less in the future.

Finally, *Typha*-fields are present on a small scale, and occur more frequent in the western part of the middle valley (Figure 5.1). In the eastern part of the valley *Scirpus*-fields are present instead of *Typha*. This corresponds to the findings during the field visits (Appendix A and B). *Typha*-fields develop rapidly in case of standing fresh water; in the lower delta a vast area of *Typha* is found nowadays (Zwarts *et al*. 2009), blocking water inflow and triggering the prevalence of waterborne diseases. In addition, *Typha*-fields seriously hampers access to water for fishermen.

5.3 Combining water maps and land cover maps

By combining and comparing the generated water maps and the land cover analysis, it is possible to gain a better insight into the land use types that become inundated during large-scale flooding. This way, it is possible to get an impression of the potential area for flood recession culture, as well as the area comprising flood-dependant biodiversity.

5.3.1 Methodology

The generated NDWI maps (water=1, no water=0) were multiplied with the land cover map by using the Raster calculator in ArcMap (ArcGIS Desktop 10.5.1). In the resulting floodmap, only flooded land cover pixels have kept their original values; non-flooded pixels were assigned value 0. Next, the number of flooded pixels for each landcover type was extracted from the attribute table. For calculating flooding in the Podor and Matam areas, the land cover maps that were generated by the UvA students were clipped to the Landsat tile outlines. The potential inundated surface in the catchment, separately for the Podor area and the Matam area, refers to the area within the individual two Landsat tiles (Figure 5.3). Finally, the Landsat pixel values were multiplied by 900 to calculate the flooded areas (Landat pixel size = 30x30m).

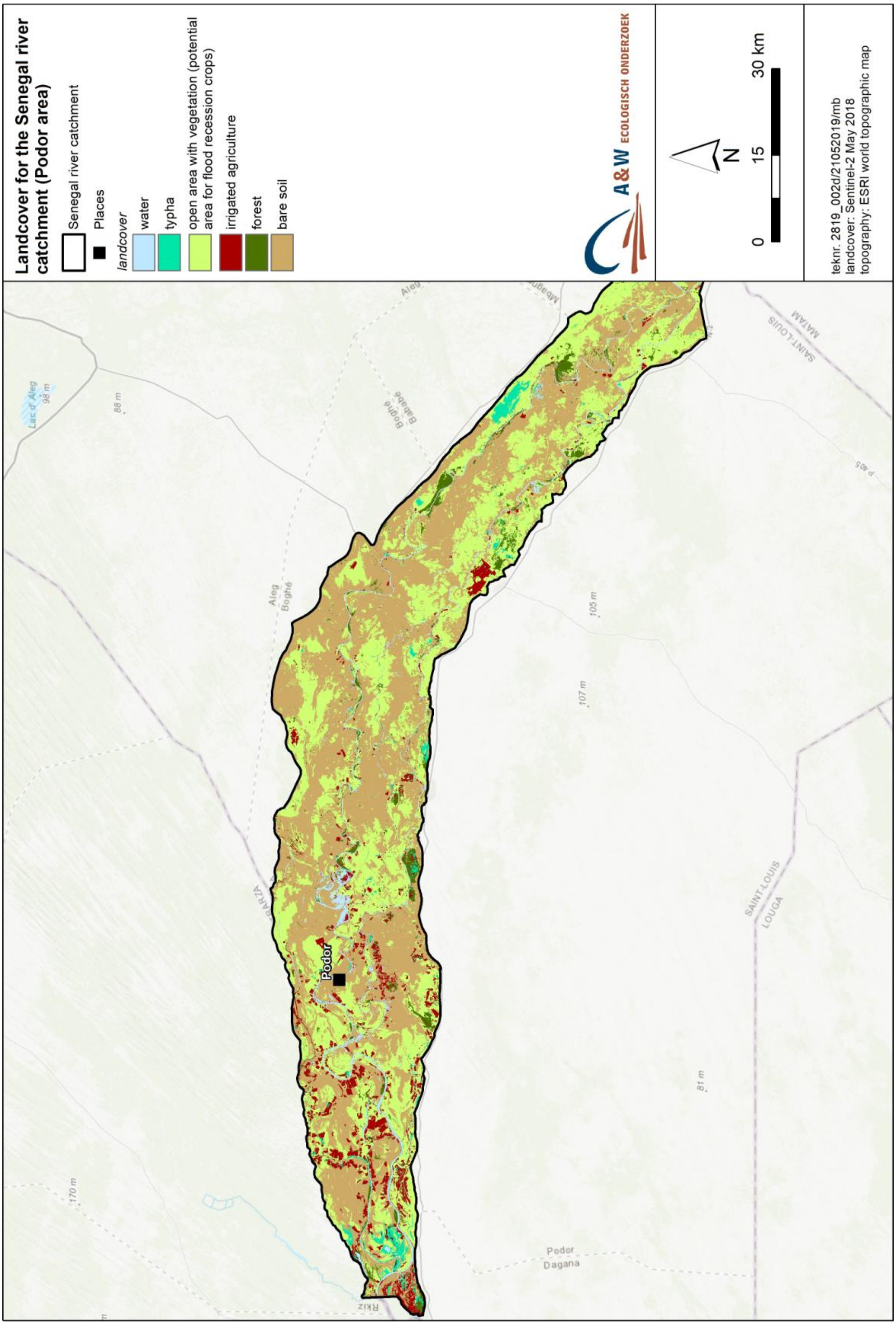


Figure 5.1. Land cover types in the selected potential floodplain area area around Podor.

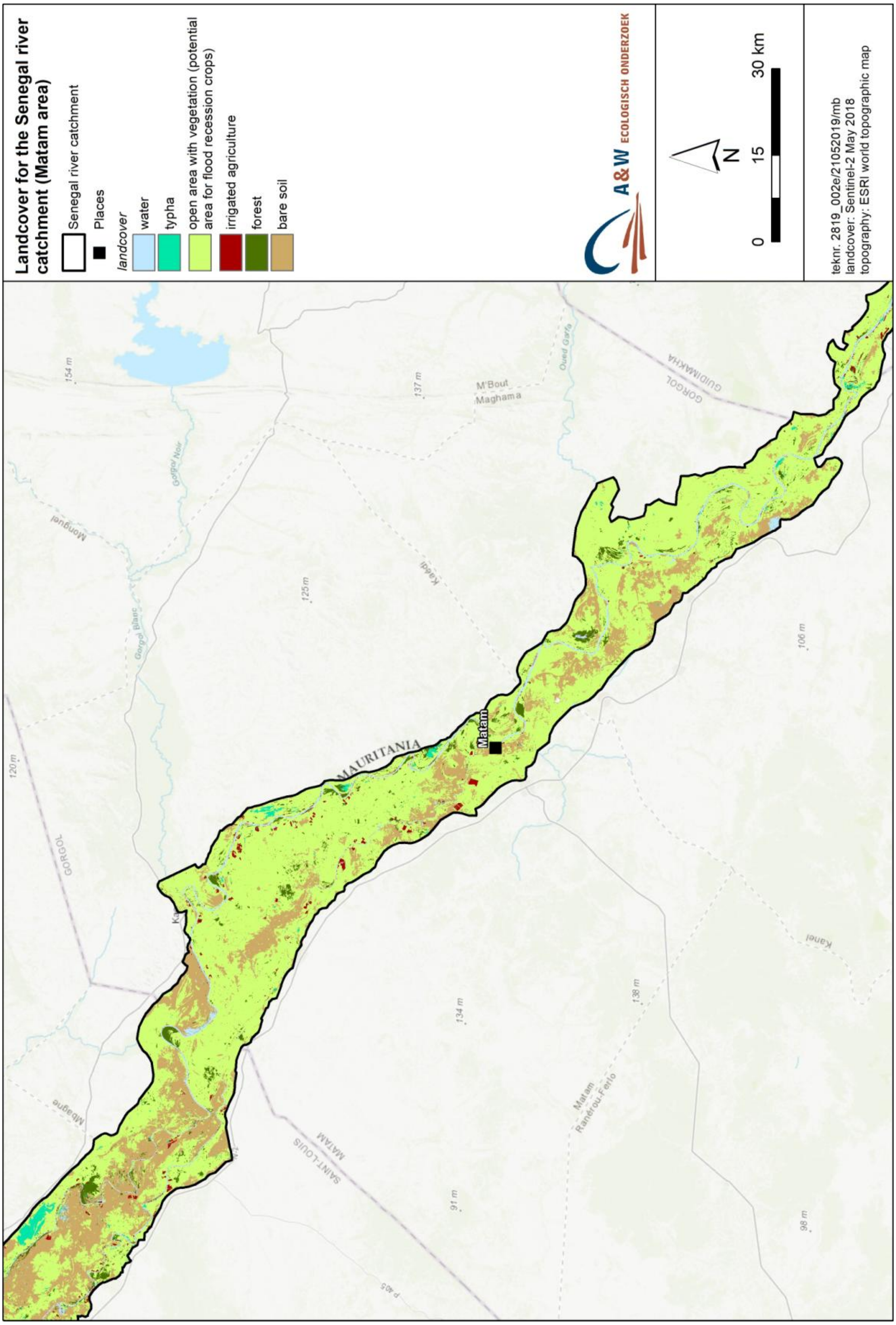


Figure 5.2. Land cover types in the selected potential floodplain area around Matam.

Figure 5.3 The Landsat tile grids versus the landcover map.

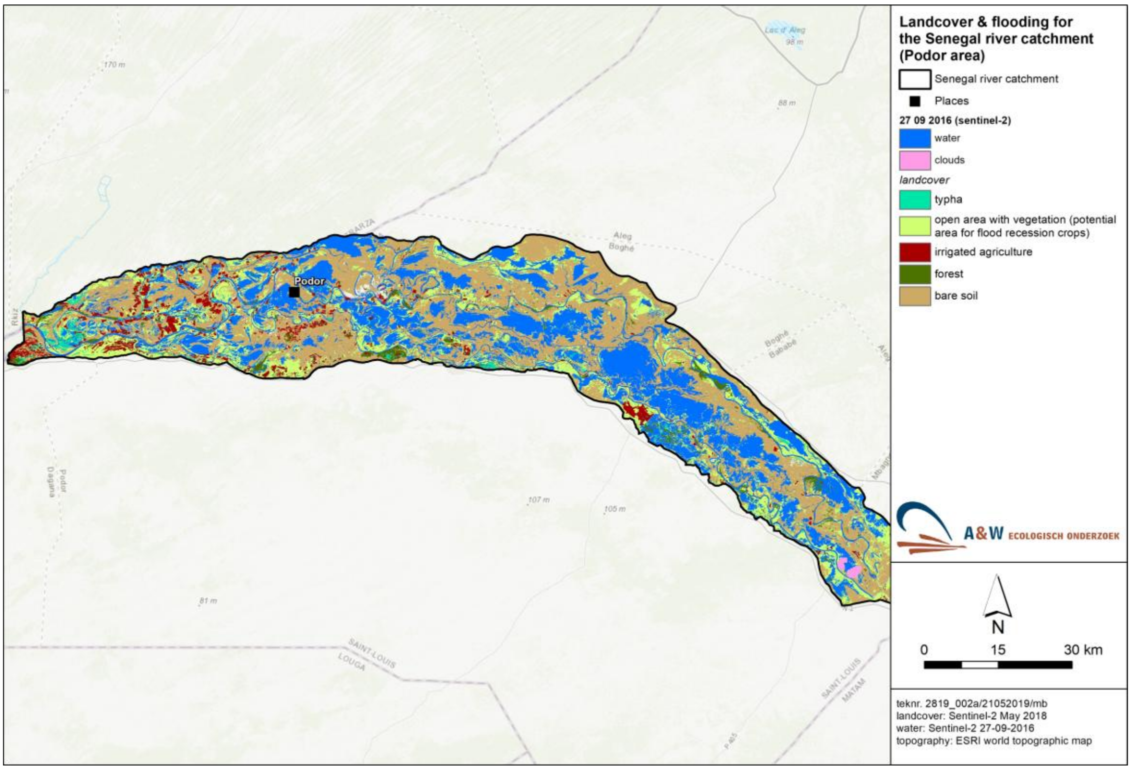


Figure 5.4 Example of a combined map of 27-09-2016, showing flooding versus land cover in the area around Podor.

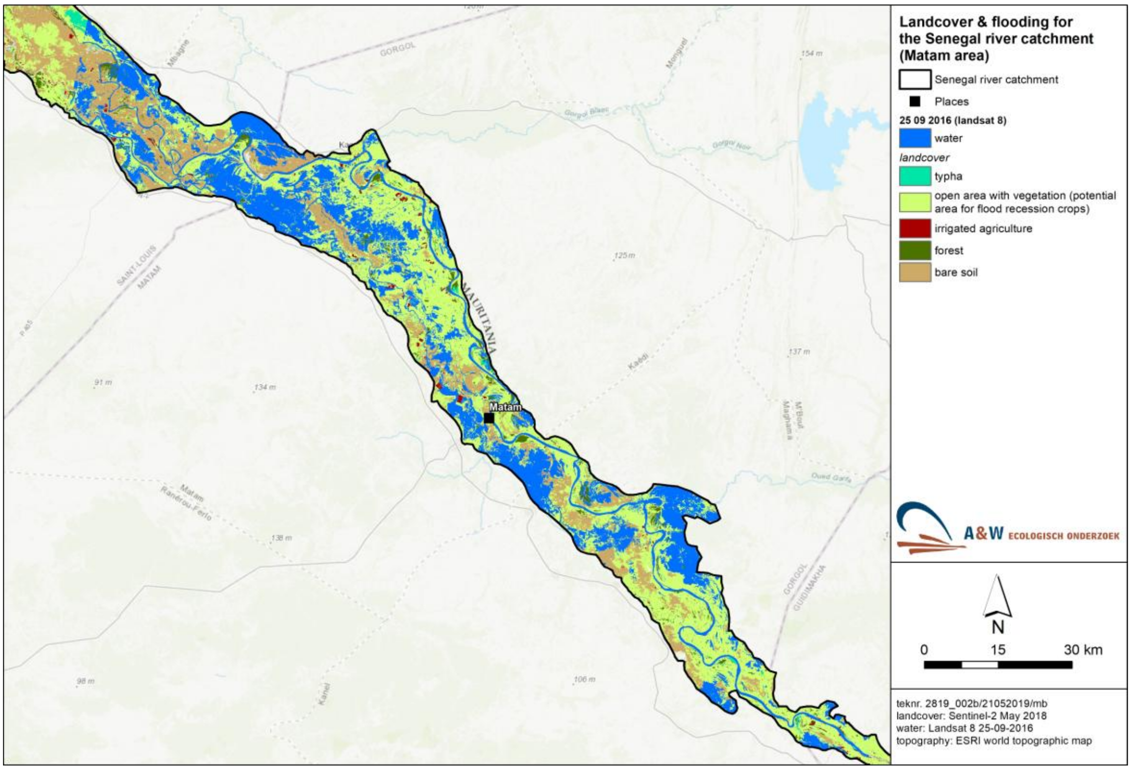


Figure 5.5 Example of a combined map of 25-09-2016, showing flooding versus land cover in the area around Matam.

5.3.2 Results

The generated maps show the six different types of land cover in the potential floodplain in combination with the standing water at particular moments. Figures 5.4 and 5.5 are examples of combined maps of flooding versus land cover in the end of September 2016 in the middle valley. We were able to conduct a total of 21 combined analyses with the generated water maps that were available (12 for Podor, and 9 for Matam). Figure 5.6 shows the inundated surface per terrain type in the potential floodplain versus the water level in the river, separately for the Podor area and the Matam area. The dates of used imagery are shown in Table 5.2 (Podor) and Table 5.3 (Matam).

Table 5.2 The total calculated area (ha) for inundation within each land cover type in the floodplain area around Podor, within the boundaries of Figure 5.4, at specific dates with corresponding river water levels. The percentage of the land cover type with respect to the total inundation area is indicated within brackets.

Date	River water level at Podor (cm)	Total flooded area	Open areas with vegetation (potential area for flood recession crops)	Barren soil	Forest	Irrigated agriculture
14-06 2017	286	11566	736 (6%)	791 (7%)	60 (1%)	1009 (9%)
17-07 2017	288	10663	1509 (14%)	739 (7%)	238 (2%)	744 (7%)
14-07 2016	293	10787	1184 (11%)	689 6%)	239 (2%)	849 (8%)
26-08 2014	351	27398	11803 (43%)	4810 (18%)	501 (2%)	2002 (7%)
07-09 2017	362	38162	16803 (44%)	9649 (25%)	672 (2%)	1761 (5%)
27-09 2014	397	36285	19553 (54%)	6260 (17%)	663 (2%)	1233 (3%)

31-08 2016	444	65688	40177 (61%)	12529 (19%)	1477 (2%)	1827 (3%)
14-09 2015	485	102398	63452 (62%)	24414 (24%)	2088 (2%)	2152 (2%)
13-11 1999	485	132486	74834 (56%)	34443 (26%)	4345 (3%)	5510 (4%)
24-09 2013	504	132076	79506 (60%)	35278 (27%)	2941 (2%)	3138 (2%)
27-09 2016	516	129094	77447 (60%)	34692 (27%)	2063 (2%)	3349 (3%)
26-09 1999	549	264294	119676 (45%)	111144 (42%)	8095 (3%)	8329 (3%)

Table 5.3 The total calculated area (ha) for inundation within each land cover type in the floodplain area around Matam, within the boundaries of Figure 5.5, at specific dates with corresponding river water levels. The percentage of the land cover type with respect to the total flooded area is indicated within brackets.

Date	River water level at Matam (cm)	Total flooded area	Open areas with vegetation (potential area for flood recession crops)	Barren soil	Forest	Irrigated agriculture
24 06 2017	251	8147	1532 (19%)	486 (6%)	76 (5%)	317 (4%)
14 06 2017	234	11215	1470 (13%)	677 (6%)	29 (1%)	575 (5%)
18 07 2014	326	18252	10838 (59%)	1032 (6%)	171 (0%)	262 (1%)
27 08 2017	453	33851	22285 (66%)	2189 (6%)	404 (1%)	640 (2%)
07 09 2017	489	47294	32709 (69%)	3927 (8%)	709 (1%)	943 (2%)
08 08 2016	616	53997	41070 (76%)	3223 (6%)	725 (1%)	641 (1%)
21 10 1999	696	121768	95042 (78%)	10924 (9%)	4277 (4%)	1224 (1%)
27 09 2016	714	117561	93634 (80%)	10572 (9%)	1883 (2%)	1115 (1%)
25 09 2016	726	114715	91590 (80%)	10428 (9%)	2102 (2%)	991 (1%)

Interesting insights emerge from the dataset of the area around Podor. Firstly, when the water level in the river rises above 3m, leading to inundation, it mostly concerns the terrain type open areas with vegetation. Generally, there is less inundation in areas with barren soil. Naturally, in irrigated agriculture areas there is hardly any flooding. The same goes for the area around Matam; the most flooding occurs in open areas with vegetation. Areas of barren soil, forest with closed canopy or irrigated areas get flooded much less in periods of high water levels.

At times when the river overflows its banks in the area around Podor, the terrain cover types 'open areas with vegetation' and 'barren soil' become flooded with exponential expansion (Figure 5.6). In case of river water levels of around 5m at Podor for instance, as was the case in November '99, September '13, September '15, September '16, some 70,000-80,000 ha of the land cover type 'open areas with vegetation' become flooded within the 402,000 kha part of the basin around Podor as shown in Figure 5.4. That means that about 20% of the floodplain area around Podor is a potential area suitable for flood recession crops when extended inundation takes place. In addition, the extreme case of September '99, when river water levels exceeded 5.5 m, showed extensive flooding, in which not only many open areas with vegetation were flooded (about 30% of the potential floodplain), but additionally a very large area of barren soil.

Relevant question is: how often does significant flooding occur around Podor? After the exceptional autumn of 1999, with river water levels over 5.5m, only in 2003 a comparable high water level occurred. In the autumns of 2007, 2009, 2010, 2012, 2013, 2015 and 2016 river water levels generally did not exceed a maximum of 5m. In the remaining years the flooding from the river was smaller; the river water levels did not exceed 3.5-4.3m. In these years there was no extreme flooding around Podor. Or at least: in these years there was no question of exponential flood expansion in the land cover type 'open areas with vegetation, which are potential areas for crop recession cultures.

For the area around Matam, a similar strong correlation between the river water level and the land cover type 'open areas with vegetation' is observed. This type becomes flooded with exponential expansion, especially during river water levels of about 7m (Figure 5.6). In such situations about 95,000 ha hectares of open areas with vegetation become flooded within the tile as shown in Figure 5.5, which is about 28% of the potential floodplain around Matam. Since the extreme wet autumn/winter of '99, river water levels of over 7m occurred in 2000, 2001, 2003, the period 2007-2013, 2015 and 2016. In the years 2002, 2004, 2005, 2006, 2014 and 2017 maximum river water levels were lower than 7m. We did not manage to find cloud-free imagery to use for remote sensing in these years. Based on the correlation analysis, we can assume that in these years there was no significant flooding. Or at least: in these years there was no question of exponential flood expansion according to the curve of Figure 5.6.

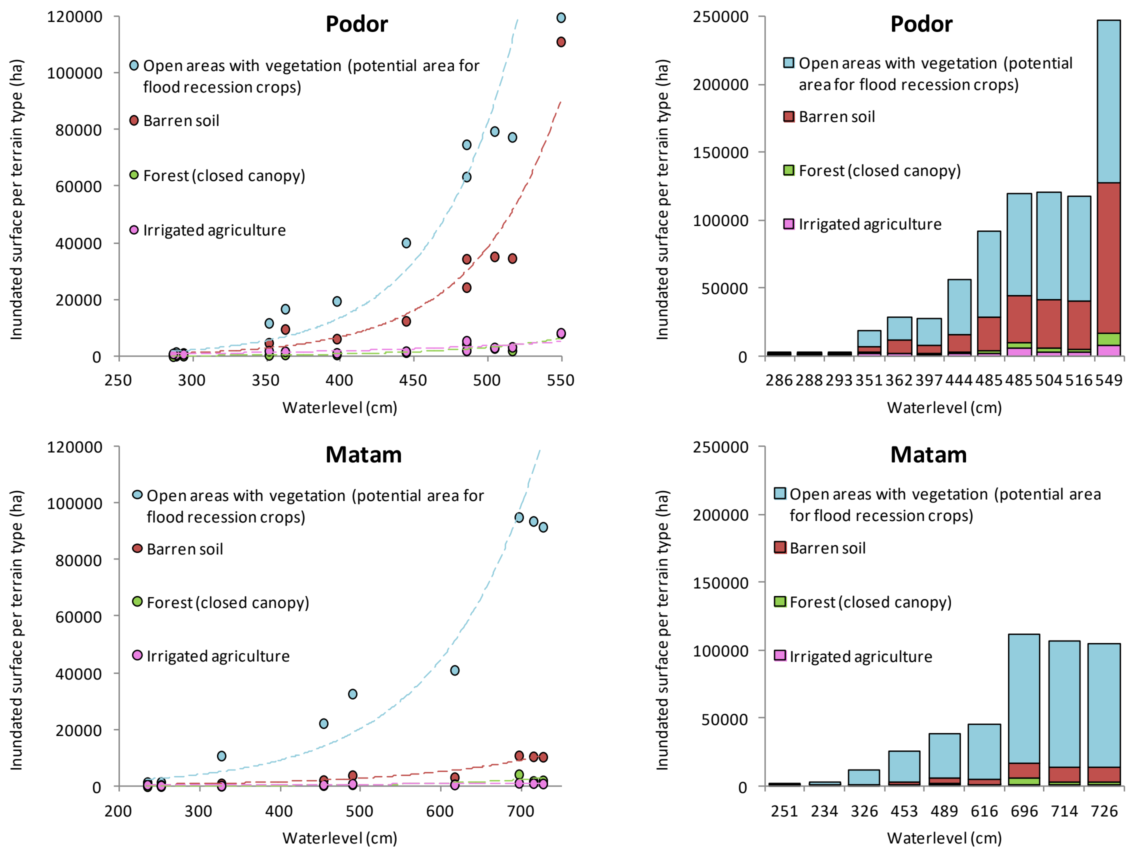


Figure 5.6 The inundated surface per terrain type in the potential floodplain versus the water level in the river, separately for the Podor area and the Matam area.

5.4 In conclusion

Based on the results of the analyzes in this chapter the following conclusions can be drawn:

1) In the Senegal valley several types of land use are classified: open areas with shrubs and a low tree density, forests (closed canopy), irrigated agriculture (mainly rice fields), barren soil, open water and *Typha*-fields.

2) A significant part of the land use types and associated ecosystem services are linked to yearly inundations and availability of water. Particularly the 'open areas with vegetation' type, the potential area for flood recession crops and important for grazing, is dependant on flooding in wet periods.
3) In recent years, however, flooding is becoming less frequent, and there is certainly no longer any question of annual large-scale inundation in areas that are not directly connected to the river bed. This development can be considered negative in terms of several ecosystem services that are provided by the river. 53% of the total surface of the middle valley, on both banks of the river in Senegal and in Mauritania, is classified as open area with vegetation, which is potentially suitable for flood recession crops in years with large-scale inundation. However, in most of the recent years, inundation is restricted to a relatively small zone directly connected to the river bed.
4) Spatial analyzes of inundation in combination with land cover show that there is a clear exponential correlation: generally, when river water levels exceed a limit of 3 meters, the river overflows its banks and flooding occurs with exponential expansion.
5) The combination of water maps and land use provides a lot of insight: the availability of water as a natural resource is increasingly being limited to the area directly along the river, which is a worrying development. Not only the decrease in potential areas for flood recession crops is worrying, but also biodiversity in these habitats is seriously under pressure with reduced flooding in the open semi-arid areas in the basin. Climatic changes will, as elucidated in Chapter 3, lead to increased evaporation rates, and hence a further decrease in water availability in the middle valley, especially in remote areas in the basin that are not directly connected to the river bed.

6 Impact pathways of climate change

6.1 Introduction

Riparian states in the Senegal River Basin aim to continue the development of using river water resources to support the regional economy and food security, and also aim to conserve and restore remaining wetland resources. For the delicate balance between these goals, Integrated Water Resources Management (IWRM/GIRE) is the key process. For the near-future management of water resources and ecosystems within the Senegal River basin this is elaborated in the SDAGE (*Schéma Directeur d'Aménagement et de Gestion des Eaux du Fleuve Sénégal*).

Future climate change effects exacerbate the problems associated with human pressure on natural resources. A comprehensive study by Artelia (2018) states that the strong demographic growth in the four BFS states, in combination with climatic changes, may lead to uncontrolled human pressure on the river's water resources. This will have severe consequences for the environment - massive deforestation, destabilization of rivers, bad water quality - and the socio-economic balance of states. In this future perspective the vulnerability of especially rural communities is very high (Artelia, 2018).

In this Chapter, we elaborate on the impact pathways of climate change, in order to better formulate adaptation measures in Chapter 7. An assessment of the impact of climate change in relation to water-related ecosystem services, such as in this study and Artelia (2018), can provide tools to local stakeholders and policy makers for future-proof water management.

Three main changes

As elucidated in Chapter 3, climate change encompasses three main future developments: an <u>increase in temperature</u> in the basin, <u>reduced precipitation in the source area</u> of the Senegal river, and a <u>more erratic precipitation pattern and shorter wet season</u> in the basin (Figure 6.1).

The projected increase in temperature between +3°C and +6°C for the end of the 21st century, compared to the end of the 20th century, can be considered quite certain, and is in accordance with previous climate projections for this area (e.g. Christensen et al., 2007). The development of annual rainfall, however, is more uncertain in West Africa (Chapter 3, e.g. Lebel & Ali 2009, Krysanova *et al*. 2015). There will, most likely, be more variation between the years and changes are expected in the timing and duration of the rainy period. The total amount of rainfall may remain the same, but the wet season is likely to be shorter. Further, intense rainfall events are predicted to become more frequent and more extreme, which may lead to destructive floods, erosion and soil degradation. Additionally, in the Guinean highlands (upstream) there will probably be a decrease in precipitation, which will most likely have an effect on the discharge rates of the Senegal river. It is important to gain more insight into the consequences for the hydrological system.

Impact pathways

These three main climate-related changes (temperature increase, reduced precipitation in the Fouta Djalon and a more erratic local precipitation pattern) will have a strong effect on various hydrological and climatic parameters (Figure 6.1). Some effects will be direct, such as the impact of a higher temperature on evaporation, other wills be indirect such as a higher pressure on the remaining water resources in the river bed. Indirect effects may take more time to manifest itself but are not less important.

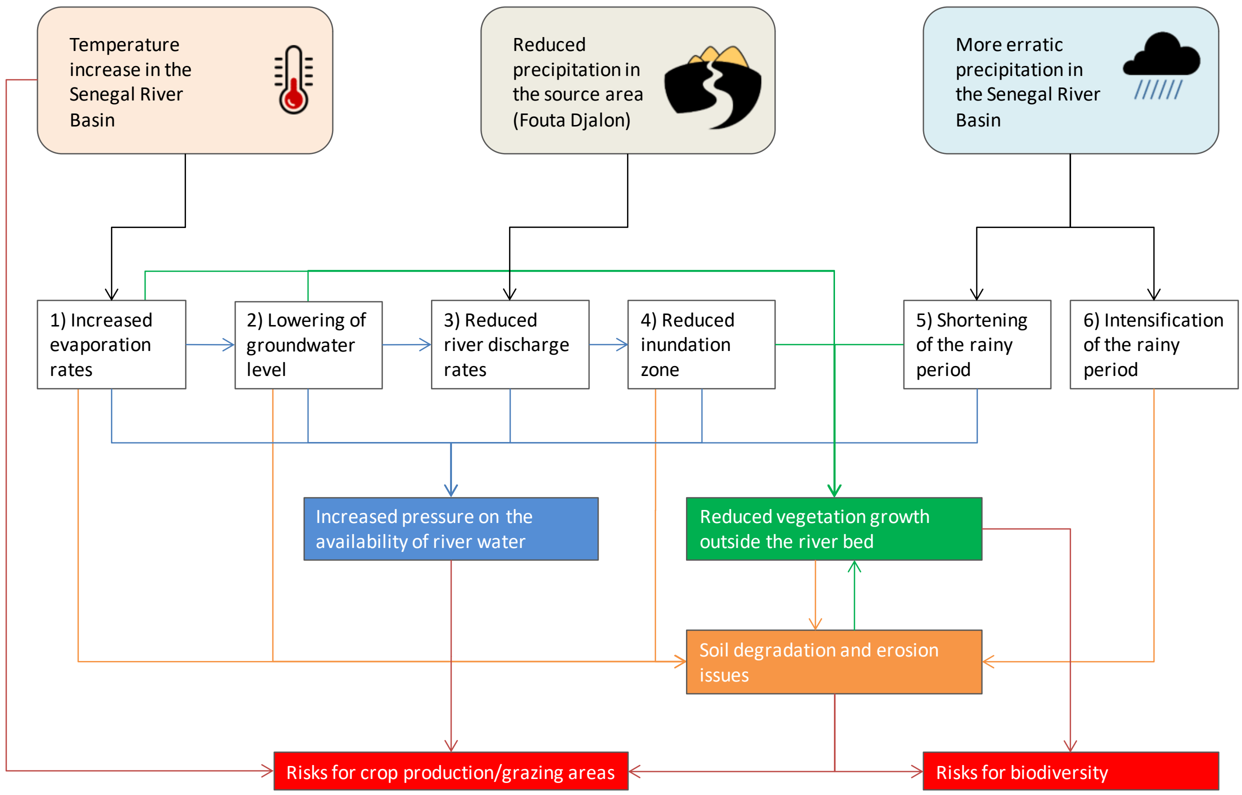


Figure 6.1 A flowchart, showing all climate-related factors and their interrelationships.

Increased temperatures in the Senegal basin will result in increased evaporation rates (#1 in Figure 6.1). Increased evaporation rates will have a local effect on the amount of standing water, but also on the groundwater level (#2). The groundwater level is generally expected to drop in the basin, especially in areas that are not directly connected to the river banks, which will have numerous consequences. First, a lowering in groundwater levels will have a direct effect on water availability via groundwater extraction, but also on the discharge rates of the river (#3). These local climate effects, in combination with the reduced rainfall in the source area (Fouta Djalon), will result in reduced water availability for temporary zonal flooding (#4), which will have major impacts on ecosystem services in the river basin.

Furthermore, the precipitation pattern is likely to change. There is no absolute certainty in what way these changes will work. There will likely be more variation, both with regard to the duration of the rainy period and the intensity of rain events. The rainy period is expected to be shorter (#5), which will result in a longer dry season. In addition, rain events are expected to be more intense (#6), resulting in erosion of river banks, an increased risk of damage to agricultural fields and soil degradation.

All these developments will irrevocably lead to more pressure on the river's water resources (blue arrows in Figure 6.1). Immediately along the river there will still be enough water available, but the need will become particularly great in remote areas within the basin, not connected to the river bed. Additionally, increased evaporation, lowering of the groundwater, and shortening of the rainy period, will seriously hamper vegetation growth, including the survival of trees and the production of rice and other crops. This may ultimately lead to soil degradation. Soil degradation will, in turn, lead to a further decrease in vegetation. These developments form a vicious circle, which poses a danger not only to the possibilities for livestock raising and crop recession cultures, but also to a great extent for biodiversity. Other factors that will exacerbate soil degradation and erosion are the intensification of rain events, reduced inundation, increased evaporation and lowered groundwater levels (orange arrows in Figure 6.1).

The key role of water in the Senegal river basin makes that changes in water availability through climate change affects all aspects of the rural live in the basin, but also will have carry-over effects on the regional and national economy (Fig. 6.2).

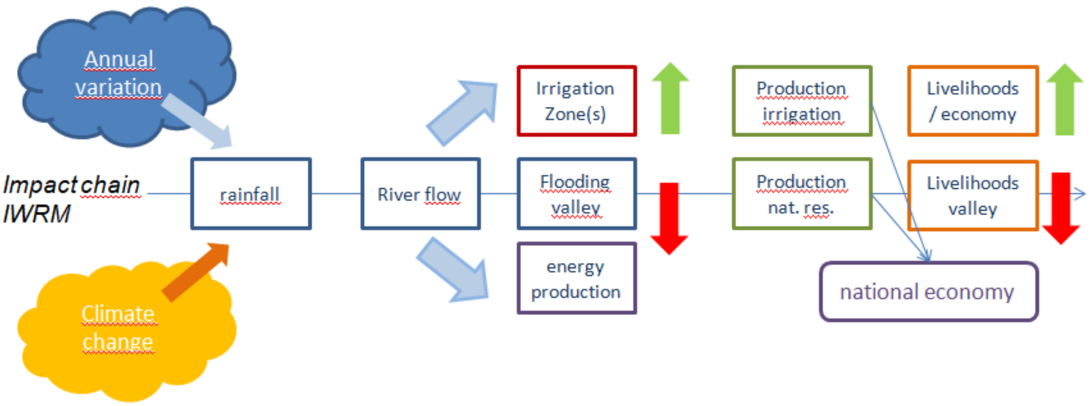


Figure 6.2. Summary of the impact chain of climate change in a Sahelian river basin. The variable rainfall determines the river flow, and the river flow determines the availability of water in the lower and middle valley and the delta. It also determines the opportunities for irrigation, flooding and energy production, which has direct and indirect effects on the production of natural resources, agriculture and ultimately on the (national and regional) economy and livelihoods of the rural communities.

6.2 The impact on the hydrological system

The main tributaries of the Senegal river proper find their source in the highlands of Guinea, in particular in the Fouta Djalon mountains (Fig. 1.1). From the assessment in Chapter 3 it is obvious that climate will change in the future in the region of the Senegal River Basin, and is already changing. The expectation is, that without drastic global climate mitigation (scenario RCP 4.5) precipitation will decrease in the source area of the Senegal river. This is especially the case in the catchment of the Falèmé tributary and to a lesser extent the Bafing. The amount of decrease is not clear and, giving the high level of uncertainty, can only be given as a direction of change.

Impact on discharge and inundation

The amount of annual rainfall is relatively high in this part of the basin, about 900-1300 mm annually (Fig. 2.3). The projected decrease of annual rainfall seems rather low (>30 mm, about 3%). It has to be stressed, however, that firstly it concerns a huge area, and secondly the projections have a high level of uncertainty. Thirdly, next to a predicted decline of annual rainfall, the temperature will rise, causing much more evaporation and related effects. At last, and maybe most important, the annual rainfall shows a large variation. In wet years the impact may be very low, but in particular in dry years the impact of a lower rainfall may be felt.

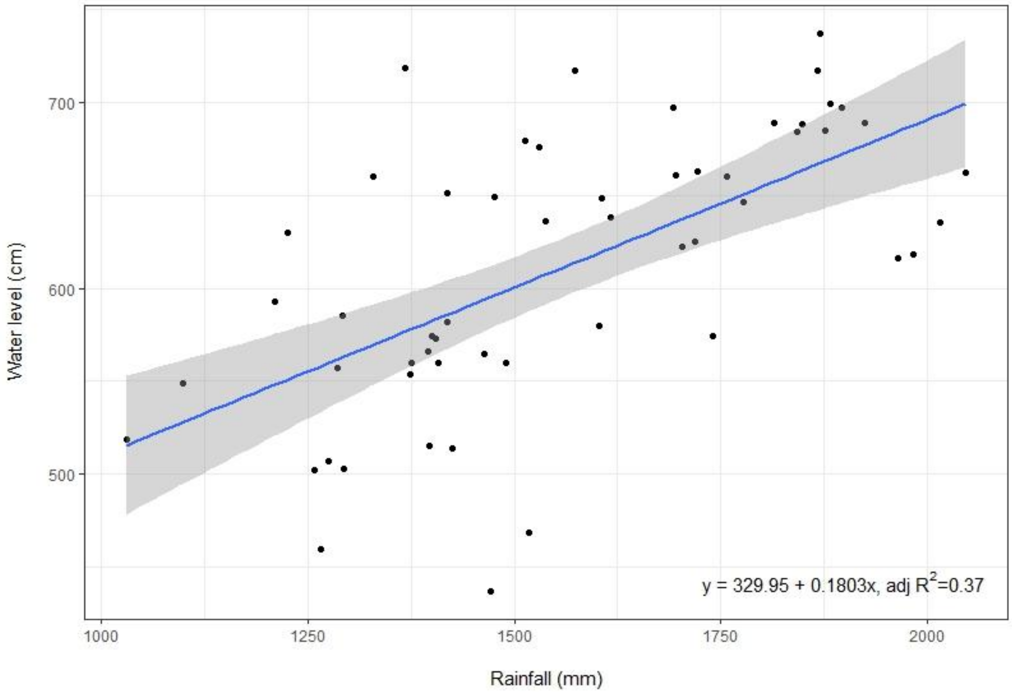


Figure 6.3. Example of the relation between total annual rainfall and maximum discharge at Kankan (Milo River, tributary of the Niger in the Guinean highlands) between 1938–1995. The grey shaded area shows the 95% confidence interval around the values predicted by the regression equation. From Klop et al. (2019).

A decrease in precipitation is expected to result in a decrease in discharge. In Sahelian river systems which rise in Guinean highlands, there is a clear relationship between rainfall in the catchment area and discharge of the relevant river system (example in Fig. 6.3). We may expect that comparable relationships are to be detected for the Falèmé and Bafing rivers. Given the strong relationship between discharge and inundation in the middle valley (Chapter 4), the inundation area in the middle valley is also expected to reduce in the future.

To quantify the hydrological impact of the expected climate change on the discharge, a hydro-dynamic model is needed which allows to model the impact of climate change in the source areas. Such an approach is tested in the Upper Niger Basin for the Upper Niger in Guinea and Mali (Liersch et al. 2018). Although also this type of modeling is highly depending on the quality of data, it is possible to forecast quantitatively the future impact of a changing temperature and rainfall pattern on discharge patterns. Using the results presented in Chapter 4, these predications can be used for a predication of spatial inundation.

Sensitive areas

From the analysis in Chapter 3 it is clear that rainfall will be erratic and there will be an even stronger annual variation than currently. From that respect we can argue, that the areas in the basin with modest rainfall, i.e. the areas north of Bakel (Fig. 2.3), will be more sensitive to climate change than the areas south of Bakel. This is especially the case for the regions in southeast Mauritania (Gorgol, Guidimakha, Assaba and Hodh el Gharbi) and the east part of the basin in Northwest Mali (region of Kaye), where temperature rise is predicted as the most severe (Fig. 3.4).

Also in the source area of the Falèmé a lower precipitation is predicted in the long run. This is a sensitive area where currently the rainfall is around 900-1300 mm. In these southern parts of the basin, with a relatively high rainfall, tree covers declines when rainfall drops below 800 mm/year. This may lead to landscape degradation and increased erosion. So, also parts of the of the source areas in Guinea and adjacent parts in Mali and Senegal are sensitive to climate change.

Shallow lakes and wetlands that are connected to the Senegal river, such as Lac R'kiz in Mauritania, are also vulnerable to climate change (Klop et al. 2016). In these areas, rain fed agriculture is not feasible anymore with increasing evaporation rates as a result of increased temperatures in combination with more erratic rainfall. In combination with limited water supply to these areas, water quality is likely to be reduced due to increased stagnancy, and in years with low rainfall these water bodies may largely dry out. These changes contribute to the degradation of freshwater wetlands, to be reflected in loss of natural resources for surrounding communities, severe biodiversity loss, colonization of invasive species and salinization. These systems will be even stronger dependent on high water levels for water supply by the river.

Summarising

- Climate change, in particular a decrease in rainfall in the sources areas and changes in rainfall patterns, will most probably lead to decrease in discharge and flooding in the middle valley of the Senegal River. To quantify this impact, a hydro-dynamic model is needed, in which current and future climate scenario's and water management options are integrated.
- Areas with modest rainfall, i.e. the areas in the northern half of the basin, will be more sensitive to climate change than the areas in the south. This is especially the case for the regions in southeast Mauritania (Gorgol, Guidimakha, Assaba and Hodh el Gharbi) and the east part of the basin in Northwest Mali (region of Kaye), where temperature rise is predicted as the most severe.
- The source area of the Falèmé river in particular can be considered as sensitive with respect to landscape degradation and increased erosion as a result of a projected decrease in rainfall.
- Shallow lakes and wetlands that are connected to the Senegal river, such as Lac R'kiz in Mauritania, are also vulnerable to climate change. These systems will be even stronger dependent on high water levels for water supply by the river.

6.3 The impact on food security : agriculture

Climate change will have a strong impact on several ways on food security, in general through increased pressure on natural resources. Food security is depending on the production through agriculture, livestock, fisheries and a range of ecosystem services. In this Section we elaborate on agriculture; in the next Sections livestock and general ecosystem services will be dealt with.

Surface area and quality of soils for agriculture

In the arid environments in the Middle Valley of the Senegal River, the supply of river water is and has always been the single most important factor that enables agriculture and other sources of food production. In the past this concerned mainly traditional flood recession cultures, and since the construction of dams the development of irrigated agriculture. This concerns large scale irrigation polders in the delta and smaller scaled irrigation in the middle valley (PIV's: périmètres irrigués villageois).

Flood recession cultures
Traditional flood recession crops strongly depend on the extent of the annual flood (Mané & Fraval, 2001). Traditionally, parts of the floodplain in the valley that were inundated for at least 45 days could be cultivated without any other activity than just planting seeds while the water receded. Fertility of the soil was provided by river deposits and by dung from animals that grazed on these floodplains during the dry season. Especially for the rural poor communities, this feasible way of agriculture was, and still is lucrative. Mainly sorghum and a variety of vegetables is being cultivated in these low-lying river beds (‘*cuvettes*’) that are flooded by the river in winter: beans, onions, tomatoes, cabbage, aubergine, chili pepper, okra, carrots and sweet potatoes.

Irrigated agriculture
Currently, water availability and the possibilities for land use in the Senegal River are not solely dependent on precipitation-induced river dynamics, but are additionally strongly influenced by water and dam management (Chapter 4; e.g. Horowitz & Salem-Murdock 1993; DeGeorges & Reilly 2006; Dumas et al. 2010). The water management facilitates year-round availability of water for irrigated agriculture, which at many locations in the basin has lead to a shift from traditional flood-recession agriculture to intensive, irrigated and permanent production of mainly rice in the basin (Dumas et al., 2010). Irrigation schemes developed rapidly in the Valley, especially on the Senegalese side, increasing from 20 ha of irrigated land in 1974 to 13.000 ha in 1986 and 18.000 ha in 1988 (DeGeorges, 2006). Consequently, a strong increase in rice production yields was achieved of 4.8 T/ha in 1990 and 5.7 T/ha in 2003 in the river basin (Gueye, 2004). From that moment rice farming through irrigation is by far the most important agricultural activity in the Senegal River Basin (OMVS, 2011).

Impact of reduced flooding on surface area and quality
Irrigated agriculture does not depend on flooding. As long as the river holds water, water supply through motor pumping is sufficient to sustain irrigation. Costs for fuel may be substantial, however.

Flood recession cultures ('cultures de décrues') do strongly depend on flooding. Changes in river discharge rates and a reduced flooding will have major consequences for the surface area for flood recession and crop yields. Secondly, the sediments (clays and silts) that are deposited during annual flooding provide fertility for agriculture, including crop recession cultures (DeGeorges & Reilly, 2006). A decrease in inundation will therefore also result in nutrient-poor soils. This means, that the existence of flood recession cultures in the middle valley strongly depends on dam management in the future.

Shortening and change in timing of the rainy season
In general, the expectation is that through climate change the rainy season will be shorter (Fig. 6.1), which means that also the growing season will be shorter. Also the wet season in West Africa and the Sahel will show more variation in rainfall intensities and the wet season may be delayed with 5-10 days (Dunning et al. 2018). Both effects will have a large impact on the timing and potential for agriculture, both irrigated cultures and flood recession cultures. In particular flood recession crops may be lost, either because of a bad timing of sowing because the dry season starts too early, or because plantations are destroyed by floods.

A higher temperature and decreasing crop yields
There is a large direct negative impact of the temperature increase on agricultural yields, in addition to the six hydrological factors indicated in Figure 6.1. High temperatures lead to increased potential evapotranspiration, crop maintenance respiration and a reduction of the

crop-cycle length. This decrease in yield of for instance sorghum or millet is irrespective of whether rainfall increases or decreases (Sultan et al., 2013), suggesting a primary role of temperature increase as the driver of yield change.

Also rice productivity is expected to be negatively affected by climate change if farmers continue using the current varieties. Without adaptation, shortening of the growing period due to higher temperatures will have a significant negative impact on yields. In irrigated rice fields in West Africa the yield may even decrease by -45% in the dry season (Van Oort & Zwart, 2017), which is considered to be mainly caused by reduced photosynthesis at extremely high temperatures (Fig. 6.4).

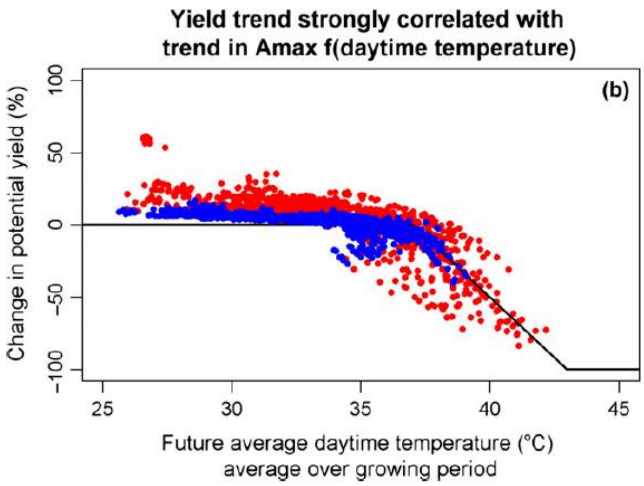


Figure 6.4. Simulated change in potential rice crop yields in irrigated sites for RCP scenarios 2.6 (blue) and 8.5 (red), in which yield is plotted as a function of average daytime temperature (AMAX). AMAX is optimal from 20 to 37°C. Each dot represents a simulation for a site (53 irrigated sites Africa) in a specific season (main season or off season) and year (1998–2002). Source and figure from Van Oort & Zwarts (2017).

Another expected future problem is the fact that insect activity in agricultural regions will rise along with mean surface temperature (Deutsch et al., 2018). This insect activity may seriously boost losses of rice, sorghum and millet for two reasons. First, higher temperatures increase insect metabolic rates exponentially. Second, warmer temperatures will increase the reproductive rates of insects. This way, climate change impacts on pest infestations are expected to aggravate the problems of food insecurity in the valley, causing food prices to rise and food-insecure families to suffer. Increased pesticide applications and agronomic practices such as crop rotations may help to control these losses from insects.

Summarising

- A climate induced decrease of flooding will have major consequences for the surface area for flood recession and crop yields. Future existence of flood recession cultures in the Middle Valley highly depend on dam management in the future.
- A decrease in inundation will also result in nutrient-poor soils through lack of nutrient supply through flooding.
- Shortening of the rainy season and a change in timing will have a large impact on the timing, potential and crop yields of both irrigated cultures and flood recession cultures.
- A higher temperature will have, irrespective of rainfall and flooding, a significant negative impact on yields.
- Also through higher temperatures, the vulnerability for pests will increase, potentially also affecting yields.

6.4 The impact on food security : livestock

Particularly in the northern part of the basin the river bed provides grazing opportunities for cattle (Klop et al., 2016, Zwarts et al. 2009, Zwarts et al. 2018, GRDR 2014). The growing cycle of annual grasses in the Sahel is short. However, local rainfall is very important for grazing. High-quality forage is only limited to the actual growing season plus a short period following the end of the rains (Senock & Pieper, 1990). Flooded pastures near the river are essential for local pastoralists, to herd their cattle in the dry season. Along the Senegal river, and throughout the Sahel, nomadic pastoralists disperse with their livestock away from the basin during the rainy season, and return to the floodplains in the dry season. In years with reduced rainfall, the floodplains are virtually the only refuge, allowing the animals to survive until the next periods of rain (DeGeorges & Reilly, 2006). As shown in Fig. 6.5 pastoralist use a huge area as grazing grounds, but are linked to other parts of the basin through a network of markets and routes (GRDR 2014).

The Ferlo in northern Senegal and the areas north of the river in Mauritania are very important for pastoralists. Over time, grazing intensity increased tremendously here, leading to overexploitation and landscape changes (Zwarts et al. 2018). The construction of a network of large boreholes, producing 10–30m3 of water per hour, permitted year-round cattle grazing in the Ferlo after the mid-1950s (Ancey et al., 2008). It was the overture of a steep increase of cattle, from 1 per km2 in 1950 to 4 and 12 per km2 in 1955 and 1970, respectively. Within the last 60 years, cattle numbers in the Ferlo must have likely increased 12–15 times, goats and sheep even about 50 times. At first, pastoralists in the Ferlo herded their livestock in the vicinity of watering points, but this routine changed after the 1980s when people brought water to their livestock (rather than vice versa), using large rubber inner tubes and 1000 l containers (see Zwarts et al. 2018, and sources mentioned in this publication).

Figure 6.5. Important grazing grounds for livestock in the Middle valley, marches and principal movements of cattle. Source GRDR 2014.

Impact of climate change on livestock raising

The expectation that the rainy season will be shorter as well as the growing season will have a severe impact on livestock, in particular the pastoralists which exploit the natural resources – annual grass growth – in the northern part of the basin. In combination with the rise in temperature, the expected changes will lead to excessive loss of grazing grounds, in particular in the northern part of the basin. Also the production of natural vegetation will be lower, due to changes in the timing of rainfall, more erratic rainfall and a higher temperature. Also the erratic rainfall and the variation in rainfall may result in a higher frequency of dry years (longer and dryer seasons). This may put the resources for livestock under a high stress, like during the Great droughts in the 1970s and 1980s.

The exploitation of grazing grounds which depend on bore holes may be more difficult when groundwater levels are dropping because of reduced flooding. This will certainly lead to a higher pressure on the grazing grounds in the middle valley.

Besides pastoralism, livestock production around the villages is sedentary. Sedentary livestock consists mostly of goats, sheep and cattle. During dry years the forage availability may become limited and villagers need to buy supplemental feed for their animals.

Summarising

- In combination with a rise in temperature, the expected changes in rainfall patterns will lead to excessive degradation of grazing grounds, in particular in the northern part of the basin. As a result, the production of grazing grounds will be lower, due to changes in the timing of rainfall, more erratic rainfall and a higher temperature.
- The exploitation of grazing grounds which depend on bore holes may be more difficult when groundwater levels are dropping because of less flooding. This will certainly lead to a higher pressure on the grazing grounds in the middle valley.
- Sedentary livestock raising in the middle valley will also be confronted with climate change. This is due to a decreased flooding (less potential grazing grounds), a shorter growing season, less production and more competition with pastoralist from other areas coming to the middle valley.

6.5 Impact on ecosystem services

The seasonal variation in flood dynamics is an essential ecosystem function to maintain or generate ecosystem services (Klop et al., 2016). In the absence of these natural flood dynamics after the construction of the dams ('*après-barrages*'), many of the regulating ecosystem services decreased with negative developments in the ecosystem. In some cases, climate change may further exacerbate these negative developments in the future.

Impact on regulating services

The middle valley offers a number of important regulating services, of which flood control and water retention are the most important.

Flood control

Flood control is extremely important in periods with excessive discharge and rainfall, leading to nearly full flooding of the middle valley, but putting off the flood pressure on the delta, the Diama dam and the areas around Saint Louis. In the years 1999, 2003, 2007 and 2012 there was a high discharge. The middle valley served as an extremely important buffer for the flooding (Fig. 4.11), although it could not be prevented that parts of St Louis flooded in 2003 (year of the opening of the brèche).

Climate change will in principal not change the potential of the middle valley for flood control, but it is of utmost importance to emphasize the importance of that function. Since in the future the variation in rainfall, and thus flooding, may grow, there may be flooding seasons when flood control in the middle valley is essential. In that respect, it is important not to reduce the floodable low-lying areas through embankment or urbanisation. This prevents damage in years with a high flood.

Water retention

Next to flood control also water retention is very important as an ecosystem service. Flooding of the middle valley offers the opportunity for water retention in water bodies and depressions. This will have a positive influence in terms of direct local water availability (to local communities, livestock, biodiversity), but also for the recharge of ground water reservoirs. Climate change may impact flooding, and successively also water retention, if no measures are taken.

Impact on provisioning services

Provisioning services include the provision of nutrient-rich soils for agriculture and grazing (Section 6.3 and 6.4), and additionally possibilities for fisheries and other provisioning services (see below). In particular the services which are linked to water may be influences by climate change.

Fisheries

Seasonal inundation of the floodplains during the wet season provides large-scale breeding habitat for numerous fish species, and is considered crucial from both the perspective of fishery production and biodiversity. Harvests from traditional small-scale fishing from the water bodies in the river basin was and partly still is an important food resource for local communities. Since the construction of the Diama dam and the Manantali dam fish populations and harvests from traditional small-scale fishing have been reduced (Mietton et al., 2007). As a consequence, fishing as a livelihood is more often combined with other sources of food and income in the past decades (Klop et al. 2016).

Fish production – and thus potential harvest - is related to the size of the inundation areas. This means, that a decrease in flooding and duration of flooding in case of a lower discharge through climate change, will affect the biodiversity and fish production in the middle valley. Fish biodiversity may also be affected through higher temperatures, when water quality is at stake.

Provisioning services linked to trees and flood forests

The flood forest stands in the river bed, in particular *Acacia nilotica*, constitute only a fraction of the large flood forest area that was present in the past (CILSS 2016, Tappan *et al*. 2004). In the past, flood forests were abundant in the Middle Valley. Although flood forest with a closed canopy only cover a small fraction of the areas, still large stands of forest patches and low densities of trees are present (part of the type ‘open areas with vegetation’). These forests offer valuable provisioning services amongst which are fruits, medicaments, charcoal, timber, and biodiversity. In addition, the forests function as spawning areas for fish when flooded, and local people put beehives in the trees to harvest honey.

Figure 6.6. Pictures from the middle valley near Podor, with patches of flood forests of Acacia nilotica. These patches provide a range of ecosystem services (grazing, fishing, fruits, honey, medicines) to local communities and are very important for biodiversity. At the same time, they are sometimes overexploited for charcoal production. Pictures were taken in February 2018.

Biodiversity in the floodplains

The biodiversity value of the Sahelian wetlands, including forests, birds and other wildlife, is outstanding on an international level (Zwarts et al. 2009). The seasonal flooding of the middle valley is of utmost important to a range of wetland species, local species and birds species which migrate to northern areas (Europe, Asia) to breed or to areas in Africa during the dry season. The trees in the flood forests host highly important biodiversity on an international level. Extensive *Acacia nilotica* flood forests have become rare in Western Africa (Zwarts et al., 2009; Zwarts et al., 2015). These forests harbor a wide variety of species, among which particularly bird species.

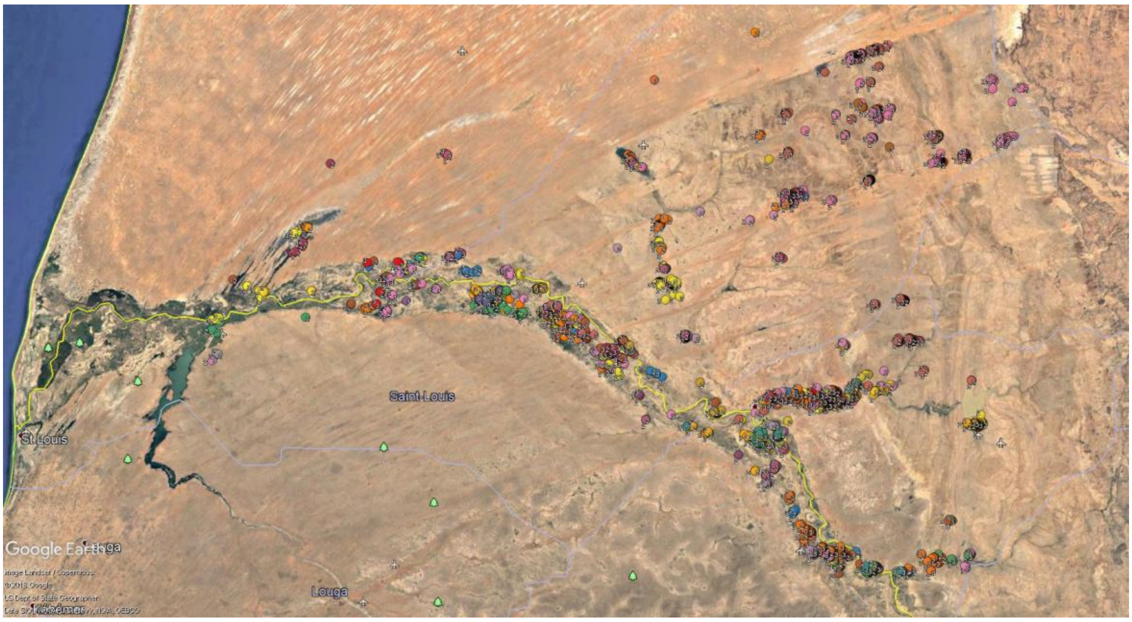
Rainfall and flooding are the 'life-giving instruments' of the Sahelian ecosystem: abundant rainfall brings lush vegetation, promotes the leafing, fruiting, seeding and flowering of trees, shrubs and grasses, and leaves behind temporary pools that will hold water well into the dry season. The diversity of insects is correlated with the biomass of grasses and leaves, whereas temporary pools are important as refuges for insects and as vital egg-laying sites for phytophagous insects (Zwarts et al., 2009). For migratory birds, conditions on the African wintering grounds determine survival rates. Factors such as pre-migratory fattening, departure dates and migration timing are affected by these conditions. Adverse conditions may have a negative impact on breeding performance (Zwarts et al., 2009). When evaporation increases in the Senegal basin, flooding decreases and the availability of river water decreases, the conditions for migratory birds also deteriorate.

BOX 3. The natural link between Senegal river valley and The Netherlands

In spring and autumn a few billion birds are migrating from their African winter quarters to their northern breeding areas and vice versa. The Netherlands is situated on the crossroad of migratory flyways and hosts millions of birds in spring and autumn, when they take a rest and forage in coastal or inland wetlands, pastures and forests. Also, many species breeding in The Netherlands are finding home in Africa, in particular the Sahel, to spend the non breeding season.

Senegal and Mauritania are part of the western Sahel. Parallel to The Netherlands, these countries are of paramount importance for migratory birds in the East Atlantic flyway. The combination of coastal and inland wetlands with other important natural inland habitats likes wooded savannas provide foraging and resting habitats for many species of migratory birds. Especially in the Senegal Delta – Djoudj NP, Diawling NP - and the Senegal Valley many of these habitats and ecosystems are found. The migratory birds – ducks, waders and many species of land birds – literally and figuratively make the link between the Senegal valley and the Netherlands.

As an example we show in this box the distribution of the Black-tailed Godwit, the national species of The Netherlands. Recently a number of Godwits were equipped with a transmitter, showing their daily whereabouts in high detail. On the map below, all locations are plotted where Godwits were registered in the Senegal Valey and southern Mauritania. Godwits, which are bound to shallow water levels where they forage on small benthic animals, are using the entire Senegal Valley between Podor and Matam. It shows the ecological importance of the region in an international context. Many other species breeding or passing through the Netherlands are showing the same link with the Senegal Valley and Senegal Delta.



Locations of Godwits with a transmitter between 2014-2018 in the Senegal valley (Note that the Senegal Delta – also very important – is not shown on this map). With courtesy of Ruth Howinson, Joslyn Hooijmeijer and Theunis Piersma, Groningen Institute for Evolutionary Life Sciences, University of Groningen. See also https://volg.keningfanegreide.nl/king-of-the-meadows-transmittersite/

The Sahelian ecosystems are already affected by climate change, and future climatic impacts are expected to be substantial, beyond the effects of land-use change and other factors non-climatic stress. Rising temperatures and rainfall variations in the region have already had significant impacts in the West-African Sahel-region, including increasing tree mortality or dieback, with declines in tree density and species richness recorded in the last half of the 20th century (Gonzalez et al., 2012). In addition, the decline of forest land cover, and hence biodiversity, in the past decades is induced by non-climate stressors such as clearing of forest for land cultivation and grazing, mining activities, high demands for biomass and timber and lack of forest resource management (USAID, 2018). Climate change is likely to indirectly aggravate these non-climate stressors affecting forests.

Summarising

- Flood control is an important regulating service of the middle valley on a basin-level. The expected more erratic rainfall and more variation in rainfall in the future make it very important to maintain this regulating function.
- Water retention after flooding is essential for local water availability as well as for the recharge of ground water reservoirs. Climate change may impact flooding, and successively also water retention possibilities.
- Climate change is likely to affect provisioning services as fisheries (higher temperature, less flooding) and services provided by flood forests (less flooding, higher pressure on resources).
- The Sahelian ecosystems are already affected by climate change, and future climatic impacts are expected to have substantial effects on biodiversity, aside from the effects of land-use change/intensification and other non-climatic stress factors.

6.6 Growing potential competition and conflict

As previously stated by Artelia (2018), climate-related problems are very likely to exacerbate a situation of human pressure in the basin that is poorly controlled and has severe consequences to the environment. Rural communities will continue to exploit the available resources intensively, resulting in e.g. massive deforestation (charcoal), destabilization of rivers and connected water bodies, and a range of other water-related physical problems.

The forecasted climate change will put the natural resources in the arid environment north and south of the middle valley, in particular grazing grounds and forests, under high pressure. Zwarts et al. (2018) performed a detailed analysis of the trends in woody cover (coverage by trees and forests) in the terrestrial areas north and south of the western part of the middle valley (including the Ferlo). Between the 1960s and 2010s, woody cover across the entire region decreased substantially (Fig. 6.6), especially north of 16.75°N where the woody cover declined by 91%, but less so south of 15.75°N (minus 40%). The contrast is still larger for large trees (canopy width>10 m), declining by 98% north of 16.75°N and by only 12% south of 15.75°N. The savanna, densely scattered with large Acacia trees at 17°N in the 1960s, has changed in later years into an open landscape with few trees.

The enormous decline in woody cover as quantified in detail by Zwarts et al. (2018), is partly linked to the Great droughts but much more caused by overgrazing. In the context of this study, it shows that the buffer capacity to accommodate future climate changes of the arid areas on the left and right bank of the Senegal river are extremely limited. At the same time, these areas are most sensitive to temperature rise and erratic rainfall.

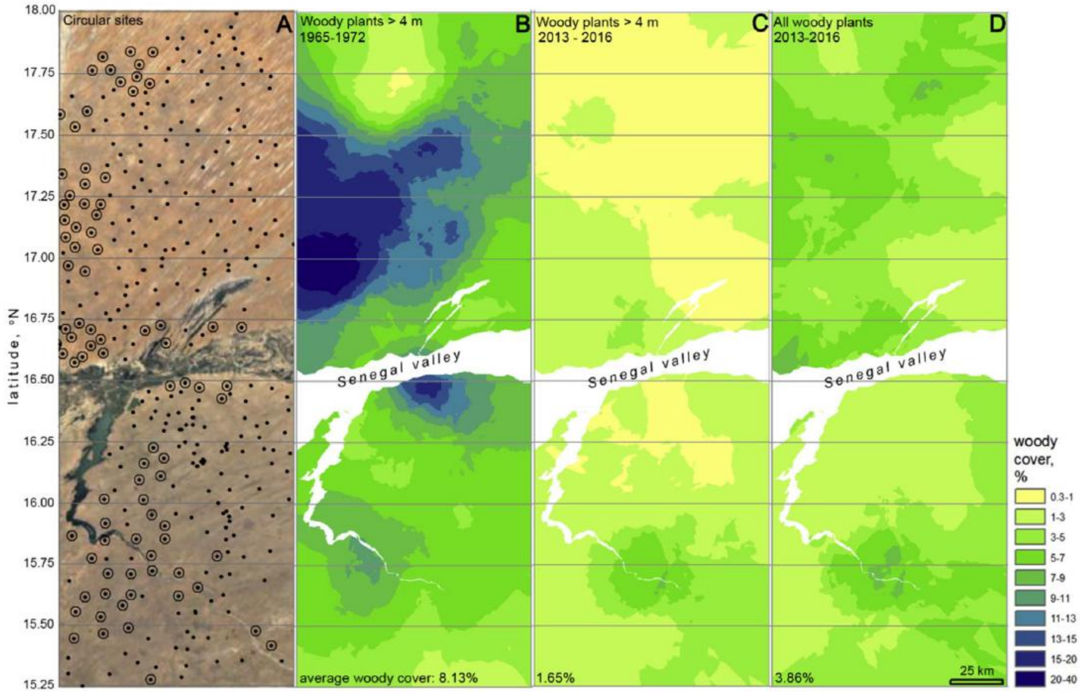


Fig. 6.7. An interpolated map of the woody cover between 15 and 16°W and 15.25 and 18°N, based on the 390 circular plots (black dots in panel A), using a kriging technique; the 87 plots surrounded by circles indicate plots where satellite images were available for 2013–2016 as well as for 2002–2004. Since the contribution of woody plants ≤4m is unknown for 1965–1972 (B), woody cover in 2013–2016 is given without (C) and with (D) small woody plants. Source and more information about methods and backgrounds: Zwarts et al. (2018).

The predicted climate change will worsen the situation in these arid areas, which means that grazing grounds are expected to be lost or at least not sustainably productive anymore (Section 6.4). The middle valley, where flooding feeds the grazing grounds, is an oasis in this respect. Therefore, climate change will inevitably lead to a higher pressure on the middle valley for grazing or other means for subsistence. This may raise land ownership issues, thereby increasing the risk in investing in irrigation infrastructure (Adhikari et al., 2015). The competition between space for irrigated agriculture, flood recession cultures and for grazing will grow, potentially leading to more conflicts.

Next to an increased pressure on the river valley, in the future pastoralists will be expected to move also more to the south where rainfall and thus grazing potential is higher. In general, the impacts of climate change are believed to have already increased the number of environmental refugees in the Sahel (Epule et al., 2015). The combination of climate change and poorly controlled human pressure may have disastrous consequences for the environment and impact on the socio-economic balance of states (Artelia 2018). Taking all this into account, the vulnerability of the ecosystem, the population and the biodiversity in the Senegal Middle Valley is very high.

Vulnerability of poor and remote local communities

Particularly the poor communities are highly dependent on the direct use of local natural resources. This strong reliance on climate sensitive activities, such as rainfed agriculture, together with limited capacity for adaptation, recurrent food crises and water scarcity, make these communities particularly vulnerable to future climate change effects. Providing support to the poorest farmers is critically important, given that this group is the most vulnerable to long-term climate change, and least-equipped to make the changes needed to sustain their livelihoods in the face of such a threat (Bryan et al., 2009). Poor communities in remote villages in particular have to deal with problems related to water-related diseases, since they do not have the facilities and means to prevent these problems. The impacts of rising temperatures and rainfall variations may include enhanced occurrence of malaria and diarrheal diseases (Costello et al., 2009; Watts et al., 2015).

7 Options for climate adaptation

7.1 Introduction

There are many measures for climate adaptation, differing in scale of both space and time. For example, important hydrological measures can be taken at the level of the river basin that affect the entire valley. Additionally, there are several relevant adaptation options at the regional and local level, by which a lot can be gained in particular for agriculture and animal husbandry.

Adaptation to climate change is relevant for several sectors, and has a high priority also in other initiatives and programs. In this context, it is important to mention the programme of the Great Green Wall (https://www.grandemurailleverte.org/). In the framework of the GGW, partly located in the Senegal valley, several actions are being researched and implemented. It is interesting to search for synergy with these programs This may empower the support amongst the local communities and stimulate concrete implementation of measures in the region.

This chapter provides an overview of the most important options for mitigating the negative future effects of climate change in the valley at different levels of scale.

7.2 Maintaining an artificial flood

The importance of flood dynamics
The future water availability in the Senegal River basin hinges on active water management of the river. Consequently, the operational management of the constructed dams is very important. Considerable annual fluctuations in rainfall, and consequently a highly dynamic river, have always been characteristic in the Sahel (LeBarbé et al., 2002; Zeng, 2003, Zwarts et al. 2009). The importance of artificial flooding is recognized within current management. However, over the past years, extensive floods are certainly not occurring every year and in most years the floods are only restricted to the areas directly connected to the river bed. There is a huge annual variation in the flooded surface area, as elucidated in Chapter 4. Flooding during the wet season and at least partially a dynamic water regime are necessary factors to guarantee both provisioning and regulating services of the river as well as possible in the future. Given the rise in temperature, and hence increased evaporation rates, (re)introduction of large-scale annual flooding may offer a solution for the most arid and vulnerable areas that are not directly connected to the river bed.

Annual flooding is crucial to keep groundwater levels high. A dry year, without significant flooding, can lead to a serious lowering of groundwater levels. In the following years, drought-related problems are likely to occur, since it takes a long time before the groundwater level is restored. This aftermath-effect was a rather determining factor during 'La Grande Sécheresse' in the eighties.

An artificial flood regime would be highly beneficial to the flood-recession cultures in the most arid parts of the valley. Before the construction of the dams an average area of 459.000 ha was flooded every year on both sides of the bank (DeGeorges & Reilly, 2006), of which between 15,000 and 150,000 ha could be used for flood recession crops (National Research Council, 2003). We can conclude that in recent years (since '99) there have been less frequent and, moreover, less extensive flooding in the potential recession crop areas in the valley than in the years before the mid-1970’s. This development is caused partly by climatic changes, and partly by anthropogenic influences such as dam management.

Annual flooding is not only important for agriculture in terms of direct water availability, but also for river deposits. The sediments (clays and silts) that are deposited during annual flooding provide a good foundation for agriculture, including crop recession cultures (DeGeorges & Reilly, 2006). These clays and silts provide fertility. Without these river deposits, the sand subsoil would not be suitable for agriculture. In addition, improved soil fertility is highly beneficial for grazing grounds, hence livestock farming. During field visits, the importance of nutrient-rich sediment supply by the river has repeatedly been indicated by local farmers in the flood plains.

Biodiversity in the flood forests is also promoted by introducing an artificial flood regime. Restriction of natural river dynamics and consequently loss of floodplains, continues to cause serious degradation of habitats and biodiversity including migratory birds and the development of trees. The expected hydrological impacts as described in paragraph 5.1 will only exacerbate these water-related problems for biodiversity.

Practical implementation of artificial flooding
Artificial flooding would seem to be at least a partial solution for the climate related problems faced in the future. It is important that artificial floods, generated via releases at Manantali, mimic natural patterns and show a high degree of regularity. Farmers can easily anticipate on these artificial floods when the floods are regularly released and the water management is being communicated, while irregular floods and poor communication may lead to catastrophes (Adams, 2000).

The Manantali dam is currently presumed to be holding as much water as possible at the end of the summer. As precipitation rates will decrease in the Fouta Djalon in Guinea, as predicted, the dams will become less lucrative and it will become (even) more difficult to achieve flood support. The consideration between an increasing demand for hydro-electric power on the one hand, and the agricultural and ecological benefits of flooding on the other hand, will become even more important in the future (e.g. DeGeorges & Reilly 2006).

In the SDAGE, several large dam projects are presented in addition to the Manantali dam in the upper basin of the Senegal river, including the creation of large reservoirs on the Falèmé (Gourbassy) and the Bakoye (Badoumbe). With these additional dams, it would become possible to completely regulate the flow of the Senegal river downstream. Furthermore, the SDAGE promotes ecologically responsible water management and reaffirms its commitment to provide flood support. Therefore, we strongly suggested to focus on artificial flood support, without compromising too much on energy production and investments.

An important question is: which river water levels are needed for extensive inundation, in order to guarantee high groundwater levels, suitable circumstances for crop recession cultures, and safeguarding of biodiversity? Although half of the surface of the middle valley is potentially interesting for water-related incomes and ecosystem services (Chapter 5), inundation is generally restricted to a relatively small zone directly connected to the river bed. As elucidated in Chapter 4, water levels of 3.5-4 m lead to inundation of an area of 40-50% of the potential surface for food security in the middle valley. Allowing water levels of at least 3.5 meters, preferably even higher, in the annual wet period would be very favorable from the point of view of climate adaptation in the dry parts of the middle valley.

Summarising

1. Annual flooding during the wet season is necessary to guarantee both provisioning and regulating services of the river, particularly for the most arid and vulnerable areas that are not directly connected to the river bed;
2. Annual flooding is crucial to keep groundwater levels high, and to prevent drought-related problems in the long term;
3. For flood-recession cultures, grazing grounds and biodiversity, an artificial flood regime would be highly beneficial. Not only because of the direct availability of water, but also because of the nutrient-rich sediments that the river supplies;
4. Allowing water levels of at least 3.5 meters, preferably slightly higher, in the annual wet period would be very favorable from the point of view of climate adaptation in the most arid parts of the middle valley.

7.3 Developing and testing drought resistant crops

Drought stress and crop yields

Increasing temperatures will threaten crop yields and transformational changes are needed (Ramirez-Villegas & Thornton, 2015). Most studies on the impact of climate change in West-Africa on agricultural production yields show negative impacts (Roudier et al., 2011). A temperature rise reduces the crop cycle duration and creates higher water stress through higher evaporation demand, resulting in a reduced crop yield. Climate-induced rainfall changes have the potential to either aggravate or to mitigate this impact (Roudier et al., 2011), but the overall effect of temperature rise on crop yield is generally considered negative. Possible strategies to counteract these adverse effects on crop yields could be to breed more resilient crop varieties, or to adopt existing varieties more resistant to climate-induced drought stress.

Sultan et al. (2013) show, for instance, that the effect of climate change is not identical for all major grown cultivars of millet and sorghum. Modern cultivars with a high biological yield potential, but a short growth cycle are expected to lead to greater crop yield losses as a result of climate change. Lower yield variability and a higher resistance to drought are advantages of traditional cultivars over modern cultivars. During our field missions in the Middle Valley, we obtained relevant information from local communities, showing the importance of identifying local crop characteristics. For instance, millet is known for its ability to grow under very dry conditions on fairly dried-out soils with a high sand-content. Thus, in future scenarios with less frequent inundation, hence less loamy sedimentation by the river, and higher evaporation rates, traditional cultivation of drought-resistant millet may offer considerable advantages over relatively modern, water-demanding cultivars such as corn. This is an example, showing that identifying such specific local crop characteristics is a key to developing a strategy that addresses the trade-off between intensification and resilience to climate change (Dingkuhn et al., 2006).

Also rice productivity is expected to be negatively affected by climate change a future temperature rise in the basin. If farmers adopt rice varieties that have a high temperature sum, which means that they are adapted to shortening of the growing duration induced by temperature increases, current yields can be guaranteed in the future. With this adaptation rainfed rice yields may even increase slightly (Van Oort & Zwart, 2017). In addition, changes in the agricultural calendar should be considered. The timing of planting/sowing will shift in the future, according to the shortening of the rainy season. This requires further experimental research.

Development of experimental test farms – concept of FACI
It is important that research programs are initiated and coordinated at regional/national level. Pilots must be carried out at experimental test farms. This is important at the level of the entire basin. It is not only about rice cultivation, but also about other varieties and crops. These test farms do not have to be successful immediately and it is not necessary to obtain results in the short term, as it is possible that years of research may be needed. Therefore, a multi-year research program must be formulated, taking into account all aspects of changes in cultivation in remote arid locations in the valley. After all, in addition to specific crop characteristics, technical considerations play a role, and it will take a while for people to get used to applying alternative crops.

The approach mentioned above is already developed and tested in practice as part of the Great Green Wall (GMV). The concept of FACI is also interesting to test climate change mitigation measures at community level, including local adaptation (crops, agricultural calendar, agroforestry etc). On the GMV website, the concept of Integrated Agricultural Farms (FACI) is explained (www.grandmuraillevert.org, PanAfrican Agency of the Great Green Wall):

The participatory approach in the GMV reinforces the central position of the terroirs in the model of development and local governance of the process of transformation of the Sahel by domino effect, iterative and integrative. The process starts from the emergence of Integrated Agricultural Community Farms (FACI), whose development, multiplication and dissemination generate Integrated Community Agricultural Domains (DACI) within the community or inter-community scope. FACI and ICAD strengthen agricultural production and processing capacity and stable income generation. In the short term, they favor the intervention of the private sector and the creation of Agropole Ruraux (AgropoR). The main challenge is the definition of a dynamic process of sustainable management, favoring the restoration and protection of natural capital, the identification and enhancement of local development opportunities (OLD) and the optimization of their value chains. The land development model is being redesigned to be more inclusive and participatory and in an economic approach.

7.4 Stimulate agroforestry

The importance of agroforestry
Agroforestry concerns land use systems where planting and/or active management of trees is combined with agriculture or animal husbandry. In agro forestry systems there is a complex collaboration between light, nutrients and water with an effect on the multi-layer production system. A common system is shifting cultivation, in which agricultural fields are planted with food crops for 2-3 years, followed by a period with trees in which the soil can recover, after which the cycle can repeat itself while the fallow vegetation supplies forest products and functions. There are many advantages for flood forests in particular. It is very important that these flood forests are preserved in the middle valley when the temperature rises. Agroforestry can offer great benefits for grazing, for fish (in the case of inundation), and for agriculture (shadow effect is important). Also, the forests are very important for biodiversity, such as elucidated in Chapter 5. Finally, agroforestry offers a source to capture more CO_2 from the atmosphere, which is important in the context of combatting further climate change.

Development of agroforestry test locations
Agroforestry is considered a well-adapted form of agriculture for particularly small farmers who have little access to modern agricultural resources. Specifically for these small farmers in the most arid places in the valley further research should be conducted, preferably in the form of

local experimental research programs. In the framework of climate change, the focus should be on topics like:

- Improvement of soil fertility by reforesting bare soils
- Increase of animal feed production for keeping cattle in dry times
- Diversification of additional marketable products such as firewood, fruits, vegetable oils or medicinal products, thereby generating more opportunities for income
- Achieving a sustainable balance between higher production and better management of natural resources without affecting production capacity
- Encouraging important ecological processes and qualities for sustainable agriculture: water availability, soil health, CO_2 capture, and conservation of biodiversity and ecosystem services

It is important that these agroforestry research programs are initiated and coordinated at regional/national level. Experimental pilot studies must be carried out at remote test locations in the arid parts of the valley, that are not directly connected to the river bed, since at these locations the urge is the largest for this development. Local species from the existing (flood) forests should be used for agroforestry.

7.5 Local adaptation

Although there still is a need for more consistent assessments of climate change effects on crop yields at a local scale in the Senegal valley, especially with respect to rainfall, some recommendations can be made for local adaptation. Besides adaptation via large-scale integral water management on a (inter)national level and national initiatives for the preparation of research programs on robust crops and agroforestry, as elucidated in previous paragraphs, three forms of adaptation on the ‘local community-scale’ can be distinguished:

1) Local innovative adaptation in agriculture and food security
2) Local transformational adaptation
3) Migration

The first two forms of adaptation are further explained for the middle valley.

1) Local innovative adaptation in agriculture and food security

Rainfed agriculture is particularly vulnerable to increases in temperature, changes in timing and amount of rainfall, and increases in the frequency of dry periods. The survival of local communities in the valley will strongly depend on the effective local adaptation of agriculture to climate change. Farmers in West Africa are known for their ability to adapt their practices to changes in the environment (Sultan et al., 2013).

On a local scale, it is interesting for farmers to explore additional agricultural crops in addition to regular crops. A higher diversity of crops ('crop diversication'), for example by including fonio cultivation, can also be a local adaptation option. Fonio (*Digitaria exilis*) is one of the traditional crops in the dry savanna zone of West Africa, and is widely cultivated in Guinea (Cruz et al. 2007). Since fonio matures very rapidly, as early as two months after sowing, it can be harvested well before the harvest of other cereals like maize, millet or rice. It is therefore an important food source in a time of year when other cereals are not yet available. Fonio can tolerate drought conditions to some extent, and it can grow on poor, sandy soils that are unsuitable for other cereals.

Besides developing and testing drought resistant crops, further research is needed on other adaptation options, such as shifting sowing and planting dates more into the cold dry season. Although rice thrives well in hot and warm climates, high temperatures of more than 35 ° C can damage plant processes and lead to lower yields (Van Oort & Zwart, 2017. Changes in the agricultural calendar, for example the advance of sowing and planting dates, may reduce or even avoid the risks of damage by very high temperatures.

Despite the fact that irrigation remains the key to cope with the climate change, several farm-level adaptation measures can be implemented to minimize the risk of future conditions in remote areas that are not directly connected to the river bed (Adhikari et al., 2015). Soil and water conservation are particularly important since these practices can enhance the effectiveness of irrigation, fertilizer and improved seeds (Kato et al. 2011). Micro water harnessing techniques ('Zaï" or 'Tassa"), by which pits are dug in the soil during the preseason to catch water and concentrate compost, are frequently used in the Sahel. Also the use of stone bunds has been widely adopted in the Sahel in the past decade (Barbier et al., 2009). These techniques have an effect in areas with a slight relief. Stone bunds (so called 'cordons pierreux') perpendicular to the slope direction slow down run-off processes and promote infiltration and increase water availability. Narrow grass strips or contour hedgerows (so called 'haies vives') in rows perpendicular to the slope direction have the same effect (Yossi et al., 2006).

Also pastoralists in the Sahel have already adopted some coping strategies to secure their livelihoods in view of perceived and actually occurring climatic changes (Zampaligré et al., 2014). Application of herd splitting strategies and the shift from cattle to sheep and goat rearing by pastoralists would be a valid risk aversion strategy, ensuring optimized use of pastoral resources.

2) Local transformational adaptation

When the innovation adaptations become inadequate, for financial reasons or because of a lack of information, farmers may have to switch to transformational adaptations. This means that a substantially different form of income generation is being explored. The negative impact of increased temperatures on crop yields in the arid parts of the Middle Valley may lead to a shift in household resources, where local people may focus on activities that are less dependent on climate. For instance, in areas where the production of key crops becomes really unviable, many inhabitants will need to abandon farming and take up livestock husbandry (Jones & Thornton, 2009). Land degradation is an additional cause of this transition (Brottem & Brooks, 2017). Livestock production enables farmers to diversify incomes, helping to reduce variability. However, in the most vulnerable areas, where this shift is most needed, the households are the least prepared for it. Land degradation reduces the viability of this transition for all but the wealthiest households (Brottem & Brooks, 2017).

7.6 Other possibilities for innovation

Typha: control and applications

The rapid expansion of *Typha australis* has resulted in negative effects on the fish population, stimulation of various waterborne diseases, blocking of channels, a decrease in water quality and increased evaporation rates. The development of Typha is considered a serious problem in the western part of the valley, and the expectation is that with increasing temperatures in the future, these *Typha*-related problems will become even more prominent. Therefore, ways to control *Typha* are investigated. Biological methods to control the proliferation of *Typha* still haven't proven to be effective. The mechanical removal of *Typha* stands requires considerable physical and financial efforts, while dissemination of airborne seeds makes the problem rather uncontrollable (Mietton et al., 2007). Therefore, mechanical removal is not a sustainable option unless the costs of removal can be compensated for by production incomes.

A new industry to promote the use of *Typha* would be an additional way to control the species' spread, while generating jobs for the local population at the same time (Mietton et al., 2007). Therefore, economic feasibility of developing such an industry should be further explored in the valley. The possibilities for setting up a production chain for products from *Typha* need to be described, both for local use and for export. *Typha*-biomass may be used in a large variety of ways, such as fuel, methane production, wickerwork, construction/isolation material and animal fodder.

In the Senegal basin, yields for *Typha* of 6 to 8 tons of dry matter per ha are expected, depending on soil type, water depth and availability of nutrients (Elbersen, 2005). Sustainability and continuity of the Typha growth do not seem to pose problems in the basin, since *Typha* is rapidly expanding, and the growing season lasts the whole year round because of the high temperatures. Crucial in the determination of the feasibility of a production chain for *Typha* are the costs for harvesting, drying and transport of the biomass to a processing facility, depending on the application. Drying does not seem to be problematic in the Senegal river basin. Given the high temperatures and low humidity, biomass can be air dried to 80% dry weight in less than 10 hours (Henning, 2002). However, harvest, handling and transport of Typha biomass in an aquatic environment such as the Senegal river basin is rather complicated (Dieng, 2002). In order to effectively remove *Typha* stands in total, cutting should be performed in the zone between 20 cm and 50 cm below the water surface (Hellsten et al., 1999). However, for sustainable use a different approach is required (Elbersen, 2005). The plants should be cut 20 cm above water level, in order to maintain air exchange with the lower parts of the plant. Further, the plants should be cut at senescence to maintain sufficient reserves for re-growth from rhizomes for sustainable use. There is little known about harvest frequencies. Elbersen states that harvesting can be performed once a year. However, in case additional nutrients are provided by the water, multiple harvest moments per year may be possible.

On the costs of harvesting Typha little information is available. Most literature is focused on total eradication, and not on sustainable production. Elbersen (2005) assumes that mowing equipment would cost over 2.25 million US$ for 30 machines harvesting 200.000 ton of dry biomass from 30,000 to 40,000 ha per year, that is exclusive operational costs. Assuming additional costs to be 2 times the machine costs, Elbersen estimates a total of 3,4 US$ per ton dry matter harvesting costs. The equipment for harvesting under wet conditions is costly.

TOOGA

In Mauritania a new initiative is taken for the useful application of Typha in combination with the valorisation of the fruits of the Desert Data *Balanites aegyptiaca*. The Desert data is a tree which is very common in the Sahel zone, in particular the zone of the Great Green Wall. It is also a tree which is common in the drier part of the Senegal Valley and the areas around. The fruits of the desert data have a high energy value. In the TOOGA project – www.toogga.com – the fruits are combined with the pulp of Typha, producing a nutritious pellet for livestock. This initiative shows that the valorisation of the natural resources in the Senegal valley can lead to new avenues of development and additional revenues for the local communities. Such developments may also be interesting for the Senegal valley, in particular in a participatory approach.

7.7 Recommendations

Based on the outcomes of this report, a number of recommendations is formulated. These are recommendations for concrete follow-up studies, but also concern general focus points in adaptation strategies.

1. To quantify the impact of climate change, in particular a decrease in rainfall in the sources areas on discharge and flooding in the middle valley of the Senegal River, a hydro-dynamic model is needed, in which current and future climate scenarios and water management options are included. Such a model can support the development of adaptive water management strategies for the middle valley;
2. Flooding during the wet season is necessary to guarantee both provisioning and regulating services of the river. For flood-recession cultures, grazing grounds and biodiversity, an artificial flood regime that mimics the natural floods is needed. Flooding assures the direct availability of water, the supply of nutrient-rich sediments from the river, and high groundwater levels on the long term. Annually allowing water levels of at least 3.5 meters, preferably slightly higher, in the annual wet period is favorable from the point of view of climate adaptation, particularly for the most arid and vulnerable areas that are not directly connected to the river bed;
3. It is important to gain more insight into the spatial presence of flood recession cultures, flood forests, and irrigated agriculture in the entire middle valley. This study provided an initial insight, but there is a need for spatial information at a higher level of detail and accurate verification. Monitoring by GIS and remote sensing is therefore an important focus in the coming years;
4. Increasing temperatures will threaten crop yields and transformational changes are needed (Ramirez-Villegas & Thornton, 2015). Two subjects for further research appear to be promising when it comes to local innovations for agriculture. Firstly, exploration of the use of high yielding drought tolerant species will become important. Secondly, it is important to conduct further research on changes in planting and sowing dates in the agricultural calendar. These changes can greatly reduce the adverse impact of climate change on crop yields, thereby minimizing the vulnerability;
5. Trees and (flood) forests in the middle valley are important when the temperature rises. Agroforestry can offer great benefits for grazing, fisheries, agriculture and biodiversity. It is recommended to initiate research programs and to setup experimental test sites with agroforestry to explore the added value of agroforestry in terms of ecosystem services;
6. We recommend the development of practical test locations together with local communities – similar to the concept of Integrated Agricultural Community Farms (FACI) - where local adaptation measures (drought-resistant crops, agroforestry, etc.) can be tested.

Table 7.1. A summarizing overview of climate change impacts and associated adaptation measures at different levels.

Impact climate change / adaptation measures	Basin-level	Regional level	Local community level
Impact on hydrological system			
• General decrease in discharge and flooding in the middle valley of the Senegal River.	Maintaining an artificial flood by integrated water management		
• The risk of lowering of the groundwater level in the long term	Maintaining an artificial flood by integrated water management		
• Areas with modest rainfall and a relative high temperature rise in the future are particularly sensitive to climate change: regions in SE Mauritania, NW Mali		Improvement of irrigation infrastructure	
• The source area of the Falèmé river is in particular sensitive with respect to landscape degradation and increased erosion		Developing agroforestry, initially via test locations	
• Shallow lakes and wetlands depending on water inlet from the river, such as Lac R'kiz in Mauritania, are in particular vulnerable.		Improvement of irrigation infrastructure	
Impact on food security: agriculture			
• A decrease of flooding will have major consequences for the surface area for flood recession and crop yields.	Maintaining an artificial flood by integrated water management		
• Increased evaporation rates will result in reduced water availability for agriculture		Improvement of irrigation infrastructure	Application of micro water harnessing techniques
• A decrease in inundation will result in nutrient-poor soils	Maintaining an artificial flood by integrated water management	Developing agroforestry, initially via test locations	Application of soil conservation techniques
• Shortening of the rainy season and a change in timing will impact crop yields of both irrigated cultures and flood recession cultures;		Improvement of irrigation infrastructure	Experiments on shifting sowing and planting dates
• A higher temperature will lead to significant lower crop yields.		Developing and testing drought/heat resistant crops in experimental test farms	
• Higher temperatures increase vulnerability of agriculture for pests affecting yields;		Developing and testing drought/heat resistant crops in experimental test farms	
Impact on food security: livestock			
• Loss of grazing grounds and lower production, in particular in the northern part of	Maintaining an artificial flood by	Developing agroforestry, initially	Herd splitting techniques, or shift from cattle to

the basin.	integrated water management	via test locations	sheep and goat
• Exploitation of grazing grounds depending on bore holes will become more difficult, leading to a higher pressure on the middle valley;		Improvement of irrigation infrastructure	Herd splitting techniques, or shift from cattle to sheep and goat
• Sedentary livestock raising in the middle valley will face a shorter growing season, less production and more competition			Herd splitting techniques, or shift from cattle to sheep and goat
Impact on (other) ecosystem services			
• Water retention after flooding is essential for local water availability and recharge of ground water. Climate change may impact flooding, and successively also water retention;	Maintaining an artificial flood by integrated water management	Improvement of irrigation infrastructure	
• Climate change is likely to affect provisioning services as fisheries (higher temperature, less flooding) and services provided by flood forests (less flooding, higher pressure on resources);	Maintaining an artificial flood by integrated water management	Developing agroforestry, initially via test locations	
• Future climatic impacts are expected to have substantial effects on biodiversity, beyond the effects of land-use change and other non-climatic stress factors	Maintaining an artificial flood by integrated water management	Developing agroforestry, initially via test locations	

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Appendix A: Rapport de mission 20-26 février 2018

A. 1. Introduction

Une mission de terrain dans le bassin du fleuve Sénégal a été effectuée du 20 février au 26 février 2018 par les consultants écologiques d'Altenburg & Wymenga (Eddy Wymenga et Ivan Mettrop). L'équipe de la mission de terrain est complétée par l'OMVS en la personne de madame Aram Ngom Ndiaye.

L'objectif de cette mission de terrain était d'obtenir d'informations sur le terrain concernant la disponibilité spatiale des ressources en eau (hydrologie), l'utilisation des terres (vulnérabilité de certains habitats), les services écosystémiques et la biodiversité. Les sites visités se trouvaient en particulier dans les environs de Dagana. En général, il y a certains types de terrain importants dans la région.

- Forêts (avec inondation temporaire / sans inondation temporaire)
- Cultures endiguées et irriguées (maraîchages, rizières)
- Cultures de décrues
- Zones humides avec dominance de *Typha*
- Autres habitats naturels
- Sol nu (pas utilisé)

L'itinéraire

L'itinéraire est indiqué dans le tableau. Une description plus détaillée des activités et des principaux résultats est décrite au chapitre 2; le 'journal quotidien'.

Date	Time	Location	Activities
20 Février	Après midi Soir	Amsterdam – Dakar Dakar	Voyage Reste à l'hotel Résidence Hoteliere Olympus
21 Février	Matin Après midi	Dakar Dakar	Réunion à l'OMVS Dakar Travailler à l'hotel
22 Février	Matin Après midi	Dakar – Saint Louis Saint Louis – Richard Toll	Voyage + réunion à OMVS St. Louis Voyage + réunion à S.E.A.D.
23 Février	Journée complète	around Dagana	Visites de terrain
24 Février	Matin + après midi Evening	Richard Toll – Dakar Dakar	Voyage + visites de terrain le long du fleuve Sénégal Reste à l'hotel Résidence Hoteliere Olympus
25 Février	Après midi	Dakar	Travailler à l'hotel
26 Février	Matin + après midi Soir	Dakar Dakar – Amsterdam	Atelier démarrage à l'OMVS Dakar incl. présentation Voyage

A. 2. Journal quotidien

Mardi 20 février 2018

Pendant le vol d'Amsterdam à Dakar, nous avons travaillé sur la préparation de la mission. Nous avons préparé le programme, les lieux à visiter, les sujets à discuter au l'office d'OMVS et la présentation pour l'atelier démarrage.

Mercredi 21 février 2018

La majeure partie de la journée consistait en une visite très utile au bureau de l'OMVS à Dakar. Nous avons rencontré les personnes suivantes:

Mohamed Fawzi Bedredine (Ingénieur Génie Rural et Coordonnateur Régional Adjoint du PGIRE) nous a aimablement aidé à organiser la planification des excursions. Aussi, il nous a présenté plusieurs personnes intéressantes et importantes à l'OMVS. En outre, nous avons convenu que notre étude et l'étude récemment achevée par Artelia (2017) sont très complémentaires et certainement pas similaires. Le travail quantitatif d'Artelia peut très bien servir de base à nos analyses spatiales. De plus, le programme initial pour les journées sur le terrain a été modifié un peut. Avec Fawzi, nous avons formulé un nouveau programme, comme indiqué dans le tableau en introduction. Ensuite, nous avons brièvement visité M. Brahim H'Meyada (Haut commissaire Adjoint). Nous avons rencontré madame Anta Seck (Coordinatrice Régionale du PGire). Anta était heureux d'être informé de nos activités. Nous avons aussi rencontré madame Véronique Mboss Faye Komaclo (spécialiste en changement climatique). Enfin, nous avons rencontré madame Aram Ngom Ndiaye (géographe/environnementaliste), qui nous accompagnera pendant les journées sur le terrain.

Jeudi 22 février 2018

Nous avons voyagé de Dakar à St. Louis. A Saint Louis, nous avons visité le bureau CDA (Centre de Documentation et des Archives) de l'OMVS. Après avoir expliqué le but du projet et nos activités pendant les jours sur le terrain à mr. Babacar Diong et mr. Oumar Dansogo, ils nous ont fourni les informations nécessaires pour accéder à la base de données avec des rapports, etc. Nous avons également obtenu un CD-rom contenant la bibliothèque numérique consacrée au fonds M.A.S. et O.E.R.S.

De plus, nous avons été informés de la mission de Geoconsult dans le contexte de PGIRE. L'objectif principal de l'étude de Geoconsult est de prévoir l'OMVS d'une base de données cartographiques homogènes sur l'ensemble du bassin. En outre, une étude sera réalisée afin de dégager les grandes tendances et les évolutions récentes des écosystèmes. Ce projet est également important pour notre étude. Le rapport de phase 1 est déjà disponible et nous l'obtiendrons.

Ensuite, nous avons visité le S.A.E.D. (Société Nationale d'Exploitation des Terres du Delta du Fleuve Sénégal) et nous avons discuté avec mr. Moustafa Lo sur les pratiques agricoles dans la région. Mr. Lo pourrait nous fournir beaucoup d'informations sur les sites que nous avions l'intention de visiter, et sur les caractéristiques hydrologiques de la région. Il y avait un dossier contenant des informations importantes sur les principales cultures cultivées (riz, oignon, tomate, patate douce, maïs) avec un accent particulier sur l'exploitation de ces cultures. Le S.A.E.D. est impliqué dans l'infrastructure agricole et l'établissement dans la région (seulement dans les lits de la rivière) et fournit également des conseils sur l'utilisation d'engrais et d'herbicides, etc. Enfin, mr. Lo pourrait nous dire que les cultures de décrue traditionnelles sont encore pratiquées à grande échelle dans la région à l'est de Podor. Ouest de Podor ces activités ont fortement diminué.

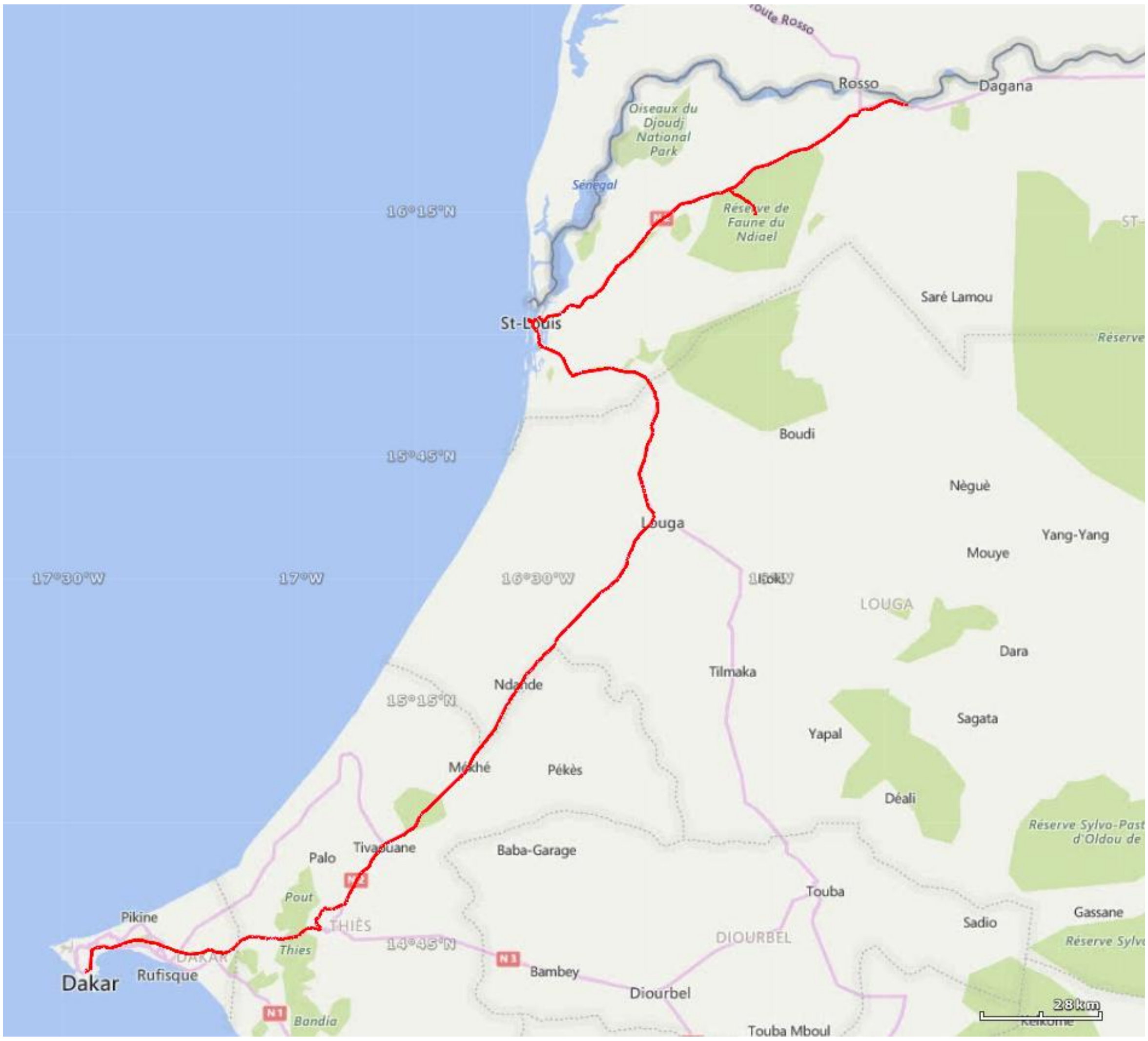


Figure 1; la route de jeudi 22 février 2018

Vendredi 23 février 2018

De Richard Toll nous avons voyagé vers la région à l'est de Dagana pour les visites sur le terrain (Figure 2). Sur le chemin et sur place autour de Dagana nous avons pris des notes à plusieurs checkpoints (CP's).

Le premier CP était au pont sur le canal d'écoulement 'Taoueye' (**CP1**). L'eau coule par ce canal vers le lac de Guyere. Le débit est remarquablement élevé, il y a beaucoup d'eau est autorisé à passer dans le canal. Sur les bords du canal *Typha* spp. se développe. Nous observons également *Vossia cuspidata* et *Echinochloa colona*. Il y a une grande diversité d'oiseaux aquatiques.

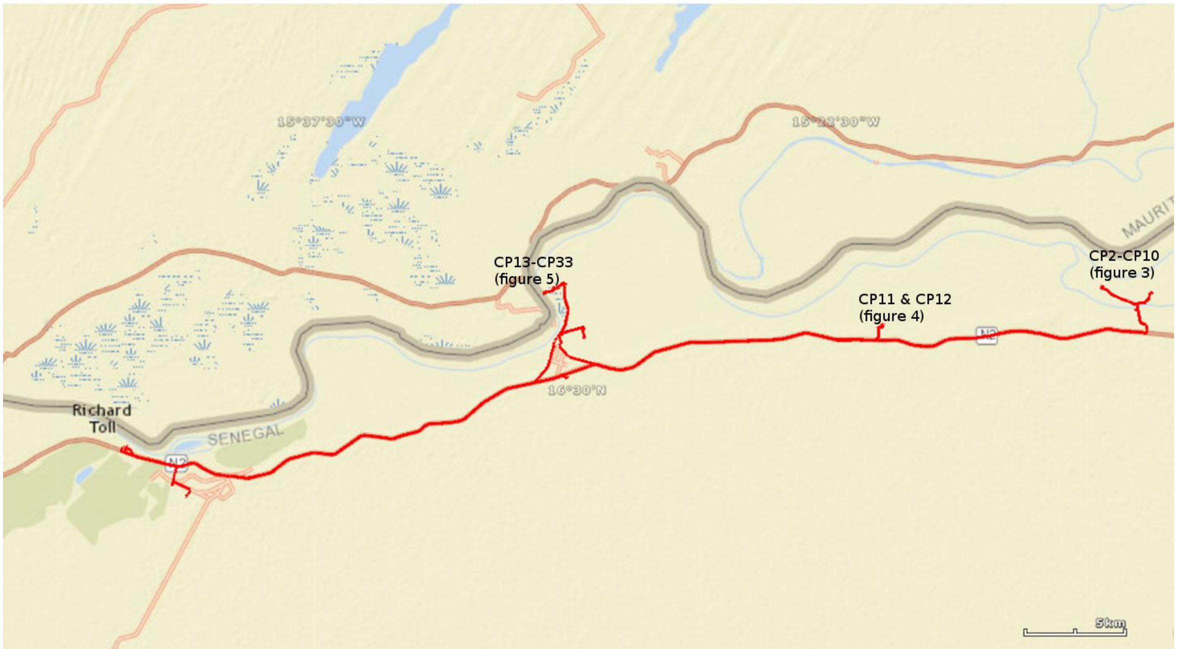


Figure 2; la route de vendredi 23 février 2018

Figure 3; locations des CPs 2-CP10


CP1


CP2

Nous avons continué à la region l'est de Dagana. Au **CP2**, nous avons visité un maraîchage. Une grande variété de cultures est cultivée ici ; oignons, tomates, courgettes, maïs et concombre. Les différentes cultures sont mélangées, et on peut facilement utiliser de l'eau du canal latéral de la rivière.

Près du Fayana Walo (**CP3**) nous avons visité une forêt avec inondation temporaire. Beaucoup d'arbres poussent ici, y compris de nombreux *Acacia* spp. avec une grande biodiversité. Presque tous les arbres sont *Acacia nilotica*, ils ont tous fleuri. L'écorce des arbres est utilisée pour la gomme arabique. Les parties basses contiennent beaucoup d'argile, la digue est de sable. Au bord de l'eau il y a beaucoup de végétations de Chypre. Ces végétations sont partiellement pâturées. I n'y a pas de *Vossia* ici et ni de *Typha*. Dans les périodes humides l'eau est ici jusqu'à la digue.

CP4 est proche de CP3. Les poissons sont capturés ici par les villageois locaux. Les écailles du poisson sont enlevés sur place, les reliques de ceci sont encore visibles sur place. En plus, il y a des ruches d'abeilles dans les *Acacia nilotica* arbres. Il n'y avait pas beaucoup de coupe dans cet endroit pour le charbon de bois et le bois de chauvage. CP4, ainsi CP3, est complètement inondé dans la période humide, mais il n'y a pas de *Typha* ici. Peut-être c'est trop sec pendant la période sans pluie. D'ici, les poissons remontent vers le fleuve Sénégal. Donc, l'endroit est est un important lien écologique. Enfin, il y a beaucoup des oiseaux ici: *Motacilla flava; Tringa glareola; Himantopus himantopus; Egretta garzetta; Ardea alba; Ardeola ralloides; Egretta ardesiaca; Phylloscopus bonelli; Phylloscopus collybita ; Phoenicurus phoenicurus.*


CP3


CP3

CP4

CP4

CP5, **CP6**, **CP9** et **CP10** sont situés dans les champs de riz. Le riz est déjà récolté au moment de la visite sur le terrain. Donc, il n'y avait pas de travail de terre à ce moment-là. Quelques femmes cherchent dans les champs arides et secs pour tubercules racines d'herbes (herbes inconnues) pour le goût en poudre (photo *CP9*).

CP5

CP9

CP7 & **CP8** étaient similaires à **CP3**: Végétation *Cyperaceae*, mais aussi de très grands Acacias (10 à 10 m) ont été abattus et brûlés en charbon de bois. De plus: les gens pêchent et tous ces champs ont été broutés par des vaches. Les vaches étaient encore dans certains endroits; partout étaient des fientes. Madame Ndiaye a expliqué un nouveau projet intéressant sur la conversion des déjections en biogaz.

Sur le chemin du retour vers l'ouest, nous faisons un arrêt intermédiaire (**CP11** et **CP12**). Ici, il y a des maraîchage avec doubles cultures (deux saisons). Après utilisation comme une rizière, les champs sont utilisés comme maraichages. Les cultures sont irrigués. Principalement, les oignons sont cultivés. Cela a une raison politique. Le gouvernement a cessé d'importer des oignons pour augmenter la production d'oignon au Sénégal. Cela a conduit à une énorme stimulation de la production d'oignons. En plus des oignons, il y a beaucoup de maïs, de citrouille, des courgettes et beaucoup de tomates ici. Beaucoup d'herbicide est utilisé dans les maraichages (Figure). C'est un développement inquiétant, parce que la qualité de l'eau dans l'environnement est négativement affectée. Il n'y a pas beaucoup d'oiseaux. En particulier, les grands oiseaux sont absents et il n'y a pas d'oiseaux de proie. Cependant, il y a beaucoup de *Vanellus spinosus*.

Figure 4; locations des CP11 & CP12

CP11

CP12


CP12


CP12

Au **CP13**, situé dans les rives étroites du fleuve Sénégal, nous visitons les cultures décrues. Dans ce domaine, on cultive des patates douces.

CP14 et **CP15** sont situés dans les champs de riz. Le riz est récolté. Donc, il n'y avait pas de travail de terre à ce moment-là.

CP16 et **CP17** sont situés dans une zone de rizicultures abandonnées. Les champs sont abandonnés longtemps (il y a déjà plusieurs années) et maintenant la région est colonisée par *Prosopus Africanus*. La biodiversité n'est pas élevée.


CP 16


CP 18

Figure 5; locations des CP13-CP33

CP18 est situé dans une forêt classée. La forêt est classée depuis 1931 et se compose de *Faidherbia albida*, *Acacia nilotica* et autres Acacia spp très vieux. Un résident local dit que le niveau d'eau dans la période humide est d'au moins un mètre plus haut. Il y a aussi des palmiers (*Borassus* spp.). Les arbres accueillent Phylloscopus bonelli, Phylloscopus collybita, et différents types de *Picides*. La zone a une très haute biodiversité.

CP19 - **CP24** sont des maraîchages cultures décrues. Les maraîchages contiennent beaucoup de cultures. Il y a des tomates, patats douces, poivriers, aubergines, et des oignons. Au moment de l'année de cette visite l'eau de la rivière est amenée dans la terre. Donc, en ce moment il n'y a pas de sécheresse. Dans la période humide, ce n'est pas nécessaire, parce que l'eau d'inondation peut être utilisée pour l'agriculture.

CP23

CP23

CP23

CP23

A l'est de Dagana il y a aussi beaucoup de ricicultures récoltés (zone autour **CP30**).

CP31, **CP32** et **CP33** sont des endroits avec d'énormes quantités de *Typha* spp. jusqu'à trois mètres de haut. Un canal de drainage traverse les champs de Typha. Le Typha est fréquemment retiré du canal, mais la vitesse de croissance des plantes est trop élevée pour gérer le canal correctement. Dans le canal il y a *Azolla* spp. et *Salvinia molesta* aux endroits où le Typha est enlevé. Dans ces endroits où Typha est enlevé très récemment, de nouvelles plantes sont déjà visibles. La zone où Typha domine est très grande; probablement la domination de Typha couvre tout le lac. Dans le canal, il y avait de *Porphyrio porphyrio*, *Ardea purpurea*, *Jacanidae* et un *Circus aeruginosus* au-dessus du Typha.

CP31, CP32 et CP33

Samedi 24 février 2018

Sur la route vers l'ouest (Figure 6), le long de la rivière, nous nous sommes arrêtés à un champ agricole de gombo (**CP34**). Gombo est une culture à manger.

CP34

CP35, CP36, CP37

Le reste de la route longe le fleuve Sénégal. Il y a un barrage d'un côté de la route (le côté nord de la fleuve). Derrière le barrage, il y a de Typha dans l'eau peu profonde (**CP35, CP36, CP37**). Il n'y a pas d'autres espèces végétales ici. De l'autre côté de la route, le côté sud, il y a une plaine vide sans végétation à cause de la forte salinité. Cette teneur en sel est augmentée car les eaux souterraines salées sont imprimées à la couche supérieure du sol. Ceci est fait par la pression de l'eau de la rivière sous le barrage.

Plus loin nous arrivons à l'entrée du parc national Djoudj, et plus tard nous visitons le barrage de Diama et nous continuons à Dakar via St. Louis.

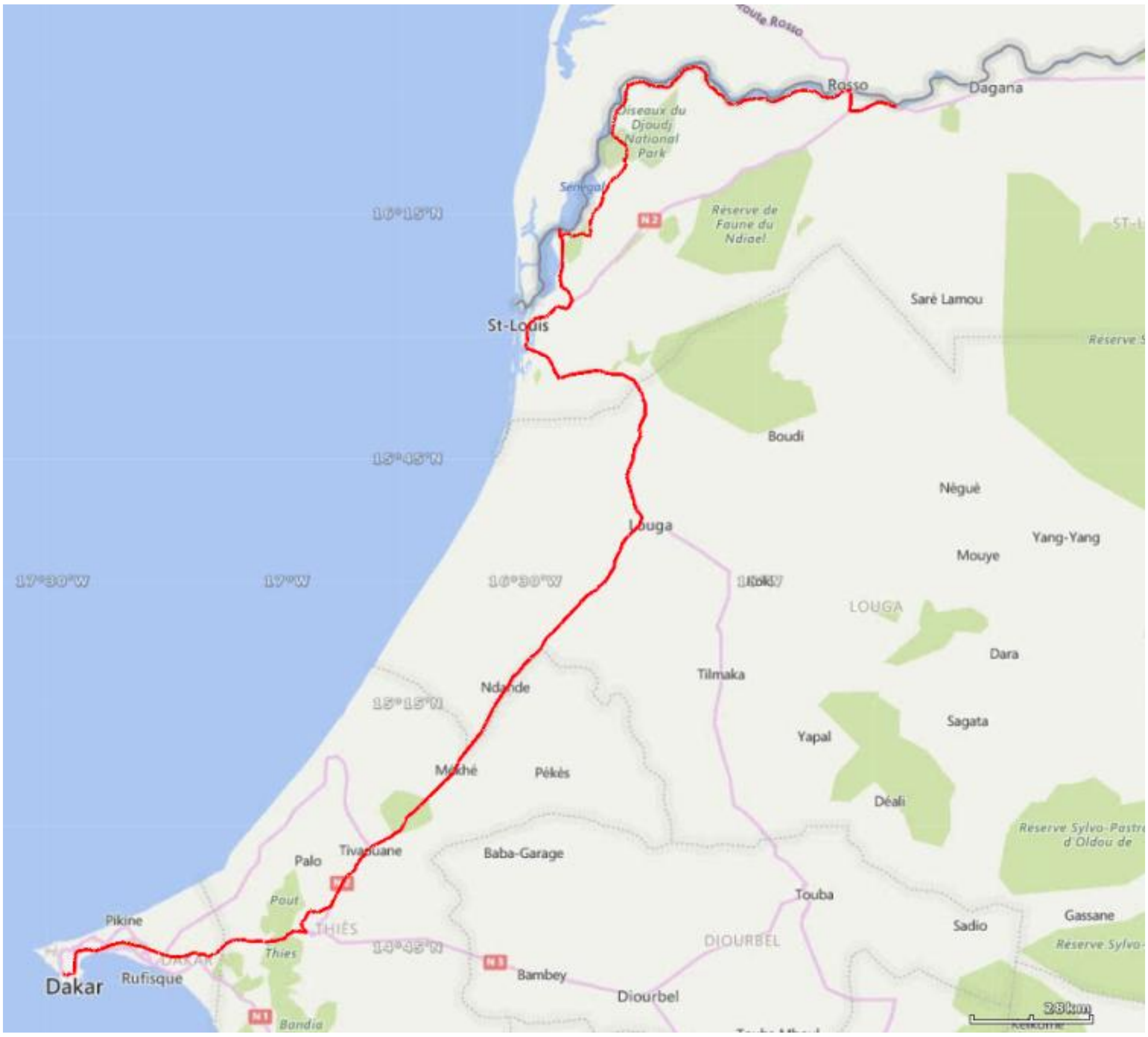


Figure 6 ; la route de samedi 24 février 2018

Dimanche 25 février 2018
Le dimanche après-midi est utilisé pour la préparation de la présentation le lundi sur le bureau de l'OMVS.

Lundi 26 février 2018
Dans le matin, Eddy Wymenga (A&W) fait une présentation (atelier démarrages) au bureau de l'OMVS. Les participants de l'OMVS: Amadou Lamine Ndiaye (Directeur de l'Environnement et du Développement Durable), Cheikh Sarr (expert SIG), Ibrahima Ba, et Abemlaye Gning.

Plus tard dans la matinée, nous avons une courte réunion avec Kandas Conde (chef de Division Gestion des Ressources en Eau et Prévention des Risques). Kandas était particulièrement intéressé par notre attention sur la relation entre les niveaux d'eau et la distribution spatiale de l'eau d'inondation. Maha Sall et NDiaye Gora sont également présents de l'OMVS. Après une brève explication de ce que nous voulons faire et ce que nous avons besoin de données, nous sommes d'accord que Maha nous enverra les données hydrologiques numériques. Il s'agit de données (cotes et débits) des différentes stations hydroliques qui nous intéressent, à partir de 1980 environ.

Appendix B: Rapport de mission 10-17 décembre 2018

B. 1. Introduction

La mission de terrain dans la moyenne vallée du fleuve Sénégal était effectuée dans la période du 09 jusqu'a 17 décembre 2018 par les consultants écologiques d'Altenburg & Wymenga (Ivan Mettrop, Erik Klop & Teun Smink) et l'OMVS (monsieur Ibrahima Samba BA).

L'objectif de cette deuxième mission de terrain était d'obtenir les données du terrain concernant la disponibilité spatiale des ressources en eau (hydrologie), l'utilisation des terres, les services écosystémiques y compris la biodiversité, et d'évaluer la vulnérabilité de certains habitats. Les sites visités se trouvaient en particulier dans les environs de Podor et Matam. Ces sites s'ajoutent aux les sites visités lors de la première mission en février 2018 autour de Dagana.

En général, il y a certains types de terrain importants dans la région.

- Zones ouvertes (semi-désertique/savane), avec des arbres et arbustes
- Forêts (feuillage fermé), dominé par *Balanites aegyptiaca* et *Acacia* spp.
- Cultures endiguées et irriguées (maraîchages, rizières)
- Cultures de décrues
- Zones humides dominées par *Typha australis* et autres plantes aquatiques envahissantes
- Sol nu

L'itinéraire

L'itinéraire est indiqué dans le tableau ci-dessous. Une description plus détaillée des activités et des principaux résultats de l'inventaire sont décrits au chapitre 2; le 'journal quotidien'. Ivan Mettrop déjà tourné retour de Podor le vendredi 14 Décembre.

Date (2018)	Endroit	Activité
Dimanche 9 décembre	Amsterdam – Dakar	Voyage, reste à Résidence Hôtelière Olympus
Lundi 10 décembre	Dakar	Réunion à l'OMVS Dakar, y compris la présentation des résultats, reste à Résidence Hôtelière Olympus
Mardi 11 décembre	Dakar – Podor	Voyage, reste à l'Auberge du Tékrour
Mercredi 12 décembre	Podor	Travail de terrain, reste à l'Auberge du Tékrour
Jeudi 13 décembre	Podor	Travail de terrain, reste à l'Auberge du Tékrour
Vendredi 14 décembre	Podor – Matam	Voyage, travail de terrain sur la route, reste Auberge Beelel Jeeri
Samedi 15 décembre	Matam	Travail de terrain, reste Auberge Beelel Jeeri
Dimanche 16 décembre	Matam – Dakar	Voyage, reste à Résidence Hôtelière Olympus
Lundi 17 décembre	Dakar – Amsterdam	Voyage

B. 2. Journal quotidien

Dimanche 9 décembre 2018
Pendant le vol d'Amsterdam à Dakar, nous avons fait des préparations de la mission. Le programme est préparé, nous avons énuméré les lieux à visiter, les sujets à discuter au bureau de l'OMVS et nous avons préparé la présentation des résultats intermédiaires.

Lundi 10 décembre 2018
La majeure partie de la journée consistait en une visite très utile au bureau de l'OMVS à Dakar. Nous avons rencontré les personnes suivantes:

Avec monsieur Ibrahima Samba BA (Expert en Aménagement), nous avons discuté le programme initial pour les journées sur le terrain. Le programme, la planification et les objectives étaient d'accord et réalisable. M. Ibrahima Samba Ba nous accompagnera pendant les journées sur le terrain.

Par la suite, monsieur Attaher A.G. Mohamed (Chef de la Division Protection de l'Environnement et Suivi Evaluation) nous a reçu. Monsieur Mohamed, qui assure l'intérim de Amadou Lamine Ndiaye (Directeur de l'Environnement et du Développement Durable, il nous a présenté plusieurs autres personnes intéressantes et importantes à l'OMVS, y compris Monsieur Mamadou Diaby (Secrétaire General).

Par la suite, nous avons tenu une présentation au bureau de l'OMVS. Peu de gens étaient présents ici: M. Mohamed, M. Ba et Madame Aminata Keita (Coordinatrice du projet d'irrigation agricole PARACI). Les diapositives de la présentation sont joints au présent rapport en Appendice I. Les souhaits de l'OMVS correspondent à les résultats présentés. Les questions posées après la présentation portaient sur l'effet d'une forte évaporation: est-ce que c'est mesurable? Cette question est difficile à répondre; il y aura un effet notable, mais il sera difficile en pratique de mesurer cet effet. Les questions concernaient également l'élevage: dans quelle mesure l'eau influence-t-elle et quel est son lien avec une période donnée (haut / bas niveau d'eau)? Y a-t-il un lien? La plupart des élevages ne sont pas transhumains (non nomades), mais sédentaires. Y a-t-il suffisamment de lieux appropriés pour l'élevage sédentaire à l'avenir? De plus, on s'interroge et discute sur la relation entre l'eau et le cadre de vie en général.

De plus, nous avons discuté la possibilité d'un atelier supplémentaire sur la validation des résultats et en particulier les possibilités d'adaptation. Les personnes présentes à l'OMVS pensent que tel atelier est une très bonne idée. Nous pouvons discuter avec un grand groupe d'experts régionaux sur les possibilités d'adaptation et d'innovation dans la région. Nous ne savons pas encore comment cela peut être organisé, pour combien de personnes et dans quelle période. Ce grand atelier ne fait pas partie du TdR de la présente étude. Si cela est convenu, ce sera un atelier supplémentaire sous la forme d'un projet supplémentaire dans l'année prochaine (2019).

De plus, nous avons montré le modèle OPIDIN et le website www.opidin.org. Il y avait de l'intérêt pour un modèle comparable pour la vallée du Sénégal. Peut-être existe-t-il des possibilités de créer un tel modèle pour le fleuve Sénégal. Nous en reparlerons bientôt.

Mardi 11 décembre 2018
Nous avons voyagé de Dakar à Podor. Le long voyage ça a pris une journée entière. Dans le soir à l'hôtel, nous avons discuté la planification avec Ibrahima Ba.

Mercredi 12 décembre 2018
Le premier jour de travail sur le terrain. Nous avons collecté des données, et pris des notes à plusieurs checkpoints (CP's).

CP 1:

A l'ouest de Podor nous visitons des champs avec cultures de décrues. On cultive beaucoup de sorgho et on cultive des haricots supplémentaires entre le sorgho. La récolte de sorgho est effectuée une fois par an, en mars/avril. Donc, le sol retient l'eau pendant longtemps, parce que c'est un sol limoneux. Les inondations annuelles du fleuve sont donc non seulement importantes pour l'approvisionnement en eau, mais également pour la qualité du sol. Les dépôts de l'eau du fleuve causent le sol limoneux, et donc la rétention d'eau. Ca, c'est un fait important pour l'adaptation au climat. Le maïs n'est pas cultivé sur ce site. Pour cela, c'est trop sec, parce que le maïs a besoin plus de l'eau. Toute la production est pour la autoconsommation par la communauté locale, il n'y a pas de vente au marché local. Le rendement n'est pas clair. Il y a une construction locative avec un locataire. Une partie du produit appartient donc au propriétaire / locataire du terrain. L'année 2018 était une bonne année pour la culture de décrue, parce que c'était une année avec beaucoup de pluie. Enfin, nous n'avons pas vu que des insecticides étaient utilisés.

CP 2:

Sur ce site on trouve l'agriculture irriguée, c'est conforme à la carte d'utilisation des sols. Ici, les canaux d'irrigation sont visibles dans les rizières. Le riz était déjà récolté. Dans des champs comparables (pas ici), le sorgho est actuellement planté entre les riz au moment de l'année, mais seulement dans des conditions idéales et humides.
De CP2, direction CP3 était une rangée d'arbres, ce qui n'a pas été produit sur la carte des types de terrain, composé principalement d'*Acacia nilotica*. Peut-être s'agit-il d'anciennes terres agricoles, donc de forme rectangulaire, qui conduisent à une mauvaise classification.


CP1


CP1

CP 3:

Dans le village de N'Gaolé, des maraichages aux légumes se trouvent directement au bord de la rivière. Les poivrons et les oignons sont cultivés, et il y a aussi d'élevage (sédentaire). A l'origine, le village est important pour la pêche.

CP 4:
Avec l'aide d'un système de pompe, l'eau est laissée entrer ici quand c’est nécessaire. Les tubes étaient toujours là, donc le système a été utilisé récemment. La pompe est utilisée au début de la nouvelle saison. C'est à ce moment que le nouveau riz est semé/planté (mai/juin en la période des premières pluies). Une fois par an, ces canaux sont nettoyés par la SAED.

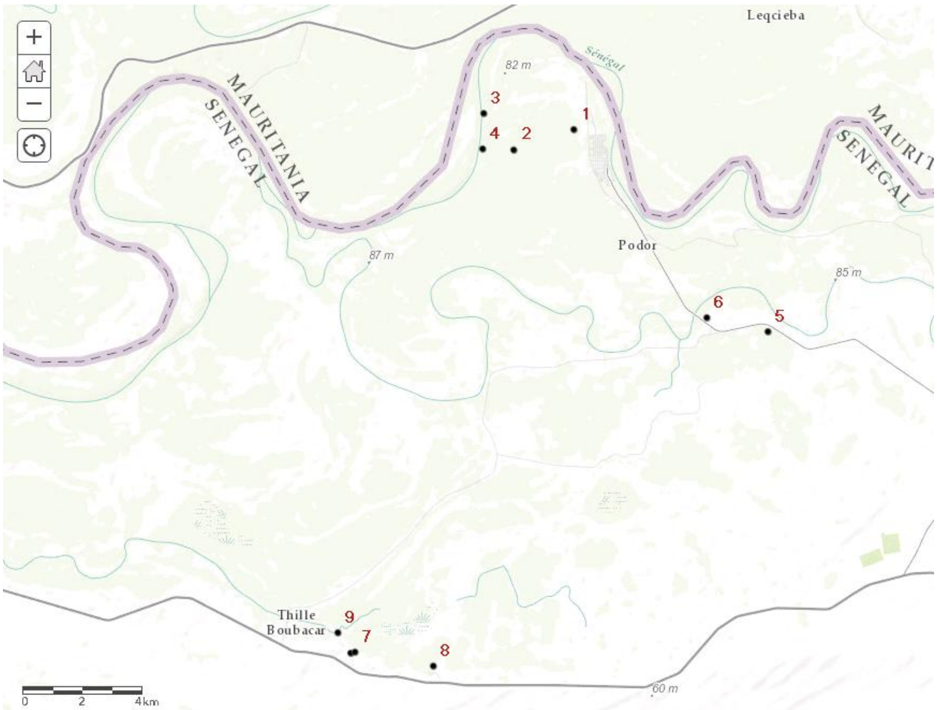
CP 5:
Sur ce site il y a des rizières irriguées (monoculture) près du village de Madiyou. Il n'y a pas beaucoup de Typha dans les canaux; ils sont relativement propres. La plupart du riz est récolté à la fin de la saison des pluies, mais il y a aussi un champ non récolté. La SAED a creusé les canaux.

CP 6:
Près du village de Guya il y a beaucoup de cultures de décrues sur une grande surface. Selon la carte d'utilisation des terres, il ne s'agit pas d'une zone ouverte avec de la végétation, mais il y a toujours de l'agriculture à cette période. Donc, le moment (saison) de imagerie satellite est très important pour la production de la carte d’utilisation. L'utilisation actuelle des terres ne peut pas être extraite de photos de plus tôt dans la saison. Il y a des grains de café, des haricots, de la pastèque, des courgettes et du maïs dans les endroits les plus humides. Il n'y a pas de pompes présentes. Toute la production est pour la autoconsommation par la communauté locale, il n'y a pas de vente au marché local.

CP6

CP 9:

Il y avait là une belle forêt le long de l'eau N'Galanka Samba Nayel Dieri. Il y a beaucoup de filets de pêche ici, et il y avait beaucoup d'oiseaux d'eau, en particulier de nombreux hérons (biodiversité élevée). Encore beaucoup de *Persicaria* et de très hauts roseaux. La forêt se compose *d'Acacia nilotica*, d'*Eucalyptus* sp. et *Balanites* sp. Nous avons vu la *Sylvia inornata*. Il y a beaucoup de *Calotropis procera* à la lisière de la forêt. Aussi dans d'autres endroits, où le sol est perturbé, cette espèce est très commune.



Une indication des locations des CP numéros 1-9, autour de Podor.

Jeudi 13 décembre 2018
Le deuxième jour de travail sur le terrain.

CP 10:

Voici les rizières près de Guedé. Plusieurs Madames ‘frappent’ du riz sur des barils de pétrole. Les champs étaient asséchés très récemment, juste avant la récolte. À côté des champs se trouve un grand canal d’irrigation bien entretenu (dépourvu de végétation). La récolte est faite en novembre/décembre. Il faut 3 jours pour récolter plus de 40 ares, avec un rendement pour 5 familles. La récolte sur cette surface produit 38 sacs de riz, et chaque sac pèse environ 90 kilos. Environ 12-14 sacs sont destinés au paiement des dépenses: diesel, eau, etc., et les autres sacs sont destinés à être consommés par les familles pendant environ 2-3 mois. Chaque année, ils choisissent la meilleure variété en fonction du rendement. Il n'y a pas d'exportation commerciale, seulement autoconsommation au sein de la communauté. Ils vendent quelque chose pour obtenir un peu d'argent pour les coûts quotidiens. Les femmes ‘frappent’ le riz, les hommes tamponneront et moudront etc. Le nettoyage des canaux est effectué par les habitants du village. Il y a un peu de Typha présent, mais ce n'est pas un problème. Il y a des champs de légumes dans un endroit différent, où sont cultivées des tomates, du chou, du concombre et du gombo. Beaucoup s'est amélioré ces dernières années.

CP10

CP 11:

A Jabbe Fresbe (village) se trouvent des maraichages le long de la rivière, appartenant à plusieurs familles (un quartier proche du village). Il y a de la cassave, des oignons et du poivre. L'irrigation est effectuée à l'aide d'une pompe de la rivière.

CP 12:

Sur ce site, il y a une zone humide avec une énorme quantité de *Scirpus littoralis*. Il y a beaucoup de chèvres. Les chèvres paissent principalement à *Acacia nilotica*. Il y a aussi quelques champs de légumes, y compris le maïs (le site est assez humide), mais il y a aussi des oignons. Les chèvres paissent également les *Scirpus* spp., mais surtout les Acacias. Il y a aussi du sorgho et des haricots. M. Ibrahima Ba explique la raison de l'absence de mil dans cette région. Le mil se dresse sur des endroits plus secs et sableux que le sorgho.

CP12

CP12

CP 13:
Une grande surface d’eau avec de nombreuses espèces d’oiseaux, la forêt d’Acacia nilotica et de nombreuses chèvres. Le lac est un vestige d'inondation (les eaux de pluie et les eaux des rivières s'évaporent lentement et se retirent de plus en plus).

CP13

CP 14:
Une impressionnante forêt inondable à NDioum, constituée d’*Acia nilotica*. Une grande partie de la forêt est inondée, entourée de savane sableuse ouverte. Il y a une sorte de végétation de type *Azolla* avec une inflorescence jaune sur les basses eaux. Nous avons vu la *Sylvia inornata*. La forêt est bien catégorisée par télédétection. Typha semble être absent, mais est classé sur la carte. Il semble que d'autres plantes aquatiques soient également classées comme Typha par la technique de télédétection. Une attention particulière doit être accordée à cela dans l'étude de suivi sur la fiabilité de la technique SIG.


CP14


CP14

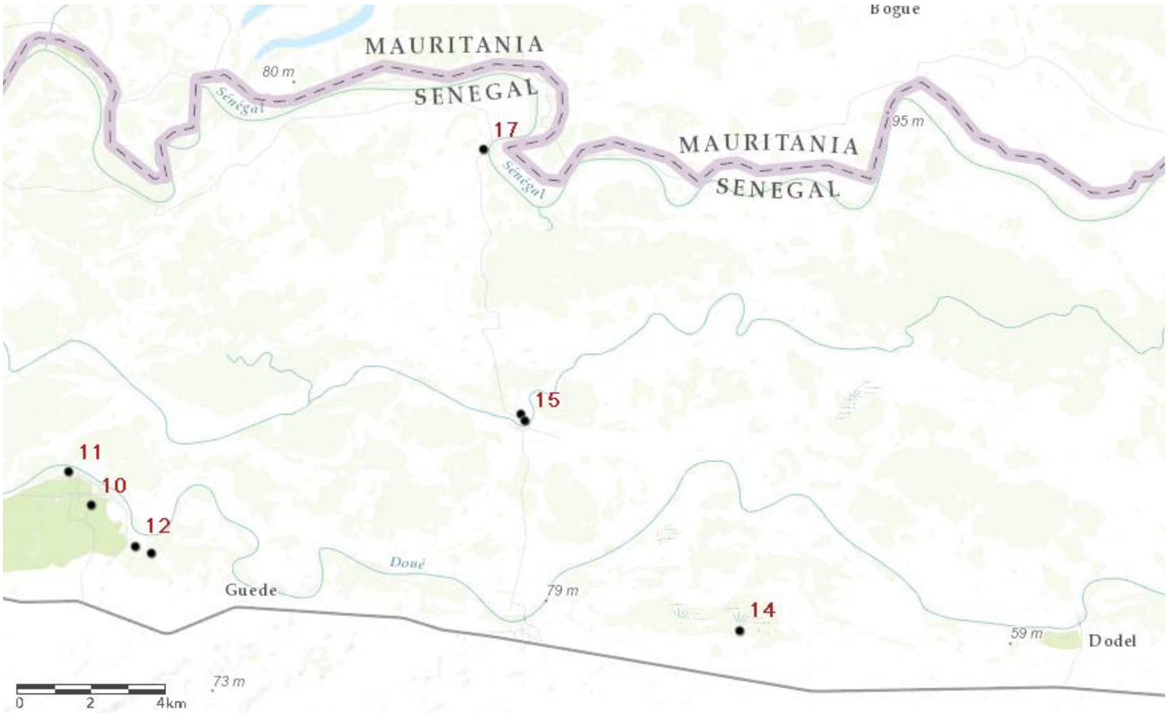
CP 15:
Sur ce site, il y a des cultures décrues près du pont au village Gayo Toufndé Bali. Les gens cultivent des haricots, du sorgho et des tomates, des patates douces, et il y a aussi des champs de légumes ailleurs. Ils voulaient acheter une pompe.

CP 16:
De l'autre côté du village se trouve un grand complexe de riz irrigué. Ici, les femmes sont occupées à récolter ('frapper'). Il y avait déjà une récolte précédente. Celles-ci étaient les restes qui ont ensuite grandi à nouveau (cela ne se fait pas partout/toujours). Ils ne connaissent pas du tout *Typha* (!). Donc, Typha n'est vraiment pas un problème ici. Les champs appartiennent à Halwar, un village plus loin. En février, ils plantaient déjà le riz (très tôt). Le reste après l'expulsion du riz est utilisé pour l'alimentation animale.

CP 17:
Voici des rizières abandonnées (cette année non utilisées). Pourquoi ces champs sont-ils partis? Il n'y a personne, donc personne ne peut donner d'explication.
Un peut loin il y a un complexe privé. Les maraichages contiennent des oignons, des poivrons, des tomates, des courgettes et des aubergines. Les champs sont irrigués avec une pompe. Des insecticides sont utilisés. Le complexe est à grande échelle et il n'est pas inondé pendant la période humide.


CP17


CP17



Une indication des locations des CP numéros 10-17, à l'est de Podor.

Remarques générales après deux journées de travail autour de Podor:

Les forêts sont principalement constituées *d'Acacia nilotica* sur les parties inondées. *Acacia nilotica* avec *Faidherbia albida* et *Balanites aegyptiaca* et beaucoup de *Leptadenia pyrotechnica* se trouvent également sur les parties les plus sèches, et il y a beaucoup de *Calotropis procera* sur les sols perturbés. L'impression générale est que Typha n'est pas très présent; en tout cas moins que dans les environs de St. Louis - Richard-Toll. Nous avons atteint la limite de l'extension de Typha.

Le pâturage concerne principalement les chèvres, les moutons et parfois le bétail (principalement sédentaire). Il y a de la pêche, mais cela ne semble pas être très important.

La carte d'utilisation des terres produite avec télédétection n'est pas correcte partout. La raison est le moment de l'enregistrement des images satellites. Peut-être il est préférable d'utiliser des images d'une autre période de l'année. Les rizières sont correctes dans la classification, mais les forêts et autres unités plus diffuses s'avèrent plus difficiles. Et la végétation dans l'eau est souvent *Typha* sur la carte, mais en réalité il y a souvent de grands champs de *Scirpus littoralis* et à plus petite échelle beaucoup de végétation de *Persicaria*.

Enfin, il y a encore beaucoup d'eau dans les parties les plus basses du paysage autour de Podor.

Vendredi 14 décembre

CP 18:

Ce site est situé entre les villages Aere Lao et Koitel. Sur le côté est de la route, il y a d'anciennes rizières qui ne sont pas cultivées en 2018. À l'ouest, il y a une bande de forêt avec *Acacia nilotica* et *Balanites aegyptiaca*. À environ 0,5 km au nord se trouve une bande de dunes de sable recouverte de *Balanites aegyptiaca*, *Acacia* et *Leptadenia*.

CP 19

Voici un waypoint situé juste au nord des dunes de sable (voir ci-dessus). Ici se trouvent d'anciennes rizières, non cultivées en 2018. Selon un agriculteur local, il s'agit normalement de riz irrigué destiné à la consommation de la communauté locale.

CP 20:

Ici se trouve un grand complexe de champs pour la culture des oignons. Actuellement, le terrain est en préparation pour la plantation d'oignons à la fin du mois de décembre. Les champs sont utilisés conjointement par trois villages. L'irrigation est effectuée au moyen d'une pompe et d'un canal d'irrigation. Selon les populations locales, la superficie est de 12 ha, mais selon notre estimation, la parcelle est plus grande.

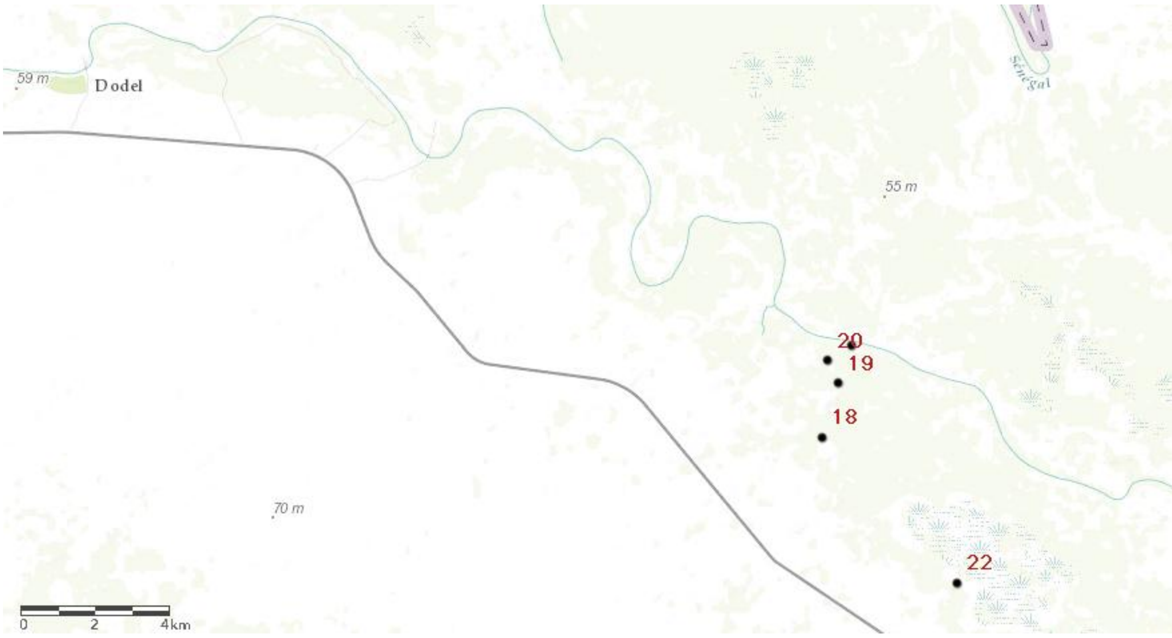
CP 21:

Les habitants du village de Koitel, situé au bord de la rivière, cultivent principalement des patates douces et du maïs en culture de décrue.

CP 22:

Un grand lac près du village de Neoure contient de nombreux nénuphars. Nous n'avons pas observé de typha. Autour du lac se trouve une forêt d'Acacia nilotica. Au moment de la visite, environ 150 à 200 vaches zébus se sont rendues à l'eau, ainsi que plusieurs charrettes à ânes. Au sud du lac, il y a un grand espace ouvert d'herbe.

CP22



Une indication des locations des CP numéros 18-22, à l'est de Dodel.

Samedi 15 décembre

CP 23:

C'est une forêt inondable d'*Acacia nilotica* à l'ouest de Matam. Il y a beaucoup de déchets. Nous avons observé *Acrocephalus scirpaceus* dans la forêt avec *A. nilotica*. En outre, il y avait de broussailles, notamment *A. seyal* et *A. nilotica* avec entre autres *Sylvia inornata*.

CP23

CP 24:

Une zone de culture de décrue juste à côté de Matam. Ici, ils cultivent des courgettes, du maïs, des oignons, des haricots, des tomates, du chou et du poivre. C'est principalement pour un usage privé, éventuellement un surplus est vendu sur le marché. Les maraichages sont séparés par famille et mesurent environ 10 x 25 m.


CP24


CP25

CP 25:
Une zone avec culture de décrue (maïs) à côté du pont (Pont de Diamel) sur le bras latéral du fleuve Sénégal.

CP 26:
Ici il y a des champs de riz récoltés.

CP 27:
Une zone intéressante avec des champs entourés de très hautes digues dans lesquelles des tubes installés pour réguler l'irrigation du canal environnant. C'est le seul endroit où nous avons observé ce mode de culture. Apparemment, le riz et le sorgho sont cultivés dans les compartiments. Il y a un champ de maïs du côté ouest.


CP26


CP27

CP 28:
Un champ de haricots, à côté du maïs.

CP 29:
Un grand lac d'environ 1 km de large, entièrement recouvert de nénuphars. Beaucoup d'oiseaux aquatiques (y compris *Alopochen aegyptiaca*, *Plectropterus gambensis*). Le lac est complètement entouré par la forêt d'Acacia.


CP28


CP29

CP 30:
Voici des maraichages privés à côté de la rivière, avec principalement des oignons. Plus haut sont hautes dunes/collines sur le côté Mauretan de la rivière.

CP 31:
Sur ce site, il y a une étroite bande de culture de décrue, sur une longueur de 5 km. Seulement les patates douces sont cultivées. En plus de la autoconsommation, il y a aussi des ventes sur le marché. Le nom du village était Toufunde Tokomadji. L'un des hommes à qui nous avons parlé vivait dans le village de l'autre côté du fleuve, en Mauritanie. Il cultivait des patates douces sur le sol Sénégalais.


CP31

CP 32:
Ici se trouve une grande plaine avec une savane ouverte des *Balanites aegyptiaca* sur un sol sablonneux. Il y a aussi un grand lac (environ 1,5 km de long) entouré de forêt de *A. nilotica* avec beaucoup des oiseaux, y compris *Sylvia inornata* et *Phylloscopus bonelli*. Le nom de ce lac est Tiguere Yene.

CP 33:
Ici il y a une haute digue (barrière anti-inondation), non praticable pour le voiture.

CP 34:
Voici des champs déserts (rizières autrefois irriguées) au sud de Matam. Au nord, il y a des forêts avec *Acacia seyal* et *Balanites aegyptiaca*.


CP32


CP34

CP 35:
Juste à côté du point ci-dessus se trouvent les rizières en cours d'utilisation (déjà récoltées). Bissap et le gombo sont également cultivés entre les rizières (quelques-unes seulement).

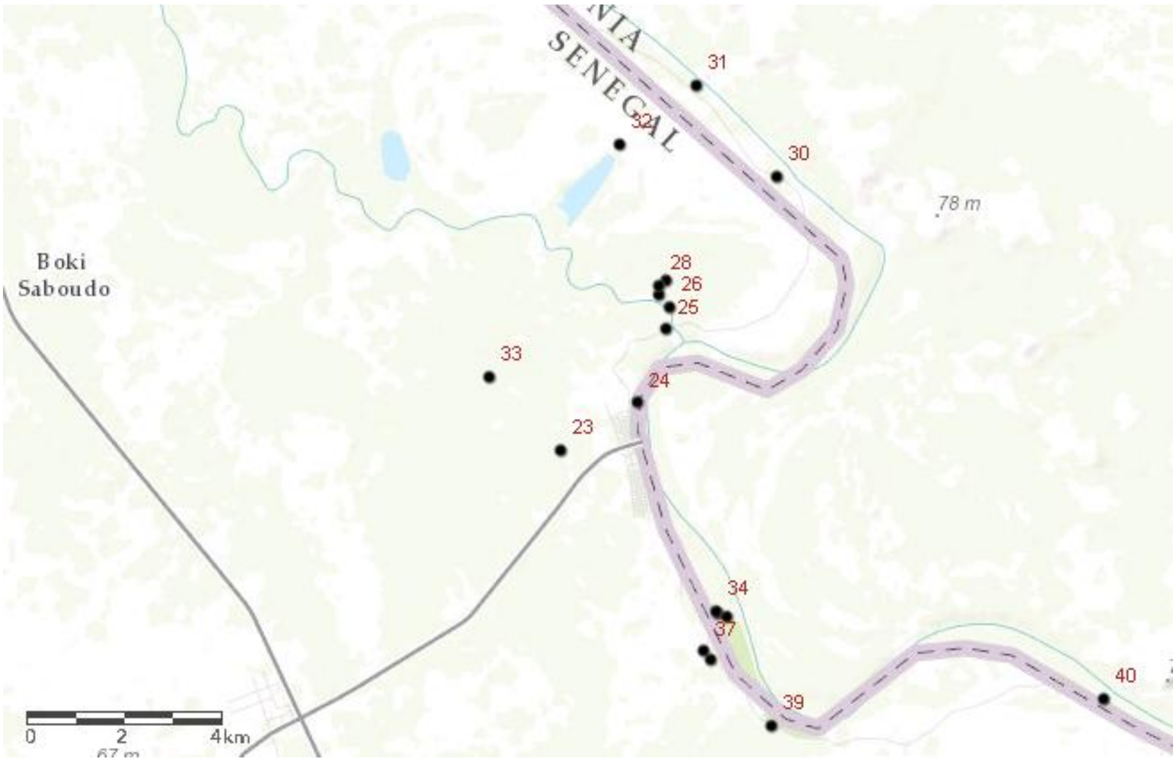
CP 36:
Les champs de riz sont maintenant récoltés, surtout pour la consommation au sein de la communauté. Aussi maïs est cultivé ici. Au niveau de la rivière se trouve une étroite bande de légumes avec patates douces et maïs. Voici également une motopompe dans l'eau pour l'irrigation. Les arbres environnants sont principalement *Acacia seyal*, *Acacia nilotica*, *Balanites aegyptiaca* et *Eucalyptus*.

CP 37:
Sur le côté est de la route, il y a des champs de cultures décrues, avec des haricots et de patates douces.

CP 38:
Juste à côté du point ci-dessus, il y a un lac (Sowandou, environ 17 ha), couvert de nénuphars. En outre, une bande avec du maïs et des haricots. Ce point se situe à environ 650 m après la traversée d'un canal d'irrigation propre. C'était un lac permanent, indiqué par les nénuphars qui ont besoin de plus d'un an pour s'épanouir.

CP 39:
Dans cette région, il y a de nombreuses rizières à grande échelle, jusqu'à environ 2 à 3 km plus à l'est du côté sud de la route. Ces champs ne sont pas visibles sur Google Maps; probablement ces champs ont été récemment effectués.

CP 40:
On y trouve des maraichages des légumes activement irrigués avec principalement du poivre, clôturés par une clôture. C'est apparemment un projet financé par la Suisse. À l'ouest de celle-ci (dans le méandre de la rivière) se trouve une grande savane ouverte avec *Acacia* spp. et *Balanites aegyptiaca*.



Une indication des locations des CP numéros 23-40, sud-est de Matam.

Remarques générales après les journées de travail autour de Matam:

La zone autour de Matam donne une impression différente de celle de Podor. En général, Matam est dans un endroit plus sec et plus ouvert, avec moins d'occupation. Le long de la rivière se trouvent de belles zones de culture de décrue, parfois d'une longueur de plusieurs kilomètres et parfois utilisés couramment par plusieurs villages. Parfois, ces parcelles sont même utilisés par des personnes de la Mauritanie (où aussi l'abondance de la culture décrue sur les banques).

Entre les points 39 et 40, il y a de grandes rizières au sud de la route, qui n'étaient pas encore récoltées lors de la visite sur le terrain. Ces champs ne sont pas visibles sur les images satellites; peut-être ce sont des champs nouvellement créés.

Une grande partie de la région est une savane ouverte avec principalement des *Acacia* spp. et *Balanites aegyptiaca*, comme classé sur la carte de type de terrain. Il y a plusieurs lacs (mares) dans la région, souvent couverts de nénuphars et entourés par la forêt de *Acacia nilotica*. Nulle part, Typha n'est observé lors de la visite sur le terrain. Les résidents locaux ont confirmé: *Typha* n'est pas un problème ici. Les forêts d'inondation d'*Acacia nilotica* revêtent une grande importance pour les oiseaux migrateurs du Paléarctique, abritant beaucoup de *Sylvia inornata*, certains de *Phylloscopus bonelli* et, surprenant, aussi *Acrocephalus scirpaceus*. *Faidherbia albida* n'est pas très commun ici, mais apparemment il y a plus *d'Acacia seyal* que dans la partie occidentale. Les forêts sont principalement dominées par l'*Acacia nilotica* et *Balanites aegyptiaca*. Enfin, *Calotropis procera* est présent sur des sols perturbés.

Dimanche 16 décembre

Un travail de terrain supplémentaire était prévu le dimanche. Cependant, il fallait rentrer à Dakar à cause d'une formation imprévue pour M. Ibrahima Ba le lundi.

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