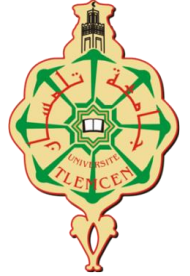




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Racky Diallo

**Evaluation of Lake Guiers' (Senegal) water resources availability under climate
change and human activities by using WEAP model**

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DECLARATION


STUDENT'S DECLARATION

I, Racky Diallo, hereby declare that this thesis titled "Evaluation of Lake Guiers' (Senegal) water resources availability under climate change and human activities" is my original work to the best of my knowledge and has not been submitted to the University or any other institute or published earlier for the award of any degree or diploma. I also declare that all the information, materials and results from other works presented in this thesis have been duly cited and recognized as required of academic rules and ethics.

Name: Racky Diallo

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Signature:

A handwritten signature in black ink, appearing to read 'Racky Diallo', written over a horizontal line.

ABSTRACT

This study assesses the future availability of water resources in Lake Guiers, Senegal, by 2050, under the combined impacts of climate change and human activities, using the WEAP (Water Evaluation and Planning) model. As the main freshwater reservoir of Senegal, Lake Guiers faces multiple threats, including intensive agriculture, aquatic plant proliferation, conflicting stakeholder interests, rising water demand, and the effects of climate change. Our methodology integrates original field data on water quality, hydrological flows, and agricultural water uses, combined with climate projections (SSP4.5 and SSP8.5). Future climate scenarios were downscaled and bias-corrected using CMHYD, Multiple Linear Regression (MLR), and the Mann-Kendall test. The WEAP model calibration yielded statistically robust results (NSE = 0.95; $R^2 = 0.96$). Climate projections (2015–2100) indicate a decline in precipitation of 0.66 mm/year (SSP4.5) and 1.71 mm/year (SSP8.5), alongside a temperature increase of 0.040°C/year and 0.080°C/year, respectively. Significant water losses were observed in the Taouey canal (6.32 m³/s, or 546,048 m³/day), while annual agricultural water withdrawals (79.33 million m³) exceed crop water requirements by 10.21 million m³/year, causing severe inefficiencies. Scenario analysis reveals that high water demand combined with SSP8.5 accelerates the lake's volume depletion, with critical declines beginning as early as 2026, while a moderate demand increase (2%) under SSP4.5 could maintain water availability until 2050. The PREFERLO_Grand transfer project, requiring 556 million m³ annually, is incompatible with the lake's capacity, rapidly driving it toward the inactivity threshold of 149 million m³. This research provides critical insights for sustainable water resource management and policy development, offering practical guidance to address the growing climatic and anthropogenic challenges in the Lake Guiers region.

Key words: Lake Guiers, WEAP model, Climate Change, human activities, water resources

RÉSUMÉ

Cette étude évalue la disponibilité future des ressources en eau du lac de Guiers, au Sénégal, à l'horizon 2050, sous les effets combinés du changement climatique et des activités humaines, en utilisant le modèle WEAP (Water Evaluation and Planning). En tant que principal réservoir d'eau douce du Sénégal, le lac de Guiers est confronté à de multiples menaces, notamment l'agriculture intensive, la prolifération des plantes aquatiques, les conflits entre les parties prenantes, l'augmentation de la demande en eau et les effets du changement climatique. Notre méthodologie intègre des données de terrain originales sur la qualité de l'eau, les flux hydrologiques et les utilisations agricoles de l'eau, combinées à des projections climatiques (SSP4.5 et SSP8.5). Les scénarios climatiques futurs ont été mis à l'échelle et corrigés en utilisant CMHYD, la régression linéaire multiple (MLR), et le test de Mann-Kendall. La calibration du modèle WEAP a donné des résultats statistiquement robustes ($NSE = 0.95$; $R^2 = 0.96$). Les projections climatiques (2015-2100) indiquent une baisse des précipitations de 0,66 mm/an (SSP4.5) et de 1,71 mm/an (SSP8.5), ainsi qu'une augmentation de la température de 0,040°C/an et de 0,080°C/an, respectivement. Des pertes d'eau importantes ont été observées dans le canal de la Taouey (6,32 m³/s, soit 546 048 m³/jour), tandis que les prélèvements d'eau agricoles annuels (79,33 millions de m³) dépassent les besoins en eau des cultures de 10,21 millions de m³/an, ce qui entraîne de graves inefficacités. L'analyse des scénarios révèle qu'une forte demande en eau combinée au scénario SSP8.5 accélère l'épuisement du volume du lac, avec des baisses critiques dès 2026, alors qu'une augmentation modérée de la demande (2 %) dans le cadre du scénario SSP4.5 pourrait maintenir la disponibilité de l'eau jusqu'en 2050. Le projet de PREFERLO_Grand transfert, qui nécessite 556 millions de m³ par an, est incompatible avec la capacité du lac, qui se rapproche rapidement du seuil d'inactivité de 149 millions de m³. Cette recherche fournit des informations essentielles pour la gestion durable des ressources en eau et l'élaboration de politiques, en offrant des conseils pratiques pour relever les défis climatiques et anthropiques croissants dans la région du lac de Guiers.

Mots clés : Lac de Guiers, modèle WEAP, changement climatique, activités humaines, ressources en eau

DEDICATION

AKNOWLEDGEMENT

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LIST OF ABBREVIATIONS

ADCP – Acoustic Doppler Current Profiler

BOD – Biochemical Oxygen Demand

BOD5 – Biochemical Oxygen Demand over 5 Days

CNRM-ESM2-1 – Centre National de Recherches Météorologiques-Earth System Model 2-

CMIP6 – Coupled Model Intercomparison Project Phase 6

CORDEX – Coordinated Regional Climate Downscaling Experiment

CSS – Compagnie Sucrière Sénégalaise

DO – Dissolved Oxygen

DPC – Direction de la Pêche Continentale

DREEC – Direction Régionale de l'Environnement et des Établissements Classés

DRDR – Direction Régionale du Développement Rural

DTMs – Digital Terrain Models

FAO – Food and Agriculture Organization

GDP – Gross Domestic Product

GCMs – Global Climate Models

GHG – Greenhouse Gases

GPS – Global Positioning System

IAV – Invasive Aquatic Vegetation

IGN – Institut Géographique National

IPCC – Intergovernmental Panel on Climate Change

ISRA – Institut Sénégalais de Recherches Agricoles

KMS – Keur Momar Sarr

MLR – Multiple Linear Regression

NSE – Nash-Sutcliffe Efficiency

OLAC – Office des Lac et Cours d'eau du Senegal

OMVS – Organisation pour la Mise en Valeur du fleuve Sénégal

ORSTOM – Office de la Recherche Scientifique et Technique Outre-Mer

PREFERLO – Projet de Renforcement de la Résilience des Écosystèmes du Ferlo

RCP– Representative Concentration Pathway

RCMs – Regional Climate Models

SAED – Société d'Aménagement et d'Exploitation des terres du Delta

SEI – Stockholm Environment Institute

SEQ – Système National d'Évaluation de la Qualité des Eaux

SEN'EAU –Sénégalaise des Eaux

SPI – Standardized Precipitation Index

SRTM – Shuttle Radar Topography Mission

SSP – Shared Socioeconomic Pathways

WEAP – Water Evaluation and Planning

WHO – World Health Organization

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CHAPTER ONE

1. INTRODUCTION

1.1. Background of Study

Access to drinking water is a fundamental human right and a prerequisite for sustainable development. According to the United Nations World Report (2019), more than 2.1 billion people still do not have access to drinking water (Grelley, 2022; Loudière & Gourbesville, 2020). In sub-Saharan Africa, the availability of fresh water is essential to economic growth and social development, particularly for the 70% of the rural population dependent on agriculture (Sambou, 2017).

Climate change represents a major threat to the world's water resources. According to the Intergovernmental Panel on Climate Change (IPCC), most regions of the world are likely to experience a negative impact on their freshwater resources and aquatic ecosystems, with increased evaporation and changes in precipitation patterns affecting runoff and the frequency of floods and droughts (Bodian et al., 2018a; Calvin et al., 2023). In semi-arid regions, these phenomena are amplified by potential evapotranspiration that is already higher than annual rainfall (Loudière & Gourbesville, 2020).

In Senegal, although water resources are estimated at 4,747 m³/capita/year, the water sector faces numerous challenges: scarcity, rainfall irregularity, vulnerability of resources, uneven spatial distribution, conflicts of use, overexploitation and qualitative degradation (Cheikh & Sidy, 2018). In the Senegal River basin, water resources faced multiple challenges such as: climate variability, plus demographic pressures and various productive activities (Sambou, 2017).

Moreover, water is the main vector of childhood diseases in Africa, accounting for 70-80% of the continent's pathologies. According to the World Bank, water scarcity exacerbated by climate change could lead to a drop in GDP of around 6% in some regions, cause migration and trigger conflicts (Cheikh & Sidy, 2018). Faced with these challenges, assessing the availability of water resources is a fundamental step towards rational management (Cheikh & Sidy, 2018).

It is crucial to focus on water-limited areas, as these regions are particularly vulnerable to the impacts of climate change and increasing water demand. Ensuring water security in such areas is essential to sustain livelihoods, support agricultural productivity, and maintain ecosystem health. Without immediate action, water will become a scarce resource even in areas where it is currently abundant, with far-reaching consequences for all socio-economic activities (Nkiaka

et al., 2021). Failure to guarantee water security will jeopardise the achievement of several Sustainable Development Goals, including those relating to poverty, hunger, health, gender equality, clean energy and the protection of ecosystems (Nkiaka et al., 2021).

1.2. Problem Statement and Justification

Located in northwestern Senegal, characterized by a semi-arid climate, Guiers Lake is a vital water resource for the country. It is fed by the Senegal River via the new Taouey Canal spanning 17 km, holding a storage potential of 650 Million m³ of fresh water (Seck, 2005). The lake provides crucial ecosystem services such as drinking (e.g., 50% of Dakar water supply), small-scale local farming, agribusinesses, livestock, and household needs for the nation (Kamara, 2013). Consequently, the basin fosters diverse socio-economic activities, including fishing which generates 15 Million XOF per week; agriculture with an irrigable land potential exceeding 100,000 hectares; and livestock farming involving various animal species (P. Diop, 2017).

The soil fertility and abundance of water have promoted the establishment of many agri-industries, such as CSS, West Africa Farm, and Swame Agri, which specialize in the cultivation of various crops such as rice, sugar cane, meadows, and fruit crops (Cisse, 2012). These water-intensive activities depend heavily on Lake Guiers as the main source of water supply. However, the quality of Lake Guiers is deteriorating due to the supply of nutrients, mainly from agricultural areas, through landfill stations, drainage, irrigation, and soil washing (Sambou et al., 2018). In addition, eutrophication of the lake caused by the proliferation of aquatic plants is becoming increasingly common, and tensions are emerging between the various users of the lake (Sambou et al., 2018).

Faced with these challenges, exacerbated by global climate change and increasing demand for water, it has become imperative to evaluate and plan the management of this vital water resource. Water allocation models such as WEAP (Water Evaluation and Planning) provide a suitable methodological framework for analysing the current and future state of water resources in Lake Guiers. The model integrates climatic, demographic and socio-economic variables in a systemic approach to assess future water availability and propose sustainable management strategies.

1.3. Study Objectives

The aim of this study is to assess the availability of water resources in Lake Guiers by 2050 under the combined effect of climate change and human activities using the WEAP model.

To achieve this, four specific objectives have been defined:

- Collect and analyse current hydro-climatic, qualitative and socio-economic data for Lake Guiers in order to establish a reference state for the WEAP modelling;
- Develop climate scenarios based on the SSP4.5 and SSP8.5 projections to assess the impact of climate change on water availability in Lake Guiers by 2050;
- Develop scenarios for the evolution of anthropogenic pressures integrating the expansion of irrigated areas, the increase in demand for drinking water and future water transfer projects to assess the lake's capacity to satisfy future demands over the period 2021-2050;
- Carry out a sensitivity analysis on variations in water inflows from the Senegal River (via the Taouey canal) in order to assess their impact on the storage volume of Lake Guiers.

1.4. Thesis Structure

This thesis is organized into six chapters structured as follows:

Chapter One: Introduction. This chapter presents the general background of the study, the problem statement and its justification, the research objectives, and the overall structure of the thesis.

Chapter Two: Literature Review. This chapter examines the state of knowledge on Lake Guiers, including management challenges, water quality, and climate change impacts in this area. It also provides a comprehensive analysis of the WEAP model, from its historical development to its technical description, algorithms, and its applications.

Chapter Three: Methodology. This chapter details the methodological approach adopted, including the presentation of the study area, the current climatic context, the climate projections used, the geomorphological and hydrological characteristics of the lake, methods for data collection and analysis, as well as the parameterization and calibration of the WEAP model.

Chapter Four: Results. This chapter presents the findings obtained from data collection and the WEAP modeling under different climate and anthropogenic scenarios, illustrating the projected evolution of Lake Guiers water resource availability up to 2050.

Chapter Five: Discussion. This chapter provides a critical analysis of the results, compares them with existing literature, evaluates implications for the future management of the lake, and identifies the limitations of the study.

Chapter 6: Conclusion and Recommendations. This chapter synthesizes the main conclusions of the study and formulates practical recommendations for sustainable management of Lake Guiers water resources in the face of climate change challenges and increasing anthropogenic pressures.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Challenges in Lake Guiers basin

- Salinity in Lake Guiers basin

Lake Guiers, a shallow tropical lake, has experienced significant hydrological and ecological transformations driven by natural and anthropogenic factors. Salinity persists in the delta's soils due to marine-origin salt deposits from the Nouakchottian transgression (5500 BP) (Cisse, 2012). Salinity levels vary spatially and temporally, increasing from Northern to Southern part of the lake (Richard Toll to Keur Momar Sarr) (Djiby et al., 2017). The salinity results from saline water table intrusion, evaporation, and drainage from irrigated agriculture, which contributes 56% of the salt inflow (Cogels et al., 2001; Djiby et al., 2017). Since the Diama Dam's construction in 1986, salinity regulation has reduced seasonal variations but triggered the proliferation of aquatic plants. Coverage of invasive species such as *Typha australis*, *Pistia stratiotes*, and *Salvinia molesta* grew from 5.4% in 1985 to 23.3% in 2015 (P. Diop, 2017; Diouf, 2016), occupying 7,458 hectares by 2010 and reducing open water and floodplain areas by 2,339 and 4,021 hectares, respectively (Djiby et al., 2017).

- Eutrophication of the lake

Agricultural runoff and permanent freshwater availability have exacerbated eutrophication, particularly near the Taouey canal, where nutrient loading peaks during the rainy season (Djiby et al., 2017). These conditions impede water access, reduce hydraulic capacity, and contribute to the spread of waterborne diseases such as malaria and schistosomiasis (Cisse, 2012).

- Conflicts in Lake Guiers basin

Declining rainfall and runoff, coupled with rapid and poorly managed hydro-agricultural development, have intensified tensions among users. Conflicts between farmers, herders, and fishermen over land use are compounded by inadequate governance (Kamara, 2013; Y. Tall et al., 2017). Efforts to resolve conflicts, such as the Land Use and Allocation Plan (POAS) initiated by the government through the ministries responsible for regional planning, agriculture and local authorities, have largely failed, marginalizing local stakeholders in favor of agro-industrial interests (Cisse, 2012; P. Diop, 2017).

- Water management issues in Lake Guiers Basin

In fact, Lake Guiers is Senegal's primary freshwater reserve, supplying drinking water to Dakar, Thiès, Louga, and Saint-Louis via treatment plants in Ngnith and Keur Momar Sarr. However, its management is hindered by overlapping institutional mandates (OLAC, SAED, SEN'EAU, OMVS, DREEC, DRDR, ISRA, DPC), stakeholder conflicts (farmers, herders, local users and fishermen), and uncoordinated planning (P. Diop, 2017; Kamara, 2013; Ndiaye & Mbaye, 2020; Seck, 2005; Y. Tall et al., 2021). Water management prioritizes Dakar's drinking water and irrigated agriculture, often at the expense of fishing needs, while pesticide pollution poses an additional threat (Diouf, 2016).

- Human activities in Lake Guiers basin

The lake also supports livelihoods through fishing, agriculture, livestock farming, and domestic uses. Fishing potential is estimated at 1800-2400 tons per year for Lake Guiers and 500-600 tons per year for the Ndiaël basin (Diouf, 2016). However, intensified anthropogenic pressures, including domestic and agricultural discharges, animal waste, and harmful fishing practices like monofilament nets, degrade the lake's ecological quality (Diouf, 2016; Y. Tall et al., 2021).

The Diama Dam's opening in 1985 permanently stabilized water levels, facilitating the rapid expansion of irrigated agriculture, hydro-agricultural projects, traditional fishing, intensified pastoralism, and agro-industries (Seck, 2005). This development, however, has also introduced environmental and socio-economic challenges, including the proliferation of aquatic plants, agricultural pollution from unregulated fertilizers and chemicals, wastewater discharges, and overfishing (Tall et al., 2017).

2.2. Water quality and ecology of Lake Guiers

Since the construction of the Diama Dam in 1985, the expansion of farmlands and agribusiness has raised environmental issues (P. Diop, 2017; Diouf, 2016). Indeed, Lake Guiers has become a repository for wastewater discharges, agricultural runoff laden with fertilizers and unauthorized chemicals, and irregular shoreline developments. Unsustainable fishing practices, including the use of monofilament nets and overfishing, have also exacerbated the situation (P. Diop, 2017). Moreover, pesticide pollution hampers efforts to remove the Ndiaël Reserve, fed by Lake Guiers, from the Montreux List (Diouf, 2016).

According to the study conducted by Kâ et al. (2011), the hydrology of Lake Guiers is strongly influenced by the Senegal River's flow regime, characterized by intense flooding between mid-

July and October, followed by a prolonged low-water period from December to mid-July. The lake rapidly fills with floodwaters, and its levels decrease gradually due to evaporation and water use during the dry season (Kâ et al., 2011). The Keur Momar Sarr floodgate, which releases old water into the Ferlo Valley during floods, helps regulate these levels but influences the lake's conductivity and salinity. Salinity fluctuations are further impacted by naturally saline groundwater and salty soils around the Senegal River Delta (Kâ et al., 2011).

Historical data reveal extreme salinity levels during 1977–1983, averaging over 1,300 mg/L and reaching peaks of 10,000 mg/L in some areas. However, the construction of the Diama Dam significantly reduced salinity levels, stabilizing them at 150 mg/L by 2000. The north-south salinity gradient also narrowed from a range of 300–1,600 mg/L in 1980 to 50–300 mg/L in recent years (Cogels et al., 2001; Diedhiou, 2022).

Nutrient concentrations in the lake exhibit distinct patterns. Phosphorus (P) levels are highest in the central areas, especially near water treatment plants, while nitrogen (N) concentrations peak in the Taouey Canal before stabilizing in the lake (Cogels et al., 2001). However, competition from aquatic macrophytes limits phytoplankton growth in some regions. Total nitrogen concentrations range from 1–2.5 mg/L in the lake to 6.5 mg/L in the Taouey Canal, with nitrate levels remaining below 1 mg/L throughout (Cogels et al., 2001). Dissolved oxygen (DO) levels are generally sufficient but are subject to seasonal fluctuations influenced by temperature, wind patterns, and phytoplankton activity. Zones with dense vegetation or drainage discharges often experience localized DO depletion (Cogels et al., 2001).

Phytoplankton composition varies across the lake, forming four distinct zones. The northern region is dominated by Bacillariophyceae with low biomass and is affected by point source pollution. The central zone exhibits high cyanobacteria biomass, indicative of eutrophication (Cogels et al., 2001; Kâ et al., 2011). In contrast, the southern zone and Ferlo area feature cryptophyceae, dinophyceae, and euglenophyceae, where competition with macrophytes limits phytoplankton growth (Cogels et al., 2001).

The stabilization of Lake Guiers' water levels has significantly impacted its ecology, promoting the growth of aquatic vegetation such as *Pistia stratiotes*, *Ceratophyllum demersum*, and *Typha domingensis* (S. Diop et al., 2016; Diouf, 2016; Kâ et al., 2011). These plants disrupt fisheries, hinder water navigation, and facilitate the spread of waterborne diseases like schistosomiasis (Diouf, 2016). The proliferation of macrophytes, including *Potamogeton schweinfurthii* in the

northern lake, highlights the ecological challenges resulting from water regulation infrastructure (Thiam and Ouattara, 1997 cited by Cogels et al., 2001).

Physicochemical parameters further illustrate the lake's variability. The water pH ranges from 6.8 to 9, while seasonal temperatures vary between 18°C and 30°C, averaging 25°C. Conductivity levels of 160–210 $\mu\text{S}/\text{cm}$ and total dissolved solids (TDS) of 198–250 mg/L reflect the lake's improved water quality over recent decades (S. Diop et al., 2016).

The lake is increasingly exhibiting signs of eutrophication, characterized by elevated Chlorophyll-a concentrations, reduced water transparency, and the dominance of cyanobacteria such as *Cylindrospermopsis raciborskii* and *Lyngbya versicolor* (Diédhiou et al., 2019). These species, along with diatoms like *Fragilaria sp.*, indicate a shift toward eutrophic conditions. Chlorophyll-a levels range from 4.3 $\mu\text{g}/\text{L}$ to 19.81 $\mu\text{g}/\text{L}$, with the highest values recorded during the hot season in central and inhabited areas (Diédhiou et al., 2019).

Zooplankton populations are most abundant during the warm, rainy season (July–October), with peaks for rotifers and cyclopid copepods. Cyanobacteria dominate phytoplankton composition during warm periods, while diatoms prevail during cooler months (Kâ et al., 2011). These shifts highlight the influence of temperature, flooding, and trophic interactions on the lake's ecological dynamics (Kâ et al., 2011).

While Lake Guiers remains a critical freshwater resource for Senegal, its quality is increasingly under threat from eutrophication, salinity variations, and pollution.

2.3. Impact of Climate Change in Senegal's Lake Guiers Basin

Climate change presents a critical challenge to water resources, with profound implications for socio-economic systems. Rising temperatures and increasing variability in precipitation patterns are anticipated to exacerbate water scarcity, reduce water quality, and intensify water demand (IPCC, 2014). These impacts are particularly severe for regions like Northern Sahara and West Africa, where fragile ecosystems and resource-dependent livelihoods are acutely vulnerable to climatic changes.

West Africa faces a complex water security challenge due to climate change. Studies across the region paint a contradictory picture, with the potential for both increased water availability in some areas (e.g., Sahelian paradox in Niger) and significant threats due to uneven distribution and population growth (Sambou et al., 2018, 2019; Tall et al., 2017b). Research on Senegal's Lake Guiers basin highlights these contrasting trends. While some studies suggest a temporary

increase in rainfall (Sambou et al., 2019), others predict a drying trend by the end of the century (M. Tall et al., 2017). This uncertainty underscores the need for a wider range of climate scenarios to be considered in future planning (Bodian et al., 2018b).

Rising temperatures projected to increase by 3°C under RCP4.5 and up to 6°C under RCP8.5 by 2100 (Ndiaye & Mbaye, 2020), pose an even greater threat. These temperature increases could intensify evaporation losses by 10-50% and placing additional stress in the Lake Guiers basin (Tall et al., 2017b). This essentially means more water will be lost from the system due to higher temperatures, creating a greater demand on remaining freshwater resources. The Gambia River Basin appears even more vulnerable, facing a potentially larger decrease in streamflows compared to Senegal (up to 26% decrease by 2050 under RCP8.5) (Bodian et al., 2018b).

Current climate models used for predictions have limitations, particularly at the local scale of Lake Guiers (Alioune, 2021). Studies highlight the coarse resolution of Global Climate Models (GCMs) that might not capture important regional variations (Bodian et al., 2018b). While researchers are working on improving these models through initiatives like CORDEX (Coordinated Regional Climate Downscaling Experiment), better data is still needed to precisely understand the impact of climate change on the lake's specific hydrological cycle (Alioune, 2021). Researchers recommend exploring new techniques like high-resolution Regional Climate Models (RCMs) and soft computing for improved modelling (Bodian et al., 2018b; Goyburo et al., 2023).

The situation in Lake Guiers basin reflects a wider challenge for the entire Senegal River Basin. Studies predict an increase in the frequency and intensity of droughts and floods, on top of a long-term decline in rainfall and annual average water flow observed over the past decades (Gaye et al., 2013). Such hydrological extremes are expected to intensify with global warming, which has already raised global surface temperatures by 1.1°C between 2011 and 2020, predominantly due to greenhouse gas (GHG) emissions from human activities (IPCC, 2023). Although emissions have increased in most regions of the globe, they are not uniformly distributed, both now and over the period since 1850. For instance, emissions have increased by 2% in Africa (IPCC, 2023).

Water scarcity is already a pressing issue, with almost half the global population facing acute shortages for at least part of the year due to climatic and non-climatic stressors (IPCC, 2023).

These dynamics are particularly acute in arid and semi-arid regions like lake Guiers basin. WEAP-based studies suggest that while current water availability may suffice, significant shortages could emerge under drier conditions such as those projected by RCP8.5 at the century's end (Sambou et al., 2018).

The Shared Socio-economic Pathways (SSPs) offer a framework for understanding future risks, vulnerabilities, and adaptation strategies. These scenarios illustrate a spectrum of possible emissions trajectories, from low-emission pathways (SSP1-1.9 and SSP1-2.6) where CO₂ levels decline to net-zero by mid-century, to high-emission scenarios (SSP3-7.0 and SSP5-8.5) where emissions approximately double by 2050 and 2100, respectively (IPCC, 2023). Intermediate scenarios (SSP2-4.5) maintain emissions near current levels until mid-century. These pathways underscore the interplay between societal trends and climate change, showing how development patterns can either mitigate or exacerbate water-related challenges (Miralles-Wilhelm et al., 2017).

The impacts of climate change on water resources are complex, particularly in regions like West Africa, where climatic uncertainties and socio-economic pressures intersect. Addressing these challenges requires integrated approaches that combine advanced climate modelling, improved data quality, and adaptive water management strategies to enhance resilience and support sustainable development in vulnerable regions.

2.4. Water Evaluation and Planning System (WEAP) Model

2.4.1. Background

WEAP is a user-friendly model developed by the Stockholm Environment Institute (SEI) for integrated water resources planning and management (Nivesh et al., 2022; Oti, 2019). It is a valuable tool for simulating water allocation (supply and demand) dynamics under different scenarios. WEAP is a conceptual model that allows for the representation of physical water systems like watersheds, rivers, and reservoirs (Goyburo et al., 2023). The model requires various inputs such as land cover, soil types, water sources, water demands (agricultural, domestic, etc.), and economic factors (Nivesh et al., 2022). Hydrological simulations within WEAP can be performed using different methods. Nivesh et al. (2022) employed the rainfall-runoff method, while Opere et al. (2022) and Goyburo et al. (2023) used the soil moisture method. WEAP can handle various water quality aspects. Mishra et al. (2017) used WEAP to simulate key water quality parameters like Dissolved Oxygen (DO) and Biochemical Oxygen

Demand (BOD). The model can also be linked to even more sophisticated water quality models like QUAL2K.

WEAP facilitates scenario-based water demand forecasting. Indeed, Nivesh et al.(2022) and (Goyburo et al., 2023) used WEAP to model future water demand considering population growth, economic development, and climate change. Nivesh et al. (2022) emphasized WEAP's role in water management planning under climatic and human-induced constraints and their results indicated that by 2050, increasing population growth, industrial development, and an increase in the agricultural area will rise the water demand dramatically, posing threats to the environment and humans.

2.4.2. Description of WEAP

WEAP (Water Evaluation and Planning System) is a proactive and comprehensive water management tool designed to simulate water demand, supply, streamflow, and storage (SEI, 2007). It consists of five key components (figure 1): the Schematic View, which provides a visual representation of the water system; the Data View, a hierarchical tree structure for inputting and managing data across categories like Key Assumptions, Demand Sites, Hydrology, Supply and Resources, Water Quality, and Other Assumptions; the Results View, which displays scenario outcomes through charts, tables, or maps; the Scenario Explorer View, used to compare the impacts of different scenarios on water availability, ecosystem needs, and other factors; and the Notes View, which allows for documentation and referencing. Together, these features enable users to model, analyze, and evaluate water systems effectively, supporting informed decision-making and integrated water resources management.

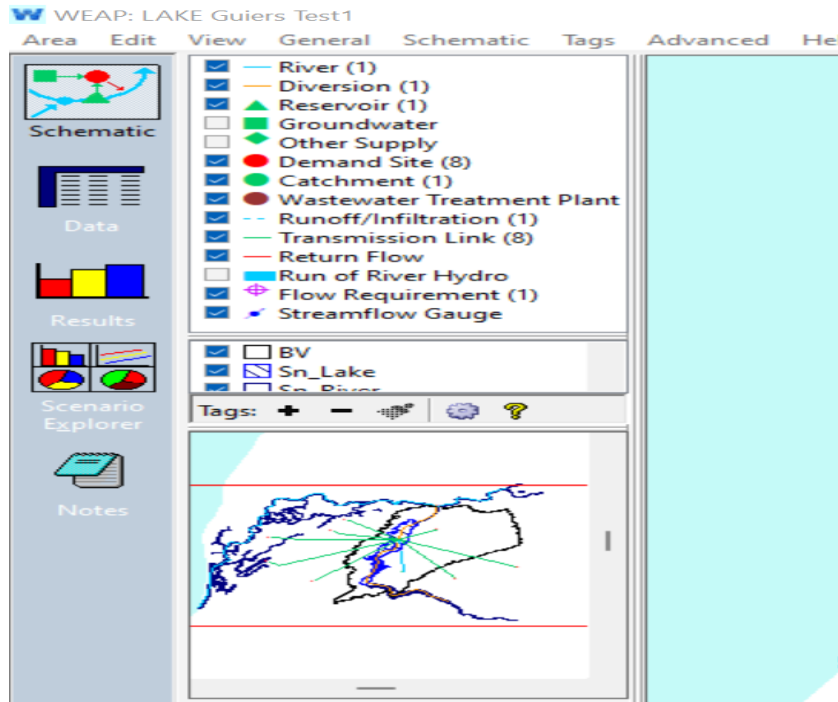


Figure 1: WEAP’s interface

2.4.3. Algorithms of WEAP

In the WEAP model, water demand is calculated using two primary methods: the Monthly Demand option, which allows users to input demand values on a monthly basis or import monthly data via a "ReadFromFile" function from a CSV file, and the Annual Demand with Monthly Variation option, where the annual water demand is computed based on an activity level (e.g., population) and a water use rate. The total water demand is calculated as the product of the total activity level and the water use rate, expressed as:

$$\text{Total Demand} = \text{Total Activity Level} \times \text{Water Use Rate}$$

In WEAP, the annual demand for a demand site is the sum of the demands from all its bottom-level branches (Br), calculated as:

$$\text{Annual Demand} = \sum (\text{Total Activity Level} \times \text{Water Use Rate}) \text{ Br}$$

According to SEI (2014), the total activity level for a bottom-level branch is determined by multiplying the activity levels of the bottom branch (Br), its parent branch (Br’), and its grandparent branch (Br’'), expressed as:

$$\text{Total Activity Level Br} = \text{Activity Level Br} \times \text{Activity Level Br}' \times \text{Activity Level Br}''$$

This hierarchical approach ensures accurate and flexible water demand calculations, accommodating varying levels of complexity and data availability.

2.4.4. WEAP applications

WEAP seamlessly integrates climate change projections into water resource management. Research conducted by Opere et al.(2022); Oti(2019); Sambou et al.(2018); Touseef et al.(2021) showcases WEAP's utility in assessing the impact of climate change on surface water availability. The Water Evaluation and Planning System (WEAP) model offers a valuable tool for planning and managing Senegal's water resources in the face of climate change (Sambou et al., 2018, 2019; Sambou & Diekkrüger, 2017). Touseef et al.(2021) employed WEAP to integrate downscaled monthly rainfall and temperature data from multiple climate models into the SWAT model, which subsequently generated streamflow data for WEAP. This highlights the model's ability to incorporate complex climate projections.

WEAP supports also the evaluation of water quality management interventions. For example Mishra et al.(2017) used WEAP's water quality modeling capabilities to assess the effectiveness of planned wastewater treatment plants. Their study demonstrates WEAP's potential for evaluating various water quality management strategies.

WEAP also aids in developing water security strategies. Goyburo et al.(2023) employed the model to assess water security in the Vilcanota-Urubamba catchment under various climate and socio-economic scenarios. Their findings highlight the importance of WEAP in informing water security strategies that consider integrated water resource management and infrastructure investments.

Despite its proficiency in simulating water quantity, WEAP's application in water quality management beyond point source pollution remains relatively unexplored (Mishra et al., 2017). Future studies could delve into the effectiveness of utilizing WEAP for mitigating non-point source pollution. Additionally, while much research concentrates on forecasting future water demand (Goyburo et al., 2023; Nivesh et al., 2022), there is a need for studies integrating WEAP with demand management strategies such as water conservation or pricing mechanisms, which could yield valuable insights.

CHAPTER THREE

3. METHODOLOGY

3.1. Presentation of the study area

Lake Guiers, located in north-western Senegal between the regions of Saint-Louis and Louga, is one of the main reservoirs of the Senegal River (Figure 2). It is 50 km long and 7 km wide, with a surface area varying between 252 and 340 km², with a management slope of 1.5 to 2.5 m IGN. Its filling capacity fluctuates between 450 and 750 million m³ (OLAC,2020).

The lake is linked to the Senegal River via the Taouey, a 17 km channel built in 1974 to optimise water transfers and reduce head losses. Two dams, Richard-Toll and Ndombo, were built to regulate the lake's water supply.

Historically, Lake Guiers received inflows from the Senegal River to the north, via the Taouey, and from the lower Ferlo valley to the south, notably via the Bounoum valley. At Keur Momar Sarr, the lake makes a bend and opens out towards this valley, which continues towards Yang-Yang, where the Ferlo fossil network begins, now dysfunctional due to the dune complex on the Ferlo plateau.

Endoreic in nature, Lake Guiers is shallow, typical of Sahelian lakes, and plays an essential role in irrigation and the supply of drinking water via the Ngnith and KMS plants.

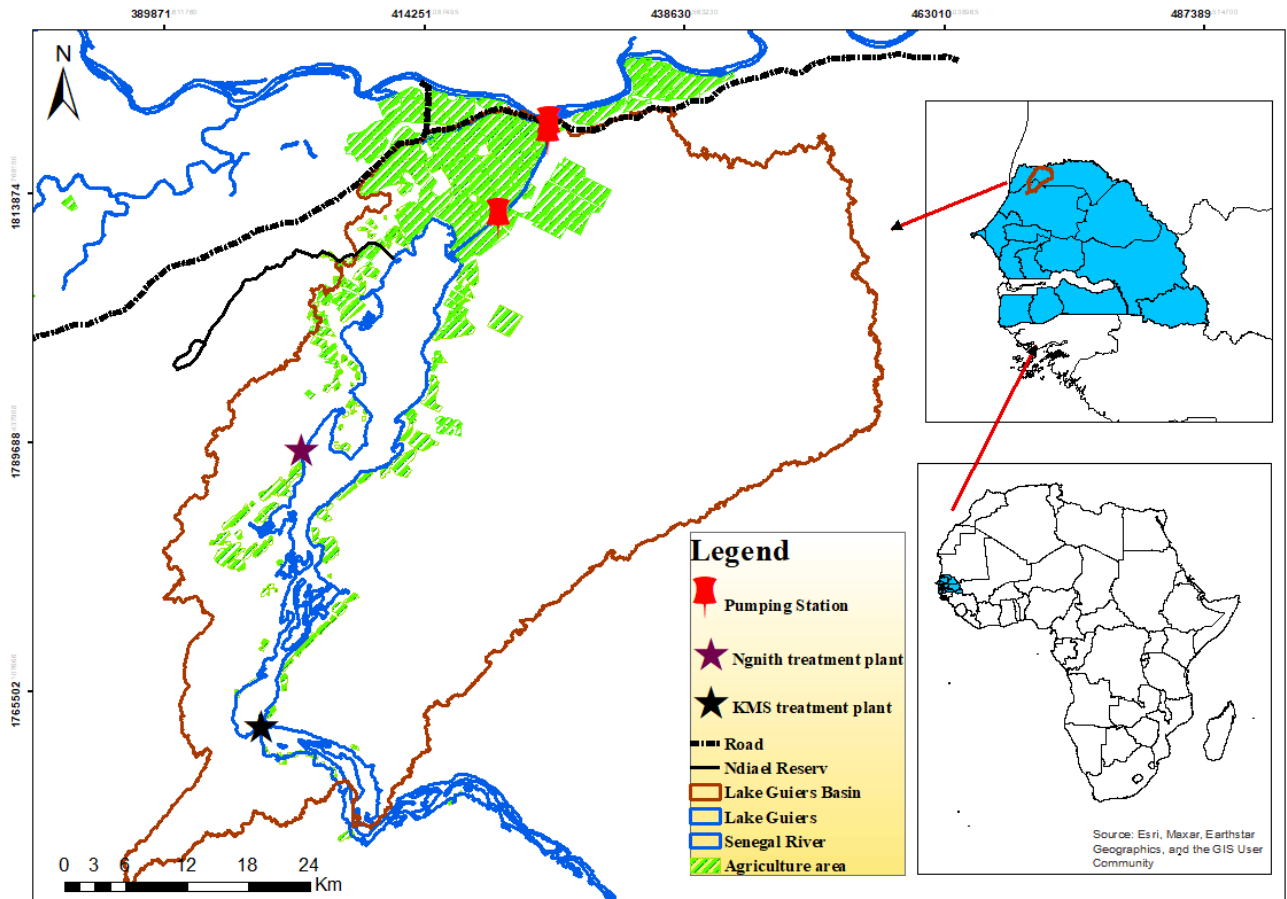


Figure 2: Carte de la zone d'étude

3.2. Climatic context

3.2.1. Standardized Precipitation Index (SPI)

The Lake Guiers basin is part of the Sahelian climate zone, characterised by low rainfall. The Standardised Precipitation Index (SPI) has been calculated to provide a more detailed assessment of rainfall anomalies. This index makes it possible to summarise information and visualise changes in rainfall series anomalies over a long period (Descroix et al., 2015). It is calculated over 12 months, according to the formula (Bergaoui and Alouini, 2001):

$$SPI = \frac{P_i}{P_m} - 1$$

SPI: Standardized Precipitation Index; P_i : Annual Precipitation; P_m : Mean Precipitation

When the SPI is between -0.99 and 0.99, it is a normal rainfall year. If the SPI is ≥ 1 , it is a wet or surplus year, and if the SPI is ≤ -1 , it is a dry or deficit year.

Analysis of the anomalies has shown that the mean annual precipitation regime has undergone a change over the period 1953-2020 (Figure 3):

- 1953-1969: a relatively wet period with brief dry spells;
- 1970-1981: during this period, the Lake Guiers area was affected by dry years, although a short period of humidity was observed from 1978 to 1981;
- 1982-1999: the Sahel experienced a major drought, with a significant peak in rainfall deficit (-1.92) in 1983;
- 2000-2010: this was a rainy decade with surpluses in rainfall, peaking in 2010 (+2.79);
- 2011-2016: these were years of relatively normal rainfall, with alternating surpluses and small deficits, with the exception of 2016, when there was a significant rainfall deficit similar to that recorded in 1983.
- 2017-2021: this corresponds to a rainfall deficit with a peak of -1.74 recorded in 2020.

In this context of climatic variability (often deficit), Lake Guiers must be monitored to preserve the hydrological system.

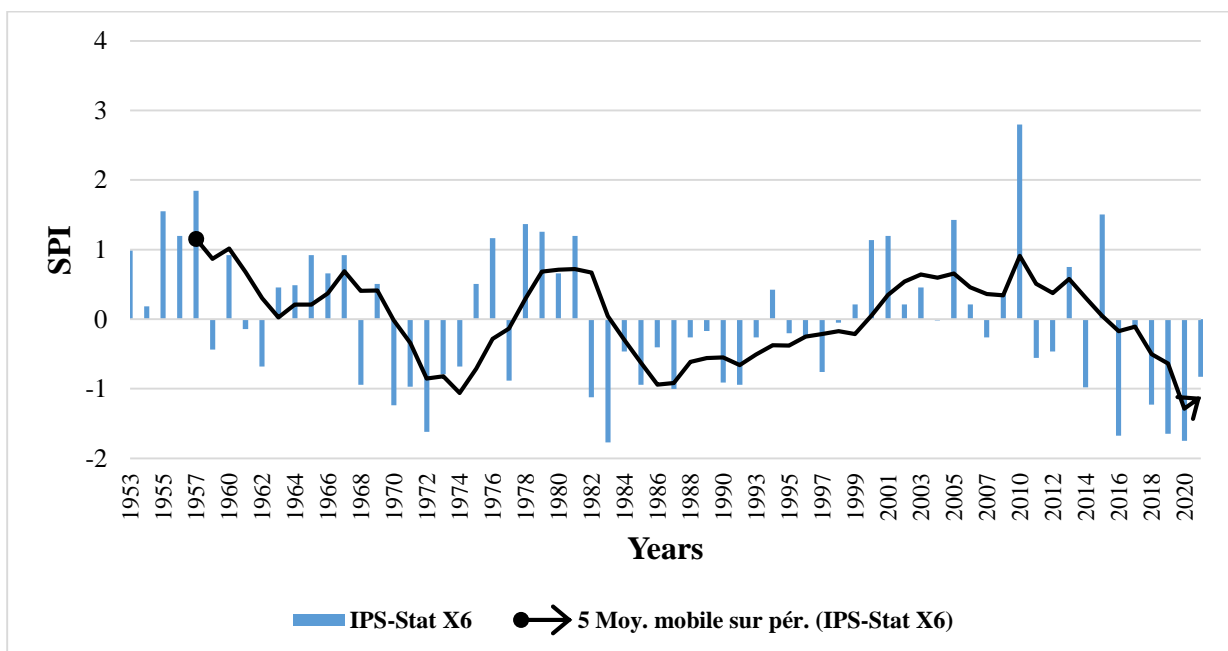


Figure 3: Standardised precipitation index curves

The average monthly rainfall pattern shown in Figure 4 highlights two main seasons:

- A rainy season lasting around five (5) months (June to October), with the first rainfall recorded in June. August saw record rainfall of 115.7 mm;
- A long dry season lasting seven (7) months (November to May).

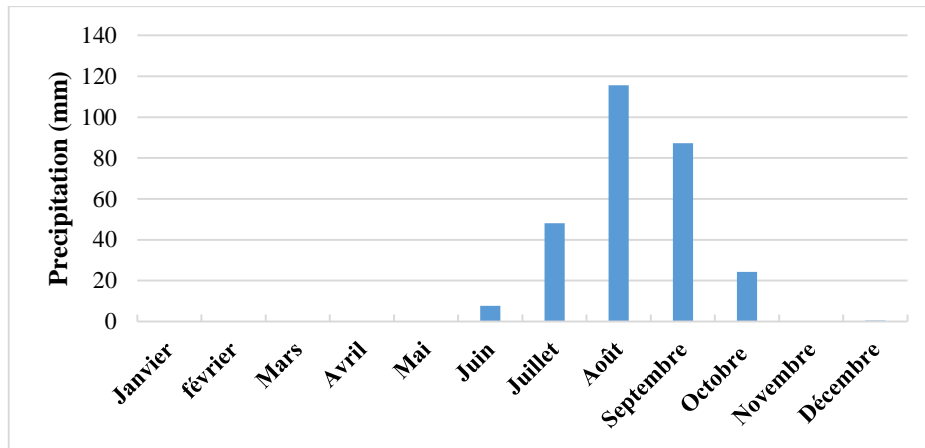


Figure 4: Trends in average monthly rainfall at Richard Toll station from 2002 to 2022 (source: OLAC)

3.2.2. Wind speed

Wind speeds measured at the Ngnith station between 2015 and 2021 show strong wind circulation during the dry season, i.e. 1.9 m/s in February. During the rainy season, wind speeds decrease, with a minimum of 1.05 m/s in October (Figure 5).

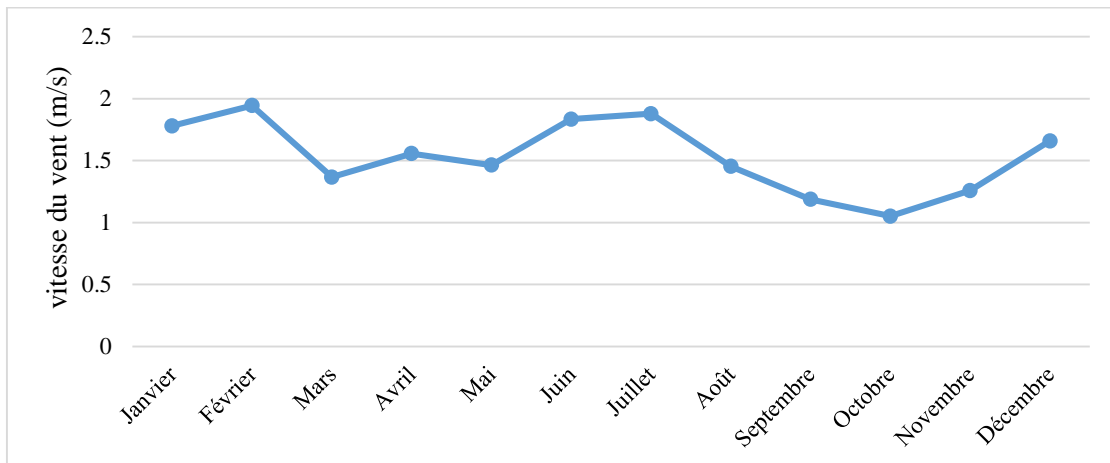


Figure 5: Average monthly wind speed at Ngnith station from 2015-2021 (source: OLAC)

3.2.3. Temperature

The temperature is measured at the Richard Toll station from 2000 to 2022. The average monthly temperature is 27.6 °C. The lowest temperatures are recorded in January with 13.4 °C. Temperatures gradually increase until the warm season to reach 39.4 °C in May (Figure 6).

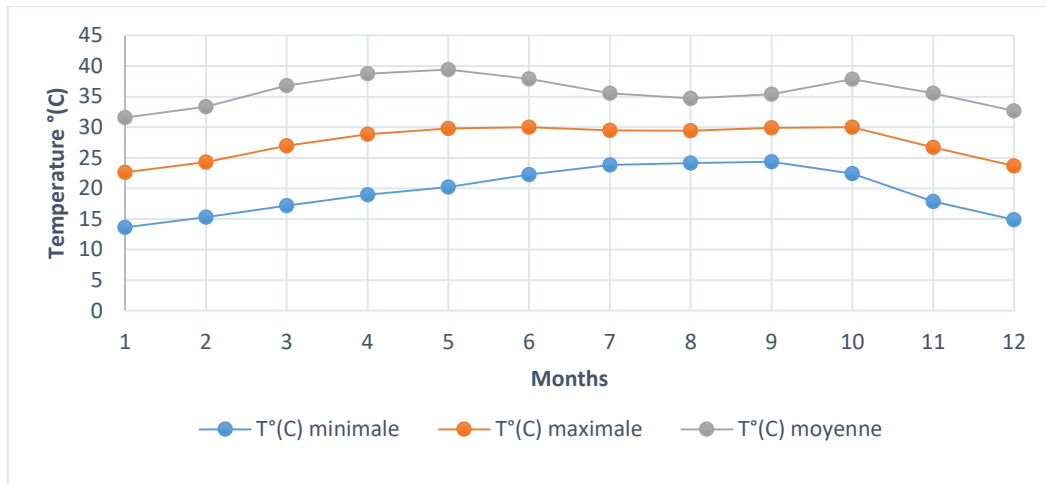


Figure 6 : Average monthly temperature variation at the Richard Toll station from 2000 to 2022 (source: OLAC)

3.2.4. Relative humidity

Precipitation in the rainy season lowers the temperature and increases the relative humidity (RH) of the air. During the rainy season, the air is full of humidity (RH>70%) and in the dry season, relative humidity falls to values below 50%. Relative humidity varies between 15.14% in March and 94.20% in September (Figure 7).

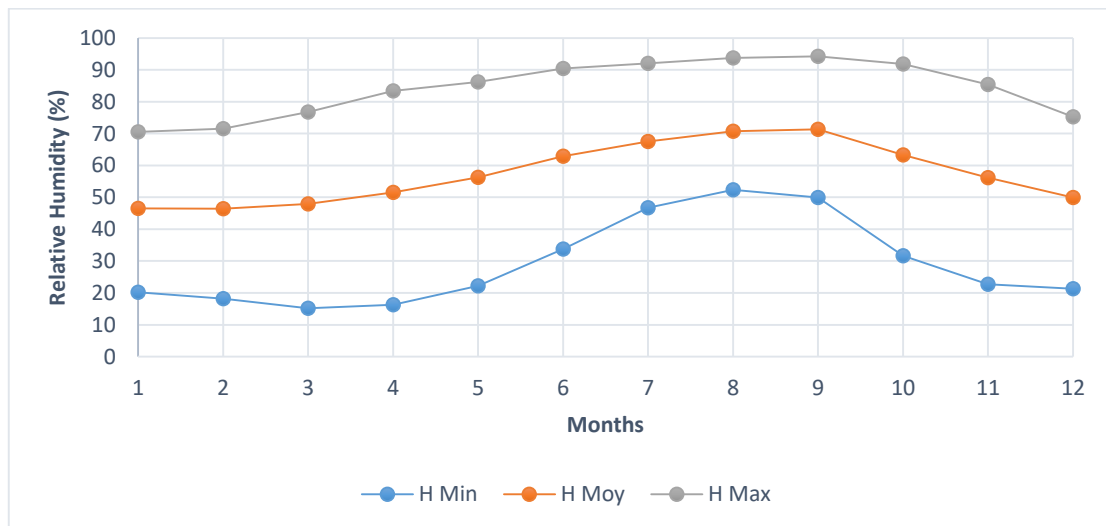


Figure 7: Average monthly variation in relative humidity at the Richard Toll station from 2000-2022 (source: OLAC)

3.2.5. Solar Radiation

Monthly variations in solar radiation from 2000 to 2020 show a peak in April and a trough in December (Figure 8). Solar radiation increases in the dry season (February-June), peaking in

April (16.6 MJ/m²/d). Solar radiation decreases between July and January, with a minimum in December (11.1 MJ/m²/d).

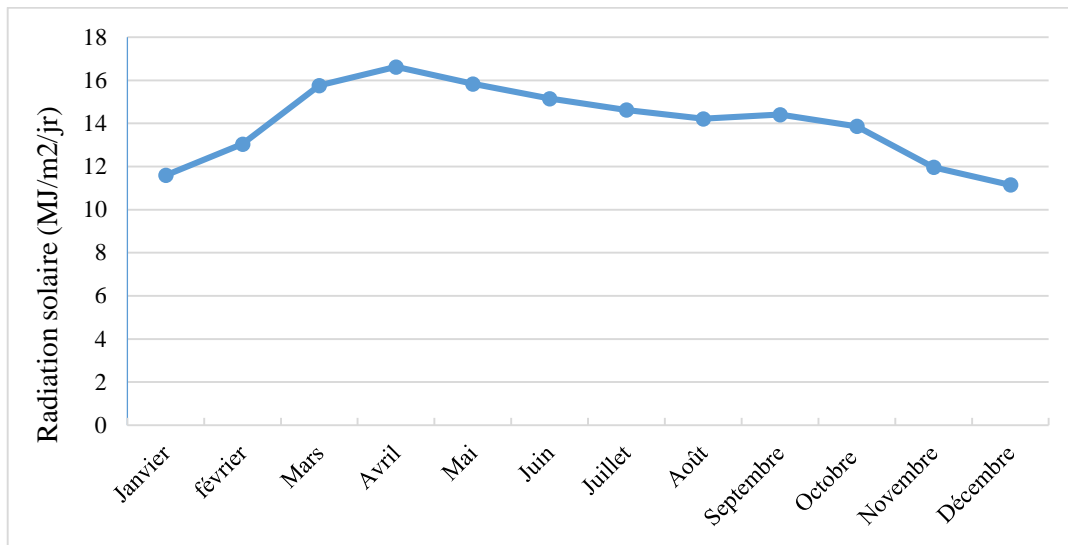


Figure 8: Moyenne mensuelle de la radiation solaire à la station de Richard Toll de 2000-2020 (source : OLAC)

3.2.6. Potential Evapotranspiration

Potential evapotranspiration is calculated using the macro EP developed by Oudin et al, (2005) with a correction factor of 0.408 (Ndiaye et al., 2017). The interannual variation in ETP shows values in excess of 1700 mm/year. This represents a water loss of around 250 million cubic metres (Mm³/year). Evapotranspiration is low during the rainy season (Figure 9).

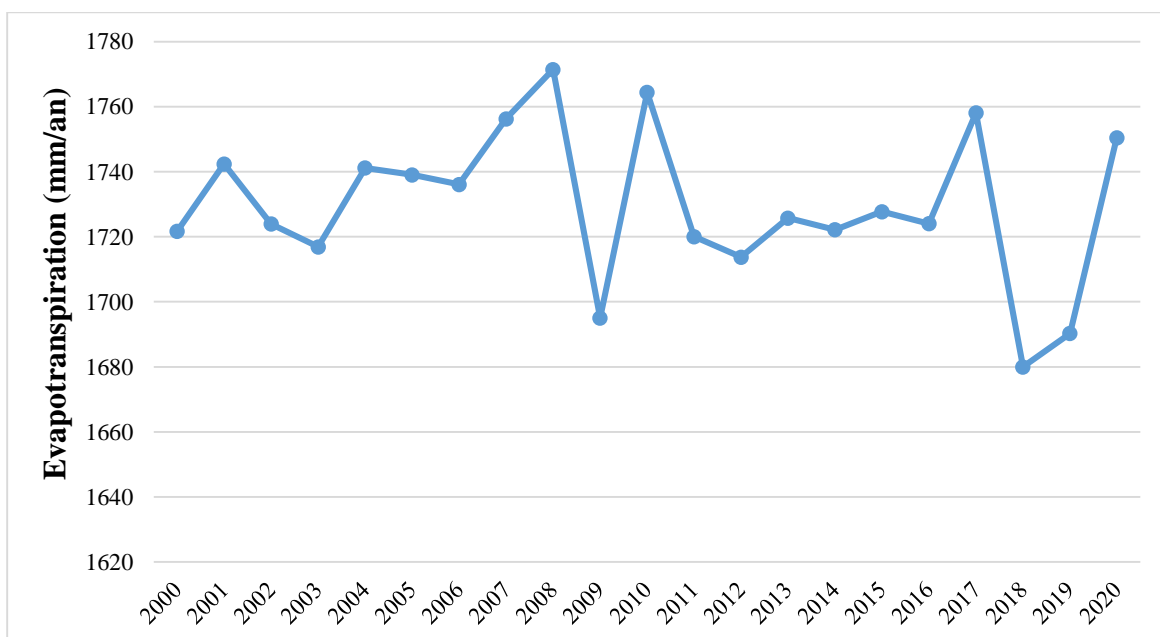


Figure 9: Annual evapotranspiration at Richard Toll station, 2000-2020 (source OLAC)

3.3. Climatic projections

Climate change is affecting many sectors, not least water resources. Future climate projections focus mainly on temperature and precipitation. For this study, the CNRM-ESM2-1 general circulation model, developed by the Centre National de Recherches Météorologiques (CNRM, France) as part of the Coupled Model Intercomparison Project Phase 6 (CMIP6), was selected for its ability to accurately simulate climate conditions in West Africa (Modou Noreyni Fall et al., 2023). The Shared Socioeconomic Pathways (SSP) used are SSP2-4.5 (intermediate scenario) and SSP5-8.5 (high-emissions scenario), in line with the simulations developed as part of the IPCC's sixth report (AR6).

Historical climate data covers the period 1985-2014, while future projections extend from 2015 to 2100. In addition, observed climate data from 2002 to 2017 from the CSS station, X6 Ndombo, supplied by OLAC, were used for calibration and downscaling. A downscaling and bias correction procedure was applied to the historical and future climate projections using CMHyd software, thereby improving the spatial resolution of the data (1.14°).

The results were analysed using a combination of artificial intelligence (AI) and Python programming, including multiple linear regression (MLR) and the Mann-Kendall test, to identify significant climate trends. The Mann-Kendall test is a widely used statistical method for detecting trends in climatological and hydrological time series (John Oyelakin., 2021). This methodological approach guarantees a better understanding of the impacts of climate change and contributes to more accurate projections for the region studied.

3.4. Geomorphology and Hydrology

3.4.1. Morphometry

The shape of a catchment influences its hydrological behaviour and can be characterised by the Gravelius compactness index (K_c) (Musy and Higy, 2004). This index compares the perimeter (P) of the catchment with that of a circle of the same area (S), according to this equation:

$$K_c = \frac{P}{2\sqrt{\pi S}} = 0,28 * \frac{P}{\sqrt{S}}$$

With :

If $K_c = 1$, the catchment is perfectly round;

If $K_c = 1.12$, the catchment is square;

And if $K_c > 1.12$, the basin is elongated.

The Lake Guiers pond is elongated with $K_c = 2.06$. To compare basins, we also use the Gravélius equivalent rectangle (Roche, 1963), defined by:

$$P = 2*(L + l); S = L*l \text{ (Laborde, 2000).}$$

Thus, if $K_c \geq 1.12$, we have:

$$L = \frac{K_c \sqrt{S}}{1.12} * \left[1 + \sqrt{1 - \left(\frac{1.12}{K_c}\right)^2} \right]$$

$$l = \frac{K_c \sqrt{S}}{1.12} * \left[1 - \sqrt{1 - \left(\frac{1.12}{K_c}\right)^2} \right]$$

The morphometric parameters of Lac de Guiers are summarised in Table 1. The surface area was determined using ArcGIS, while the other values were calculated using Excel by applying these equations.

Table 1: Morphometric parameters of the Lake Guiers basin

	Area (km ²)	Perimeter (km)	Coefficient Kc	Length (km)	Width (Km)
Lake Guiers Basin	2800	389	2,06	178,84	15,65

3.4.2. Relief

Relief influences the hydrological behaviour of a catchment, particularly runoff, evaporation and infiltration. It can be analysed using SRTM data, which provide Digital Terrain Models (DTMs), as well as hypsometric curves and slope indices (Bodian, 2014). The Lac de Guiers basin has altitudes ranging from -22 to 58 m (Figure 10).

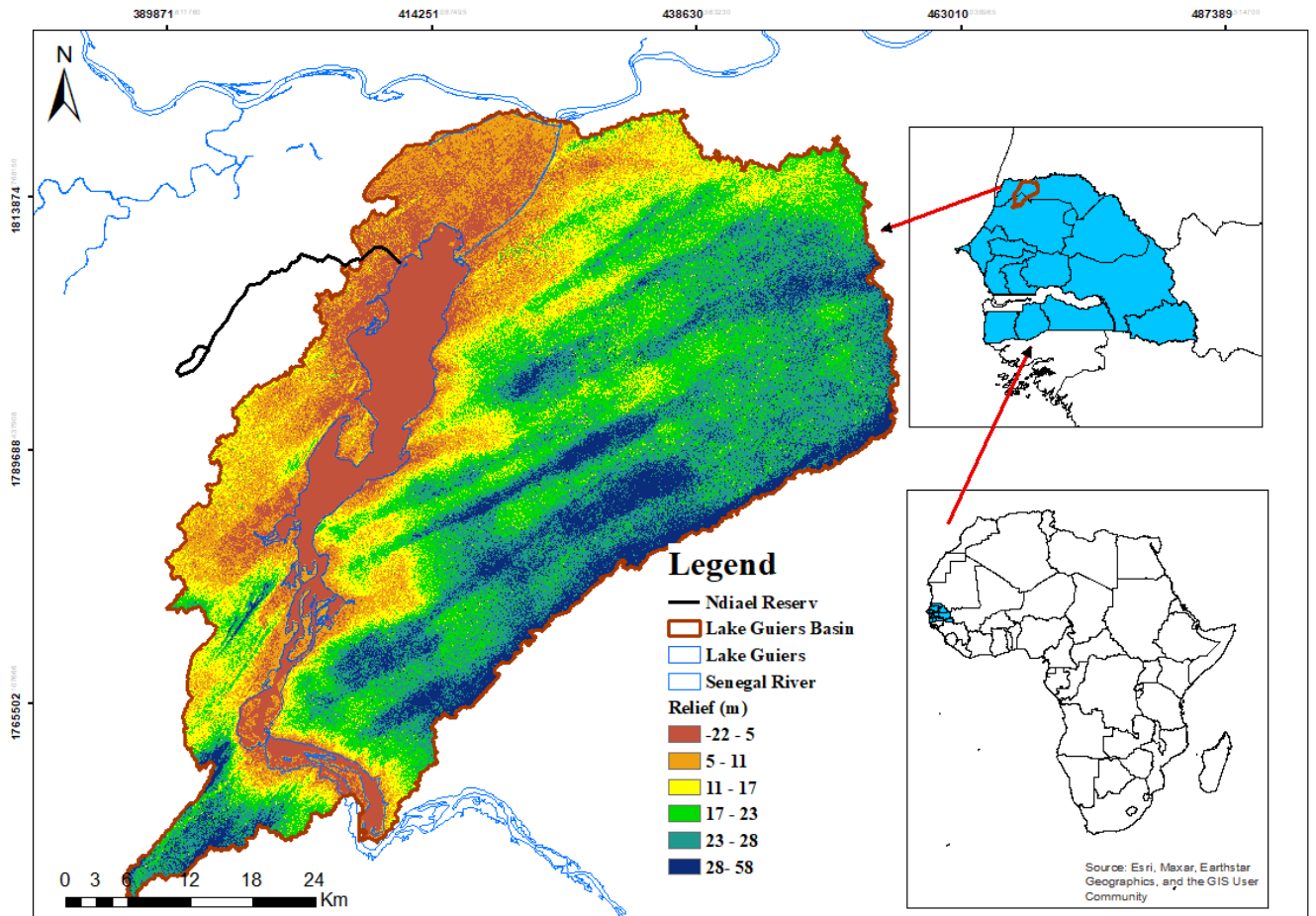


Figure 10: Relief of lake Guiers basin (ArcGis 10.8)

3.4.3. Slope

The average slope of a watercourse influences the speed of flow towards the outlet. A steeper gradient results in a more rapid hydrological response to precipitation. The overall slope index (I_g), based on the distribution of altitudes, is defined by:

$$I_g = \frac{\Delta H}{L}$$

ΔH : Vertical drop defined directly on the topographic map and expressed in m ;

L: length of main drain in km

To correct the effect of the surface on I_g , we use the specific gradient (D_s):

$$D_s = I_g * \sqrt{S}$$

According to the ORSTOM classification (Bodian, 2011), the D_s of the Lake Guiers basin (23.67 m) indicates a low slope (10 m < D_s < 25 m).

The Roche slope index (I_p), which reflects the influence of topography on flow, is given by:

$$I_p = \sqrt{\frac{I_g}{0,8}}$$

These structural parameters, calculated using Excel, are shown in Table 2.

Table 2: Structural parameters of Lake Guiers Basin

	Altitude max (m)	Altitude min (m)	ΔH (m)	I_g (m/Km)	I_p	D_s (m)
Lake Guiers basin	58	-22	36	0,45	0,75	23,67

3.4.4. Hydrography

The hydrographic network groups together all the watercourses, natural or artificial, permanent or temporary, which ensure drainage. It comprises a main river and its tributaries. Its structure is influenced by several factors: climate, geology, topography and human activities. The Lake Guiers basin is interconnected with the Senegal river basin, which flows into the Atlantic.

Figure 11 illustrates this network.

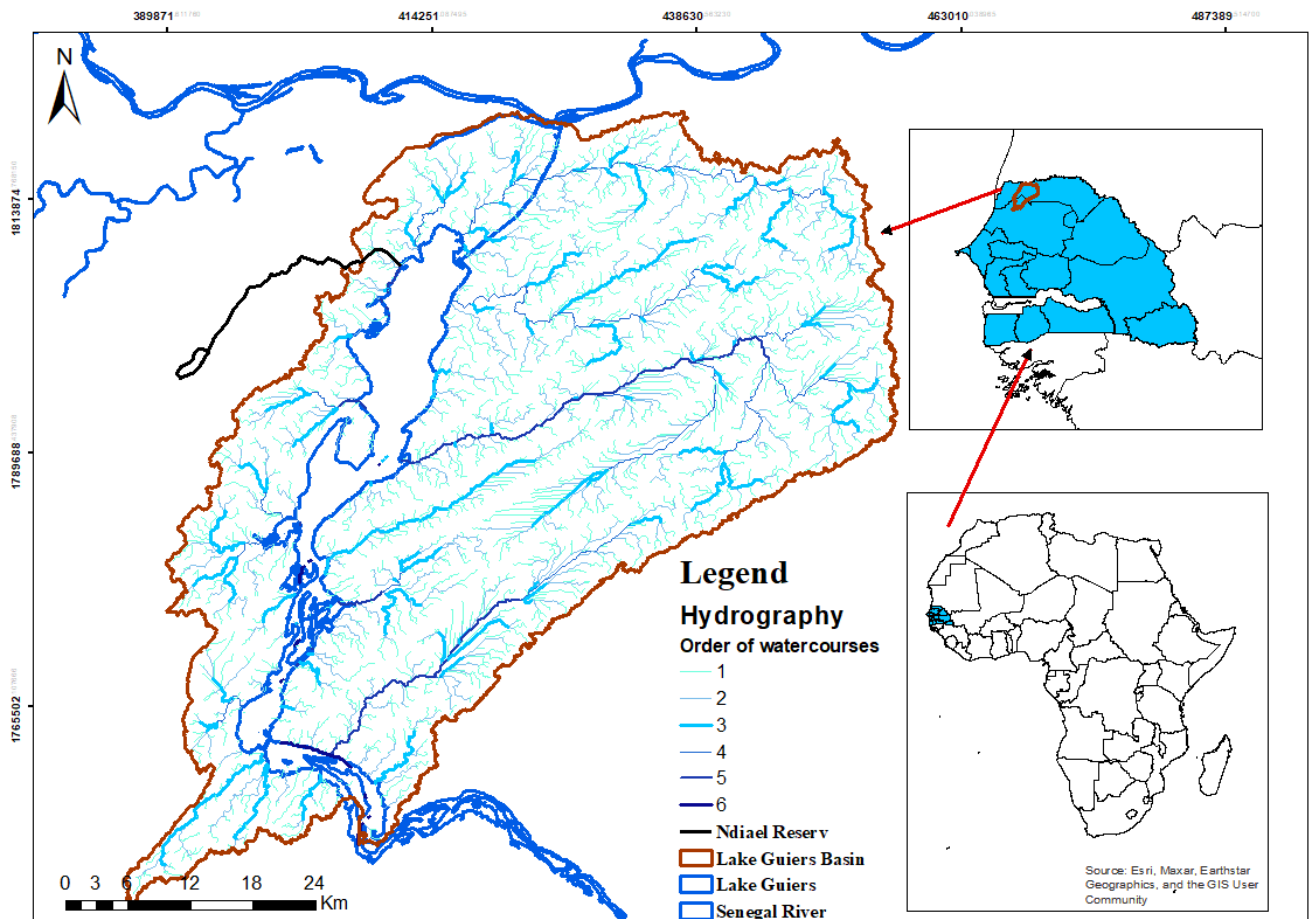


Figure 11: Lake Guiers watershed (ArcGis 10.8)

3.5. Data Collection

3.5.1. Water quality field measurement

A monitoring campaign was carried out between 25 and 28 December 2024. A total of fourteen (14) sites were sampled for water quality analysis (Figure 12). Water samples were taken at the near-surface and at depth using a pole. In situ measurements of pH, electrical conductivity, temperature and turbidity were taken using a conductivity meter, pH meter and turbidity meter. AQUA TROLL 500 multi-parameter probes were used to measure nitrate, dissolved oxygen and saturation levels in the field.

Samples for analysis in the laboratory were taken in 700 ml bottles, labelled (specifying the sampling area) and kept in a cool box to ensure that the composition of the water remained intact. In addition, a GPS was used to pinpoint the exact location of the sampling sites.

The figure 13 illustrates measurements in the field.

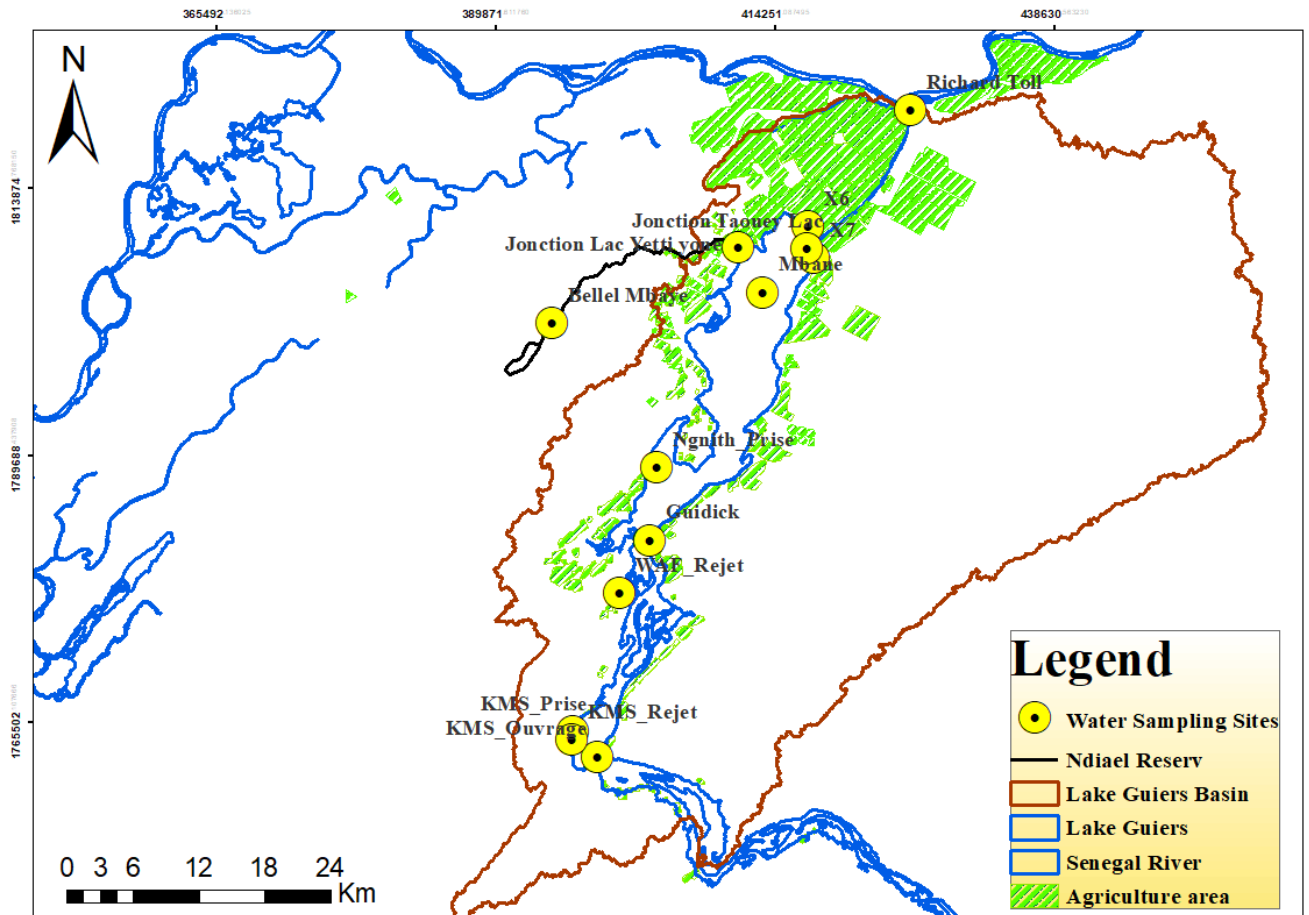


Figure 12: Spatial distribution map of sampling sites





Figure 13: Water sampling in the field

3.5.2. Flow measurement

The flows measured at the level of the control structures provide a better understanding of the flow of water, potential head losses along the axes, and the possible impacts of the clogging of the hydraulic structures by invasive aquatic vegetation (IAV).

Four (4) hydraulic structures were measured, as shown in Figure 14 below.

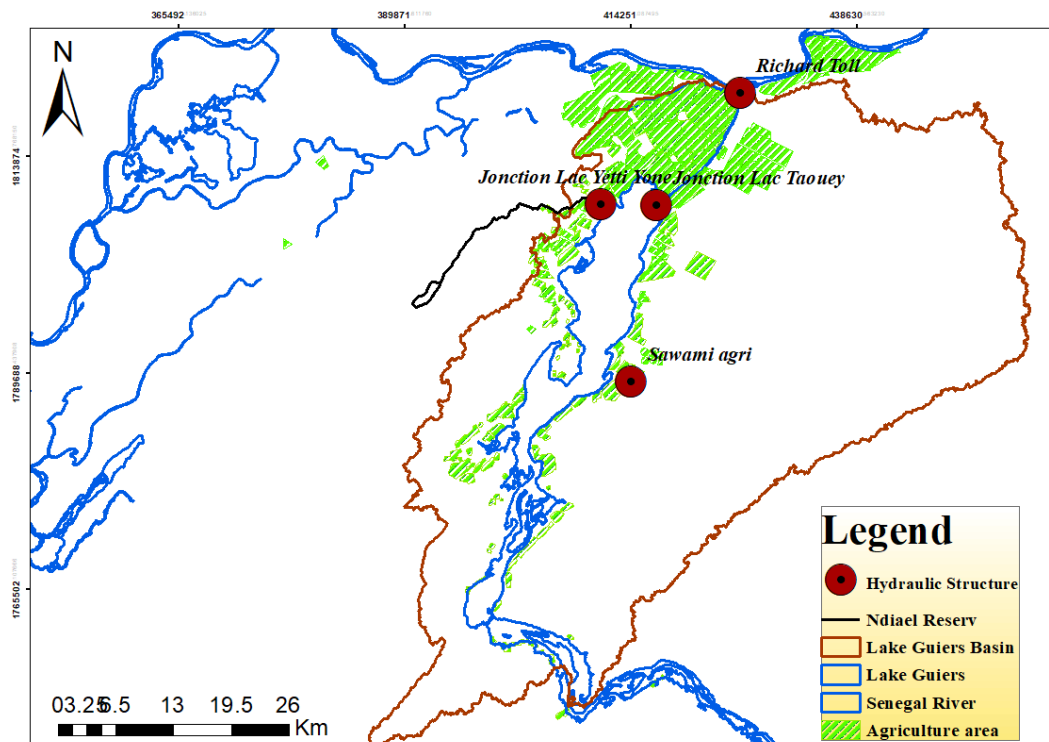


Figure 14: Map showing the spatial distribution of hydraulic structures

The ADCP (Acoustic Doppler Current Profiler) was used to measure flow at the control structures of the Lake Guiers hydraulic system and the Gorom Lampsar axis (Figure 15). The methodology followed comprises several stages.

As regards preparation and calibration, the ADCP is checked and calibrated before measurement, then the measurement parameters are configured and the measurement mode selected according to the hydraulic conditions and the depth of the site.

For data acquisition, the ADCP is installed on a moving boat (mobile measurement). The boat crosses the river at a constant speed while recording the velocity profiles. The ADCP then records water velocity, depth and other parameters in real time.



Figure 15: Flow measurement with ADCP

3.5.3. Agricultural surveys

A total of twelve (12) farmers were surveyed, representing the major local farmers water users in the region. These farmers were selected in the following localities: Nder, Mbayène, Malla, Mbane, Diakhaye, Syer, Goloum, Diaminar, Louboudou, Temey, Foss and Guidick (Figure 16).

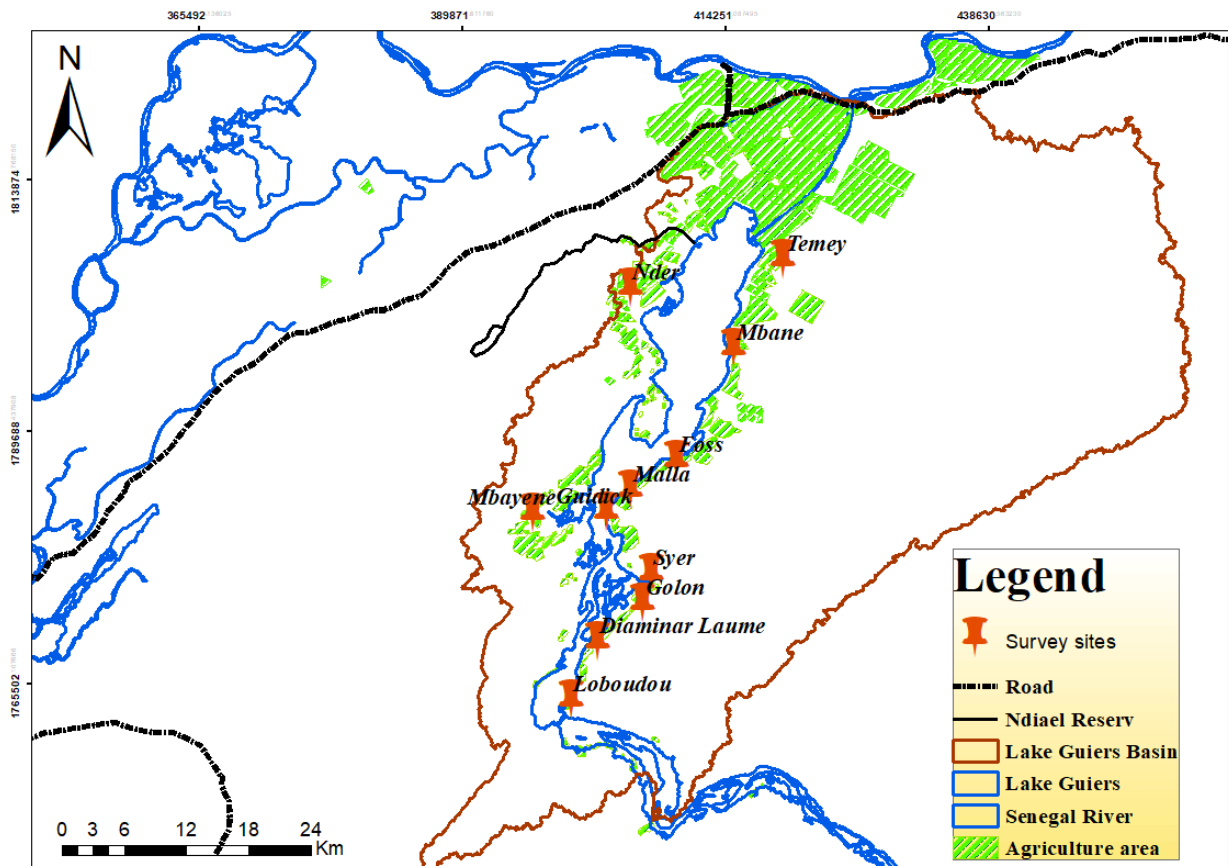


Figure 16: Maps showing the spatial distribution of survey sites

The survey sites were identified beforehand using Google Earth, following the irrigation canals directly connected to Lac de Guiers. In the field, survey sites were selected on the basis of the accessibility of the irrigated areas and the presence and availability of local farmers.

The surveys were carried out directly on the farm plots, in the local language, to ensure better understanding and smooth interaction with the farmers (Figure 17). They covered a number of key aspects, including: identification of the crops grown; the areas cultivated by type of crop; the number of motor-driven pumps connected to the lake; the operating capacity of these motor-driven pumps; the number of days that crops are irrigated; the length of the cropping seasons; problems encountered by farmers in accessing water (whether or not there are difficulties, the nature of the constraints); recommendations and suggestions put forward by farmers to improve the management of water resources and irrigation.

This approach made it possible to gather data representative of farming practices, water requirements and the challenges faced by farmers, while incorporating their perspectives and proposals for improvement.



Figure 17: Field surveys

In addition to surveying local farmers, due to lack of time and accessibility constraints, the agro-industrial enterprises located around Lake; Guiers (Figure 18) could not be surveyed directly. To overcome this limitation, the data collected in 2014 by OLAC were used to estimate their agricultural water requirements.

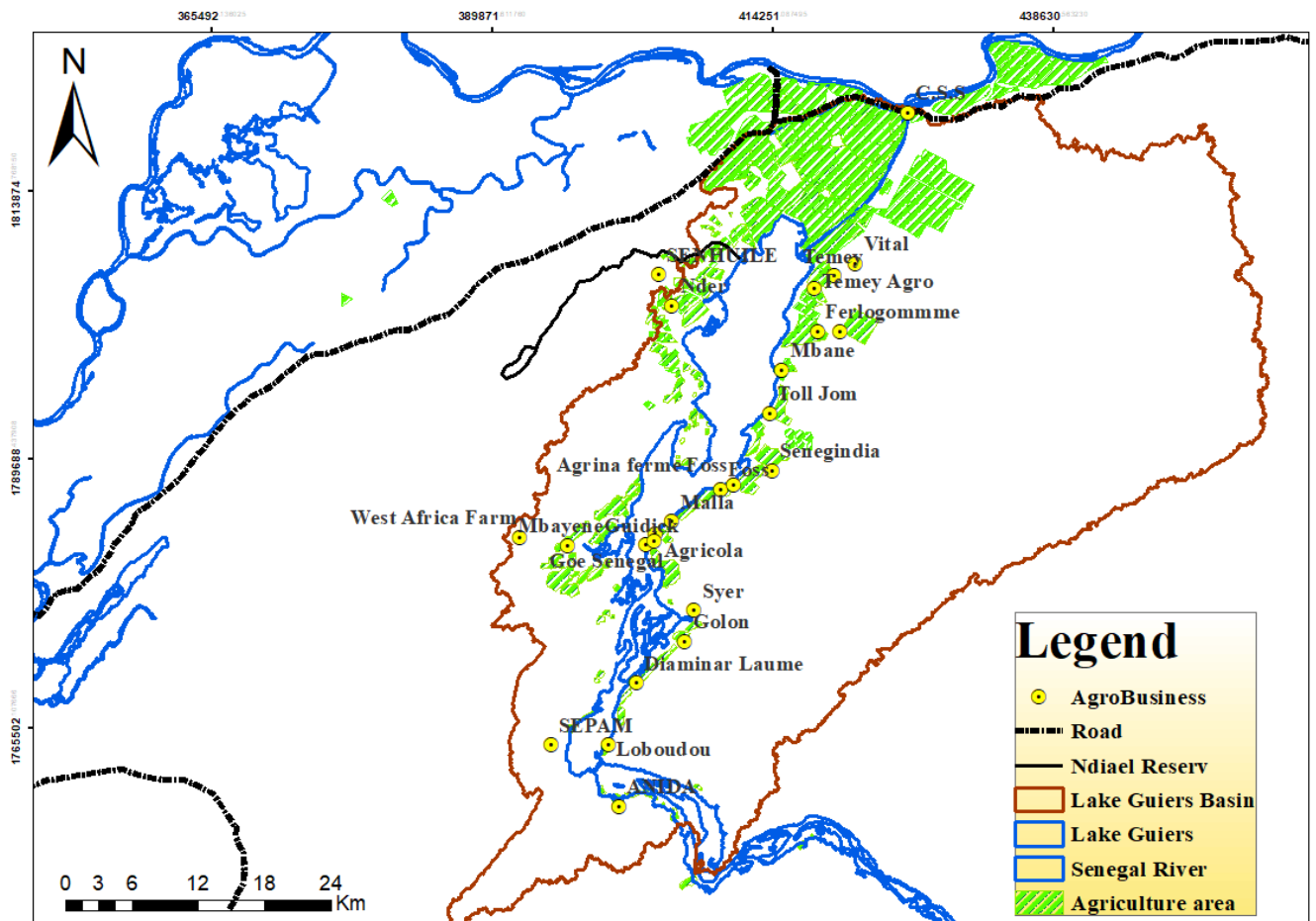


Figure 18: Map of the spatial distribution of agro-industrial companies around Lake Guiers

3.6. Data analysis methods

3.6.1. Physicochemical analysis of water

Assessment of the physico-chemical quality of water is not limited to a single parameter, but is based on a range of variables from different sources, including pH, conductivity, temperature, dissolved oxygen saturation, turbidity, nitrates, chlorophyll a, cyanobacteria, ammonium, phosphorus, nitrites, chlorides, biological oxygen demand (BOD5) and dissolved oxygen.

The materials used in the laboratory included specialised equipment such as the DR 3900 spectrophotometer, the LT 20 thermostat, the LT 200 heater and the OTT MS5 probe (Figure 19).

The results obtained were then processed using Excel, Python and ArcGIS for in-depth analysis.



Figure 19: Equipment used in the laboratory

3.6.2. Assessment of Water Flows and Agricultural Water Requirements

The flows measured with the ADCP were processed in Excel and ArcGIS.

In addition, the agricultural water requirements of small-scale farmers were assessed on the basis of the volumes withdrawn, determined by the number of motor-driven pumps (899) used, their operating times and their average capacity, estimated at 150 m³/h. Furthermore, the information gathered during the surveys, combined with the digitisation of cultivated areas using Google Earth, enabled us to identify the areas farmed, as well as the main agricultural crops and their proportions.

At the same time, an assessment of crop water requirements in the area was carried out using the following FAO formula, in order to estimate agricultural water losses by comparing them with the quantities actually withdrawn by local farmers.

$$ET_c = K_c \times ET_0$$

- ET_c : Crop water requirement (in mm/day).
- K_c : Crop coefficient specific to each crop.
- ET_0 : Reference evapotranspiration for the zone (in mm/day).

For agribusinesses, information on crops and areas farmed comes from the OLAC database. Calculations of water requirements for agriculture were based on the work of Kamara et al. (2014).

3.7. Modelling

3.7.1. WEAP model setup

WEAP (Water Evaluation and Planning) is a modelling tool designed for the integrated management of water resources. The configuration of the model for the Lac de Guiers basin follows several essential stages in order to ensure an accurate simulation adapted to the problem studied. Firstly, the basin was delimited using ArcGIS and imported into WEAP in the form of a shapefile, including Lake Guiers and the Senegal River. Next, the hydrological system was configured by considering the lake as a reservoir fed by the river via the Taouey canal, represented by a diversion. Reservoir characteristics such as storage capacity, initial storage, head-volume curve and monthly variation in observed volume were incorporated. Different water demand sites were defined, including irrigated perimeters, agribusiness, livestock, as well as ecological zones such as the Ndiael Avifauna Reserve, fed by the lake via the Yetti Yone dike, and the Bas Ferlo, which receives water releases to the fossil valley (Figure 20). The drinking water supply for Dakar and localities around the lake has also been taken into account through withdrawals from the Ngnith and Keur Momar Sarr (KMS) treatment plants, which are included as demand sites in the model. For each demand site, annual water consumption rates were used as input data. With regard to climate and hydrology, the input data of the Lake Guiers watershed, at a monthly time step, includes evaporation, precipitation, temperature, solar radiation and wind speed, as well as the essential hydrological data. The configuration thus established provides an accurate representation – based on the current understanding and data available – of the interactions between water resources and demands in the Lake Guiers basin within the WEAP model.

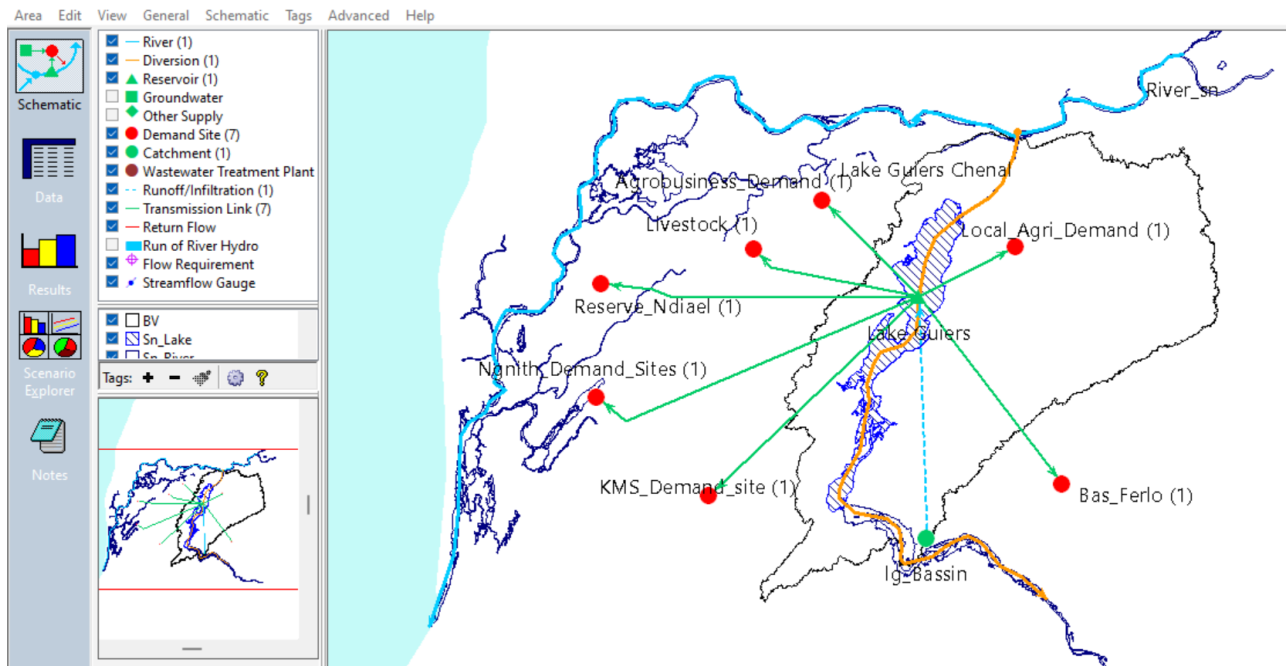


Figure 20: Schematic view of the study area in WEAP

3.7.2. Model calibration and validation

Calibration and validation of the model in WEAP are essential steps to ensure that the simulation accurately reproduces the evolution of water volumes in Lake Guiers. In WEAP, the observed volume corresponds to the actual reservoir storage data, generally derived from field measurements or historical data. For this study, the average observed volumes of Lake Guiers between 2010 and 2017 were used to calibrate the model, while the volume observed in 2020 was used to validate it.

Calibration was performed manually by gradually adjusting model parameters, including monthly agricultural demand, Bas Ferlo demand, and the lake's storage capacity

to minimise the difference between simulated and observed volumes. Once the model had been calibrated, validation was used to test its robustness by comparing the simulations with independent data.

The model's performance was assessed using statistical indicators such as the Nash-Sutcliffe efficiency (NSE) and the coefficient of determination (R^2).

The NSE, ranging from 0 to 1, measures the accuracy of the simulations: a value close to 1 indicates a near-perfect match between simulated and observed volumes.

The coefficient of determination (R^2), also close to 1, is considered a significant indicator of the quality of the simulation.

The data used to establish the reference and compare the simulations were obtained from OLAC.

3.7.3. Scenario creation

To achieve the objectives of this study, the following scenario were developed:

Scenario 1: Reference Scenario

This scenario maintains all base parameters intact with 2020 as the reference year, including:

- Current climate conditions (2010-2020)
- Existing water withdrawal patterns for agriculture, drinking water supply, and other uses
- Current operational rules for water transfers from the Senegal River

Scenario 2: Climate Change Scenarios (SSP4.5 and SSP8.5 Climate Projection)

To evaluate climate change impacts on Lake Guiers water availability by:

- Implementing temperature and precipitation projections from the SSP4.5 and SSP8.5 scenario
- Projecting changes in evaporation rates based on temperature increases
- Analysing climate change impacts on seasonal water availability and on lake storage volume

Scenario 3: Anthropogenic Pressure Scenarios

Case 1: Agricultural Demand Growth where three sub-cases considering different rates of agricultural expansion:

- Low agricultural expansion (2% increase in irrigated area)
- Medium agricultural expansion (5% increase in irrigated area)
- High agricultural expansion (10% increase in irrigated area)

Case 2: Urban Water Demand Growth where three sub-cases for drinking water supply demand, particularly focusing on KMS treatment plant which has not yet reached maximum production capacity:

- Low demand growth (2% increase)

- Medium demand growth (5% increase)
- High demand growth (10% increase)

Case 3 : Combined High Pressures

- Combination of severe climate change (SSP8.5), high agricultural expansion (10%), and high drinking water demand growth (10%)
- Analysis of cumulative impacts on water availability and lake storage volume

Scenario 4: Senegal River Inflow Variation Scenarios

Case 1 : Streamflow Reduction

- 8% reduction in streamflow from the Senegal River based on previous studies
- 16% reduction in streamflow from the Senegal River based on previous studies

Case 2 : No River Inflow

- Complete cessation of water inflow from the Senegal River
- Analysis of how long the lake can sustain water demands without river inputs

Scenario 5: Water Transfer Project Scenario

Case 1: PREFERLO Water Transfer Project

- Assessment of whether Lake Guiers can satisfy the water needs of the PREFERLO project under current account conditions
- If not feasible, development of a lake management scenario with increased water inflows from the Senegal River

Note that all scenarios will incorporate the lake regulation zones defined in the WEAP model:

- Inactive zone: 149 Mm³ (minimum volume below which no demands can be satisfied)
- Buffer zone : 453 Mm³ (sufficient volume to satisfy demands)
- Conservation zone: 652 Mm³ (volume maintained to prevent lake overflow)
- Maximum storage capacity : 750 Mm³

This scenario framework will provide detailed insights into the future water availability of Lake Guiers under various climatic and anthropogenic conditions.

This following table (Table 3) summarises the different scenarios used in this study.

Tableau 3: Summary of Scenarios for Lake Guiers Water Availability Assessment

Scenario Category	Scenario/Case
Reference Scenario	Baseline (2020)
Climate Change Scenarios	SSP4.5
	SSP8.5
Agricultural Demand Scenarios	Low Growth
	Medium Growth
	High Growth
Urban Water Demand Scenarios	Low Growth
	Medium Growth
	High Growth
Combined Pressure Scenario	Maximum Pressure
River Inflow Scenarios	Moderate Reduction
	Severe Reduction
	No Inflow
Water Transfer Scenario	PREFERLO Project

CHAPTER FOUR

4. RESULTS

4.1. Future Climatic Conditions for the Lake Guiers Basin

4.1.1. Precipitation

Analysis of precipitation trends under the SSP4.5 and SSP8.5 scenarios reveals contrasting trends, highlighting the impact of climate change on water resources (Figure 21). Under SSP4.5, the trend is relatively stable, with a slight decrease of 0.66 mm/year, although this variation is not statistically significant (p-value = 0.221). In contrast, the SSP8.5 scenario shows a marked decrease in precipitation of 1.72 mm/year, with a statistically significant trend (p-value ≈ 0).

This reduction in precipitation under SSP8.5 could lead to increased water stress, affecting surface runoff, agricultural productivity and drinking water supplies. Conversely, the relative stability observed under SSP4.5 suggests that mitigation efforts could limit these negative impacts. Specifically, the projections indicate a reduction in precipitation of 23.1 mm by mid-century (2050) and 56.1 mm by the end of the century (2100) under the SSP4.5 scenarios. Under SSP8.5, on the other hand, precipitation could fall by 60.2 mm in 2050 and 146.2 mm in 2100, a much more pronounced decline.

These results underline the importance of adopting adaptation and sustainable water resource management strategies, such as improved storage, more efficient irrigation and the preservation of ecosystems. They also serve as a reminder of the urgent need to reduce global greenhouse gas emissions, as the negative effects are much more marked under SSP8.5.

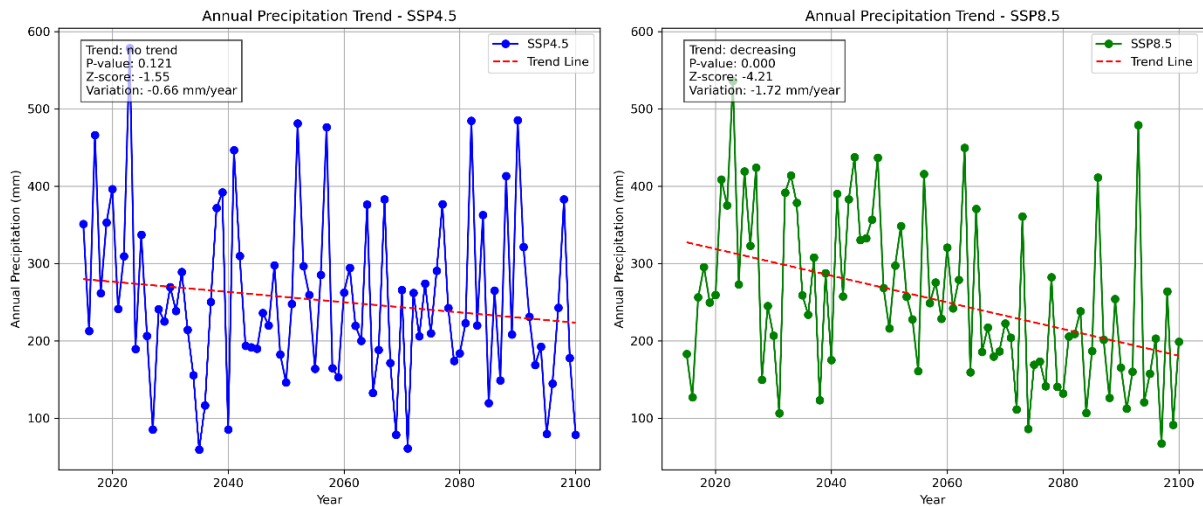


Figure 21: Variation in future rainfall

4.1.2. Temperature

The following figures (Figures 22 and 23) show changes in maximum (Tmax) and minimum (Tmin) temperatures under the SSP4.5 and SSP8.5 scenarios between 2015 and 2100. A significant upward trend is observed for both temperatures and under both scenarios, with a more marked increase under SSP8.5 ($0.080^{\circ}\text{C}/\text{year}$ for Tmax and $0.088^{\circ}\text{C}/\text{year}$ for Tmin) compared with SSP4.5 ($0.040^{\circ}\text{C}/\text{year}$ for Tmax and Tmin). The p-values of 0.0000 and the high Z-scores confirm the statistical significance of these trends.

By 2050, temperatures would rise by 1.54°C under SSP4.5 and 2.80°C under SSP8.5. By 2100, this rise would reach 3.74°C under SSP4.5 and 6.8°C under SSP8.5, reflecting the greater impact of a high-emissions scenario. The more rapid rise under SSP8.5 reflects a high-emissions scenario, while SSP4.5 shows a more moderate rise. This simultaneous increase in minimum and maximum temperatures could intensify heat waves, reduce the daily temperature range and have repercussions on evaporation, water availability and ecosystems. The impacts could be of particular concern for agriculture, water resource management and human health.

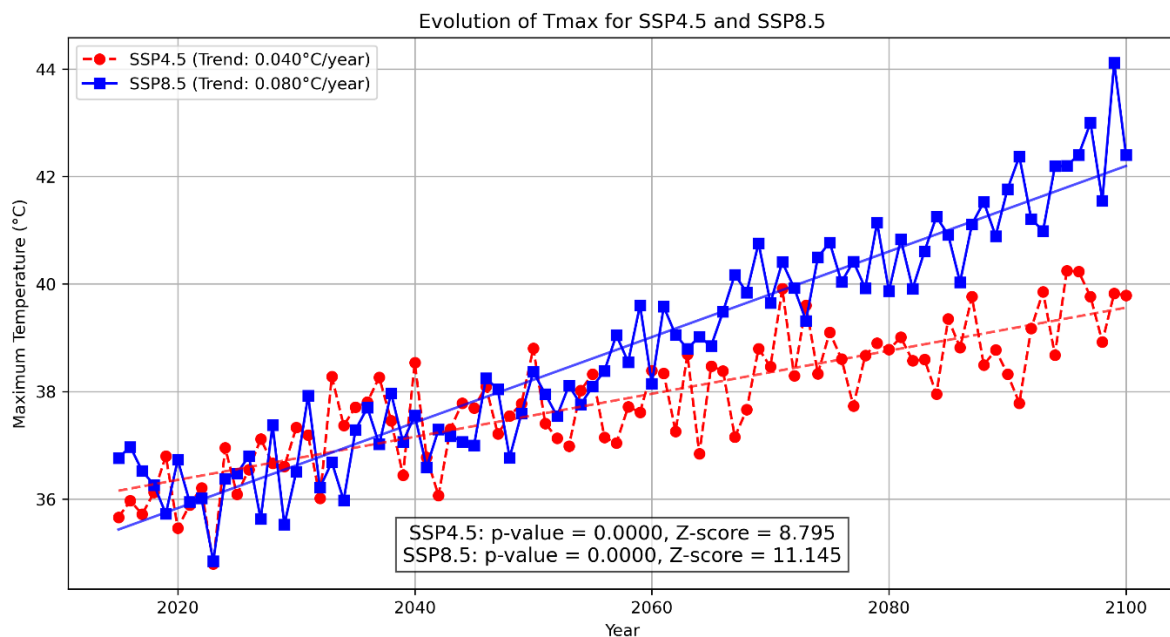


Figure 22: Variation in future maximum temperatures under the SSP4.5 and SSP8.5 scenarios

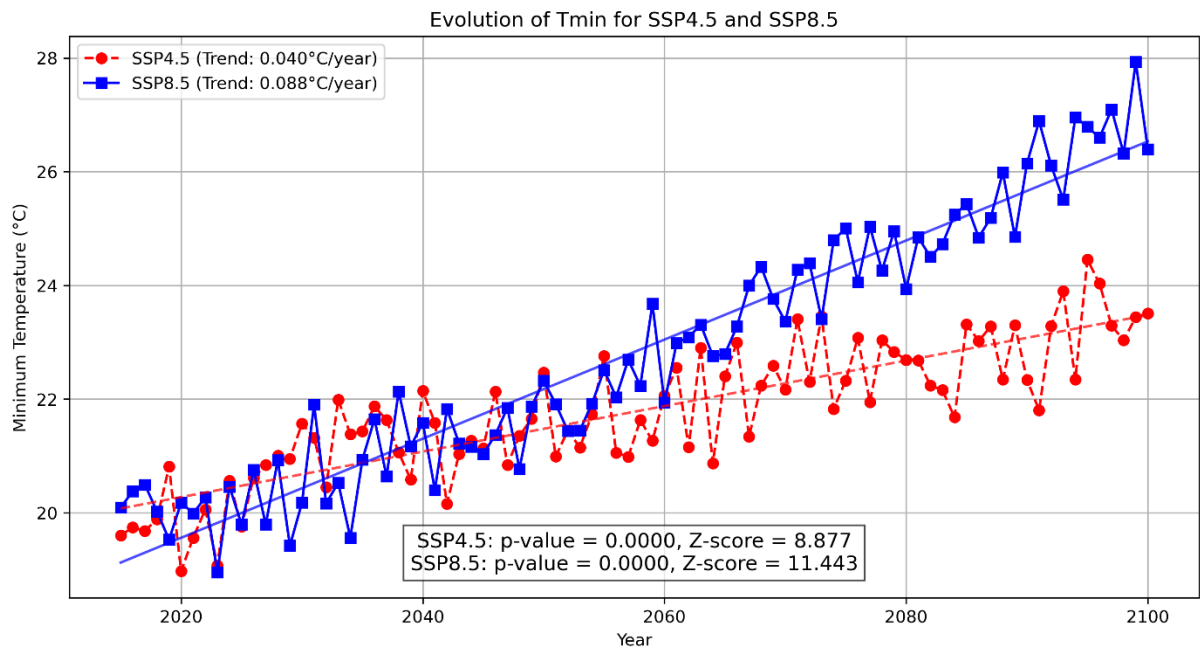


Figure 23: Variation in future minimum temperatures under the SSP4.5 and SSP8.5 scenarios

4.2. Physicochemical analysis results

The water quality results as summarized in Table 4 were evaluated according to standards established by the Système National d'Evaluation de la Qualité des Eaux (SEQ Eau) and the World Health Organisation (WHO).

Analysis revealed that most sampling sites met recommended standards for potable water quality parameters including pH, temperature, nitrates, ammonium, phosphates, nitrites, cyanobacteria, chlorophyll a, conductivity, and magnesium. However, dissolved oxygen (DO) levels at several sampling points, particularly at Bellel Mbaye, failed to meet target values specified by both SEQ Eau and WHO guidelines.

Regarding turbidity, comparative analysis with SEQ Water recommendations indicated compliance only at Bellel Mbaye and the KMS facilities (intake, structure, and discharge points). Significant turbidity exceedances were documented throughout the Lake Guiers region, with notably high readings at: X7 (144.4 NTU), X6 (91.98 NTU), Mbane (120.7 NTU), Richard Toll (143.1 NTU), Gidakhar (118.8 NTU), Lac-Yetti Yone junction (118.9 NTU), Taouey-Lake junction (152.3 NTU), Ngnith plant intake (104.3 NTU), Guidick (90.99 NTU), and the WAF discharge station (383 NTU). A clear spatial pattern emerged with turbidity values decreasing along a north-to-south gradient across the lake.

For Biochemical Oxygen Demand (BOD5), where the regulatory threshold for raw water is established at 25 mg/l, multiple sites within Lake Guiers exceeded permissible limits. These

violations were observed at CSS discharge locations X7 (29 mg/l) and X6 (29.8 mg/l), the lake-Yetti Yone junction (32.8 mg/l), Ngnith intake (28.8 mg/l), KMS discharge station (29.4 mg/l), and the KMS structure (26.6 mg/l). The Bellel Mbaye structure exhibited elevated levels of several parameters, including chlorides (44.3 mg/l), depressed dissolved oxygen (2.077 mg/l), percentage of dissolved oxygen (22.86%), and conductivity (456 μ S/cm). Additional site-specific maximum concentrations were documented at Mbane for ammonium (0.30 mg/l), while the KMS water intake registered the highest concentrations of nitrates (5.05 mg/l), chlorophyll a (4.51 μ g/l), and cyanobacteria (8780 mg/l).

Table 4: Results of physicochemical analyses

Sites	pH	EC ($\mu\text{s}/\text{cm}$)	Temp ($^{\circ}\text{C}$)	% OD	OD (mg/l)	Turbidity (NTU)	NO_3^- (mg/l)	Chlorophyll ($\mu\text{g}/\text{l}$)	Cyano (mg/l)	NH_4^+ , (mg/l)	PO_4 (mg/l)	NO_2 (mg/l)	Chloride (mg/l)	BOD5 (mg/l)
X7	7.8	108.3	23	100.4 3	9.11	114.4	0.48	2.34	7749	0.294	0.085	0.045	22.8	29
X6	7.76	214	23.2	99.81	9.05	91.98	1.63	3.1	7761	0.246	0.078	0.062	1.48	29.8
Mbane	8.14	103.3	24.4	102.3 5	9.2	120.7	3.3	3.09	7733	0.303	0.099	0.07	22.2	21.6
Richard Toll	7.37	54.7	24.3	99.57	8.6	143.1	0.72	1.83	7746	0.276	0.085	0.07	31.1	17.92
Gidakhar	7.52	57.2	26.3	74.04	6.4	156.4	0.88	1.88	7756	0.294	0.076	0.075	31.5	14.44
Jonction Lac Yetti yone	7.77	102.2	22.8	97.68	8.68	118.9	3.27	2.45	7753	0.261	0.102	0.067	23	32.8
Jonction Lac Taouey	7.64	64	23.4	79.07	6.97	152.3	0.41	1.73	7735	0.278	0.079	0.097	29.9	23
Bellel Mbaye	7.17	456	21.3	22.86	2.077	4.16	2.57	1.74	7819	0.202	0.071	0.019	44.3	22.2
Ngnith_Prise	7.95	113.2	22.5	97.33	8.83	104.3	3.91	3.74	7591	0.202	0.027	0.072	20.8	28.8
KMS_Prise	7.95	190.2	27	103.6 8	9.08	21.64	5.05	4.2	8642	0.241	0.065	0.002	8.25	29.4
KMS_Ouvrage	7.93	189.6	28.2	90.9	7.87	24.49	3.04	4.51	8780	0.108	0.103	0.029	9.4	26.6
Guidick	7.76	126.7	28.5	84.74	7.88	90.99	1.46	2.65	7670	0.279	0.041	0.068	16.2	23.6
WAF_Rejet	7.33	146.2	23.8	84.47	7.13	90.77	3.73			0.291	0.052	0.065	15.2	15.76

KMS_Rejet	8.07	383	26.8	95.86	8.27	14.64	3.97			0.216	0.028	0.024	3.17	24.4
Normes OMS	6.5 9.5	- 250-1800		>70	>6.4	35	10	10	100000	2	0.5	0.4	250	25

The figure below illustrates the spatial distribution of the physico-chemical parameters measured, highlighting the main chemical parameters dominant in each site sampled (Figure 24). This figure further confirms the high proportions of BOD5 and dissolved oxygen observed at almost all the sites, and also the high proportions of chloride at Bellel Mbaye.

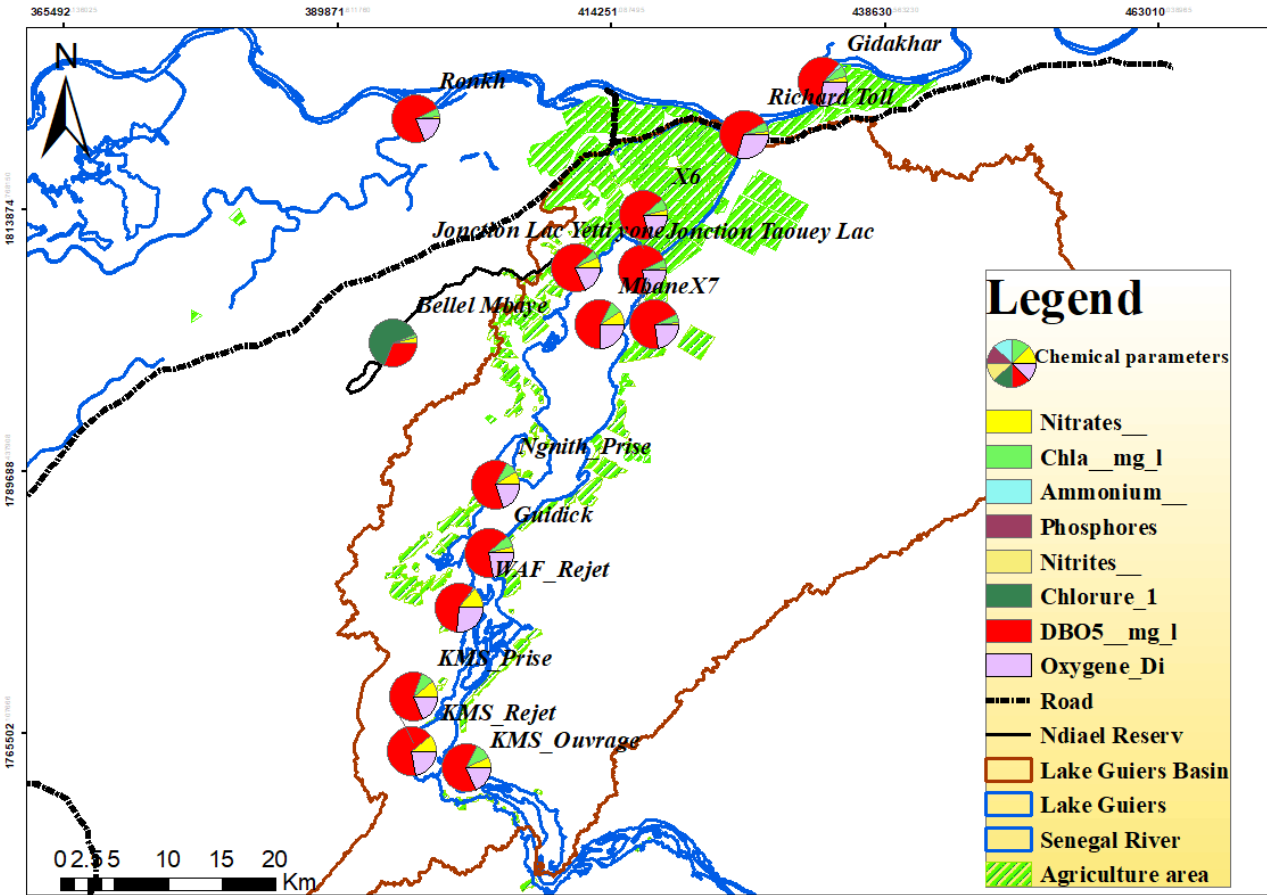


Figure 24: Carte de répartition spatiale des paramètres physico-chimiques

4.3. Assessment water flows results

The following table (Table 5) presents the primary control structures where flows were measured. Within the Lake Guiers basin, the measurements show significant inflows at Richard-Toll, with a flow of 27.88 m³/s (equivalent to a daily volume of 2,408,659.20 m³) including 5 gates open out of 8, and at the Lac-Taouey junction, with a flow of 21.56 m³/s (i.e. a volume of 1,862,438.40 m³). These locations represent the main inflows of water from the river into the lake. Conversely, some structures, including Sawami Agri (1.36 m³/s) and the Lake-Yetti Yone junction (1.56 m³/s), record modest outflows. It should be noted that during

this mission, the gates of the Keur Momar Sarr (KMS) structure were closed, limiting data collection in this area.

Table 5: Flow rates measured

Regulation structure	Total flow (m ³ /s)	Daily volume (m ³)	Number of gates open	Status (Inbound/Outbound)
Richard Toll	27.88	2,408,659.20	5/8	Inbound
Jonction Lac Yetti Yone	1.56	134,784.00	Open area	Outbound
Jonction Lac Taouey	21.56	1,862,438.40	Open area	Inbound
Sawami agri	1.36	117,849.60	Open area	Outbound

The following map (Figure 25) illustrates the spatial distribution of flows measured at the various hydraulic structures.

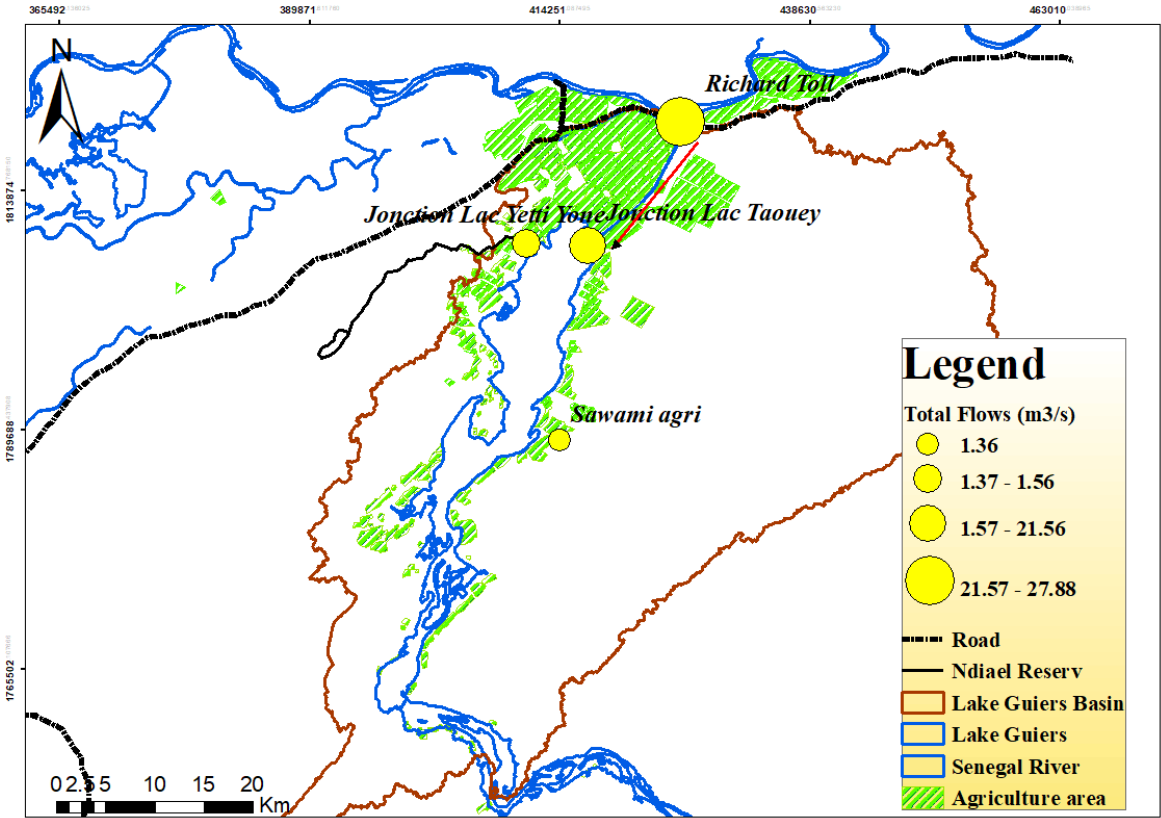


Figure 25: Map of the spatial distribution of flows at control structures

4.4. Agricultural surveys results

Figure 26 below shows the sites surveyed and the agribusinesses present in the Lake Guiers basin. A total of 14 agribusinesses were identified, and 12 villages were surveyed: Nder, Mbayène, Malla, Mbane, Diakhaye, Syer, Goloum, Diaminar, Louboudou, Temey, Foss and Guidick.

The main agricultural crops identified in the area were cassava, sweet potatoes, groundnuts, onions, watermelon and various market garden crops.

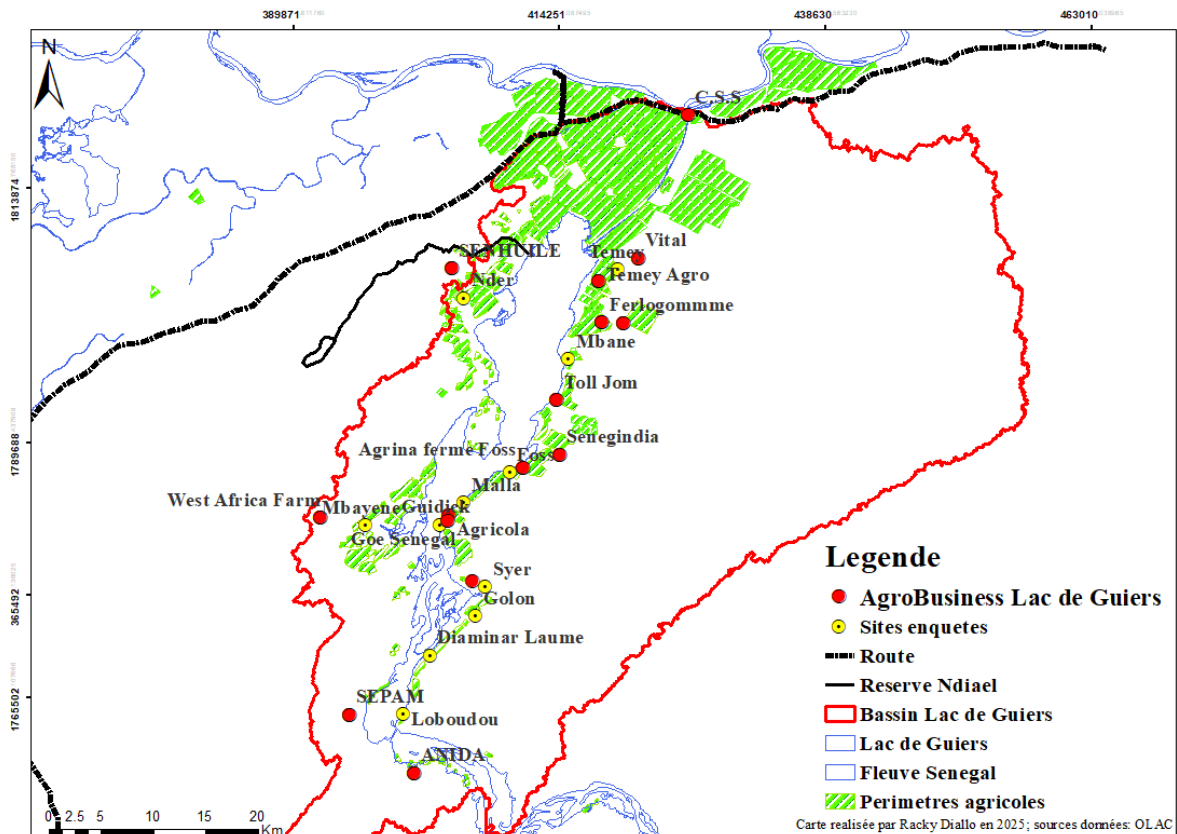


Figure 26: Maps of survey sites and agribusinesses in the area

Tables 6 and 7 present, respectively, the volumes of water currently withdrawn from the lake and the water requirements of crops. The annual volumes withdrawn are estimated at 79,331,457.14 m³, while crop water requirements amount to 69,115,088.03 m³/year. This represents annual losses of 10,216,369.11 m³, or a daily loss of around 33,496.29 m³. It should be noted that small-scale farmers do not operate throughout the year: a period of 60 days is reserved for harvesting, during which no water is withdrawn.

Table 6: Volumes withdrawn by local farmers

Sites	Total area (ha)	Number of pumps	Operating time per week	Number of irrigation days per week	Volume withdrawn (m3)	Volume withdrawn per week (m3/d)	Volume withdrawn per year (m3/year)
Zone Nder	600	55	12h	6/7	36000	15643	3973285.71
Mbayene	892	160	12h	7/7	36000	41143	10450285.7
Mbane	173	13	12h	7/7	27000	3343	849085.714
Malla	229	80	8h	6/7	288000	16000	4064000
Diakhaye	548	30	14h	6/7	23400	10500	2667000
Syer	1000	200	10h	4/7	96000	100000	25400000
Golon	138	34	12h	3/7	63000	20400	5181600
Diaminar	50	18	12h	6/7	400000	5400	1371600
Loboudou	42	12	12h	2/7	61200	10800	2743200
Temey	1175	240	12h	6/7	32400	72000	18288000
Foss	542	43	12h	6/7	21600	12900	3276600
Guidick	105	14	12h	6/7	432000	4200	1066800
Total	5494	899	-	-	1516600	312329	79 331 457.14

Tableau 7: Besoin en eau des spéculations

Sites	%Occupation of cultivated land	Water requirement for crops (m3/d/ha)	Total water requirement (m3/year)
Nder	60% Cassava, 30% Potatoes, 10% Peanuts	23682.6	7223193
Mbayene	50% Manioc, 40% Potatoes, 5% Peanuts, 5% Vegetables	31708.37	9671052.85
Mbane	50% Manioc, 40% Peanuts, 10% Potatoes	7277.591	2219665.255

Malla	10% Peanuts , 40% Potatoes , 40% Cassava , 5% Onion, 5% Watermelon	9255.035	2822785.675
Diakhaye	40% Manioc , 10% Peanuts, 40% Potatoes, 10% Onions	23764.02	7248026.1
Syer	20% Peanuts, 30% Potatoes, 30% Cassava, 10% Onions, 5% Watermelon, 5% Vegetables	43129	13154345
Golon	20% Peanuts, 30% Potatoes, 30% Cassava, 10% Onions, 5% Watermelon, 5% Vegetables	5951.802	1815299.61
Diamenar	40% Peanuts, 50% Cassava, 10% Onions	2162.35	659516.75
Louboudou	40% Peanuts, 50% Cassava, 5% Onions, 5% Vegetables	1806.462	550970.91
Temey	30% Potatoes, 40% Cassava, 30% Peanuts	50537.925	15414067.13
Foss	30% Peanuts, 30% Potatoes, 30% Cassava, 5% Onions, 5% Watermelon	23088.116	7041875.38
Guidick	20% Peanuts, 30% Cassava, 30% Potatoes, 10% Onions, 10% Watermelon	4243.575	1294290.375
Total			69 115 088.03

In contrast, agribusinesses, which consume substantially larger volumes of water, have an estimated annual water requirement of 571,958,000 m³ (Table 8). This annual volume is approximately seven (7) times greater than the volumes withdrawn by local farmers. However, it should be noted that agribusinesses employ more water-efficient irrigation techniques (e.g., drip irrigation, sprinkler irrigation, pivot irrigation, etc.).

Table 8: Water requirements in agro-industrial companies

Company	Speculation cultivated	Area (ha)	Cultivated area (ha)	Speculation water requirement m3/ha/year	Total water requirement m3/year
C.S.S (Compagnie Sucrière Sénégalaise)	Sugar cane	15000	11300	29500	333350000
Vital	Rice and vegetables (onion, sweet potato)	6000	60 ha (15ha riz)	18400 riz , 10100	724500
Temey Agro	manioc, onion, potato, groundnut, melon	1000	80	10100	808000
Exploitation Agropastoral Sanosy (EAPS)	onions	1500	200	10100	2020000
Ferlogomme	Organic crops: onions, peppers, mangoes, papayas	160	40	10100	404000
Toll Jom	Green onions, green asparagus, sweet potatoes, peppers and baby maize	700	250	10100	2525000
Senegindia	Market garden and tree crops	5600	3040	10100	30704000
Agrina ferme Foss	Market garden crops (watermelon, chilli)	5000	1200	10100	12120000
Agricola	Market garden crops (tomato, chilli, onion, cabbage, aubergine)	50	25	10100	252500
Goe Senegal	mango and citrus	200	28		0

ANIDA (Agence National D'Insertion et de Developpement Rural) ex REVA	Vegetable crops (tomato, aubergine, watermelon, chilli, melon, onion, cowpea, papaya, maize)	100	70	10100	707000
SEPAM (Societe Exploitation des Produits Agricoles et Maraichers)	Vegetable crops, particularly cherry tomatoes and green beans + melon and squash	1000	250	10100	2525000
West Africa Farm	onion-radish salad	288	180	10100	1818000
SENHUILE	Rice to wash out dirty soil and Sunflower	20000	10000	18400riz pour le lessivage des sols sales 10100	184000000
Total					571 958 000

4.5. Calibration and validation results

The WEAP model calibration results (Figure 27) show excellent performance in reproducing observed volumes. A Nash-Sutcliffe Efficiency (NSE) of 0.95 and a Kling-Gupta Efficiency (KGE) of 0.93 indicate a very good match between simulated and observed volumes. The Normalised Root Mean Square Error (NRMSE) was very low at 0.91%, reflecting a low dispersion of errors. The PBIAS of 0.025% indicates an absence of systematic bias, meaning that the model neither underestimates nor overestimates volumes. The coefficient of determination (R^2) of 0.96 confirms a strong correlation between the observed and simulated values, reinforcing the reliability of the calibration. The indicators Inverse NSE (InvNSE = 0.95) and SqrtNSE (0.95) also show low error on low and mean values, attesting to the model's robustness in reproducing flows over the entire calibration period.

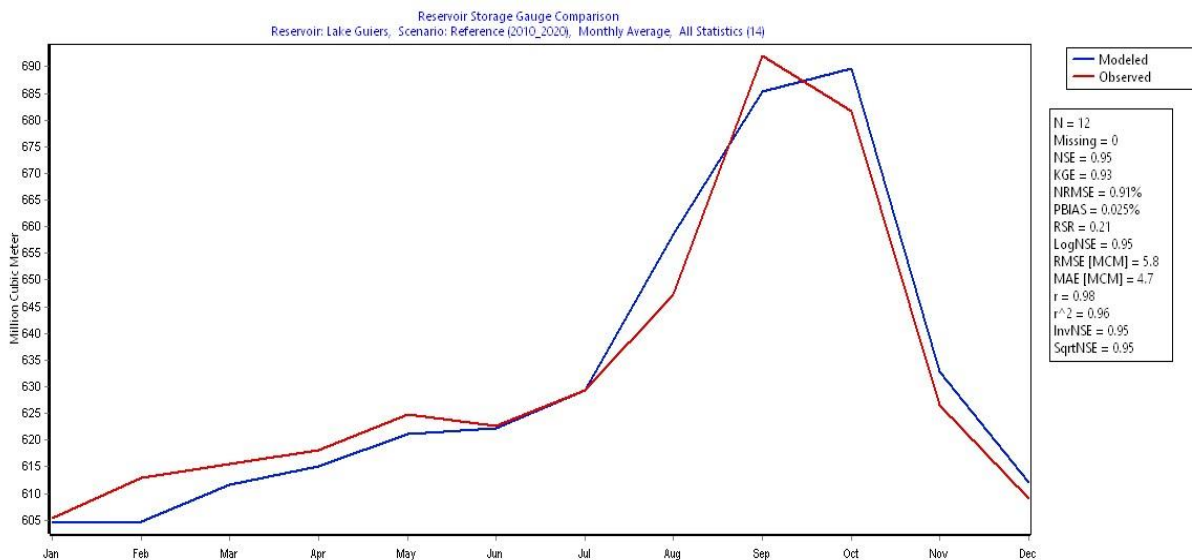


Figure 27: Calibration of the model

The validation results (Figure 28) show that the model performs moderately well in reproducing volumes over an independent period. The NSE (0.46) and KGE (0.47) show a decrease in accuracy compared with the calibration, suggesting that the model only partially captures the variability of flows. The NRMSE, evaluated at 6.5%, reflects an increase in relative error, while the PBIAS (-3.2%) indicates a slight underestimation of simulated volumes. However, with an R^2 of 0.72, the model retains a satisfactory ability to explain the overall variability of flows. The values for InvNSE (0.51) and SqrtNSE (0.48) show room for improvement, particularly in reproducing low and medium flows. This reduction in validation performance can be explained in part by the absence of detailed data on the interannual variability of water use, which was incorporated into the model on a hypothetical basis.

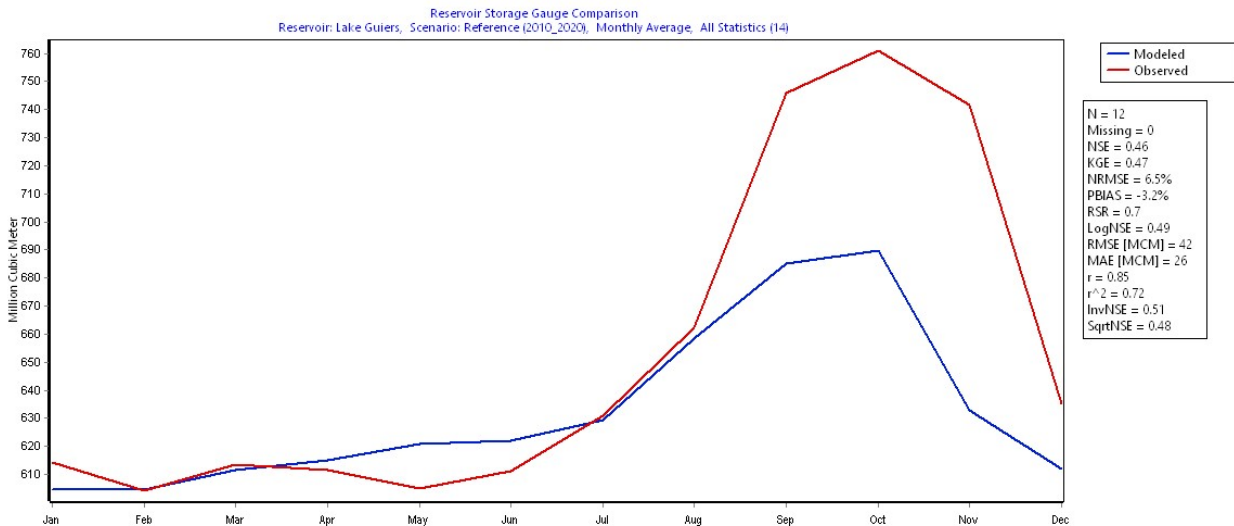


Figure 28: Validation of the model

4.6. Simulation of scenarios with WEAP

4.6.1. Climate change scenarios

This following graph shows the mean monthly net evaporation from Lake Guiers (in millions of cubic metres) under three different scenarios: a baseline scenario, a moderate climate change scenario SSP4.5 and a more severe climate change scenario SSP8.5 (Figure 29).

All the scenarios show a similar seasonal cycle, with a peak in evaporation in April (hot season) and a minimum in September (rainy season).

The SSP4.5 and SSP8.5 scenarios show systematically higher evaporation than the baseline scenario, which is consistent with the temperature increases predicted in the climate change scenarios. Indeed, the scenario SSP8.5 (the most pessimistic) shows the highest evaporation throughout the year, followed by the SSP4.5 and then the reference scenario. In April, evaporation reaches around 2.65 million m³ for SSP8.5, 2.55 million m³ for SSP4.5, and 2.45 million m³ for the reference.

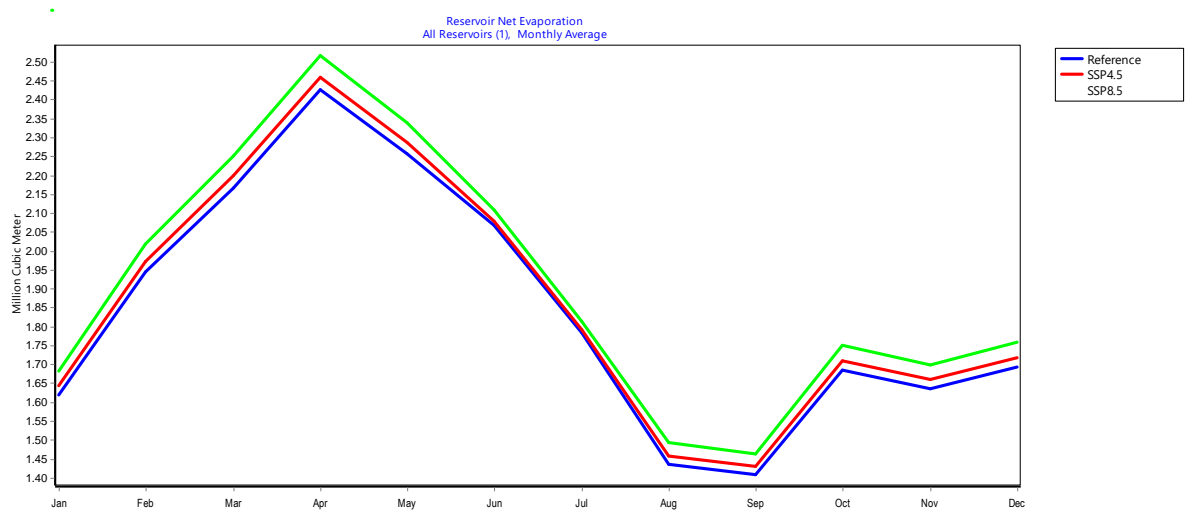


Figure 29: Monthly net evaporation of the lake Guiers

Figure 30 shows the annual net evaporation from Lake Guiers (in millions of cubic metres) over the period 2021-2050. A rapid increase in the volume of water is observed at the beginning of the period (2021-2022), probably due to the initial filling conditions of the lake. From 2023-2025, the three scenarios begin to diverge.

The SSP8.5 scenario shows the highest levels of evaporation, reaching around 23 million m³ in 2050. In comparison, the SSP4.5 scenario shows a slight decrease followed by stabilisation at around 22.2 million m³, while the reference scenario shows a more marked decrease, reaching around 21.4 million m³ at the end of the period. The gap between SSP8.5 and the reference scenario widens gradually, reaching around 1.6 million m³ by 2050.

Fluctuations are visible in all scenarios, suggesting variations in water inputs (precipitation, river inflows) and abstractions. These results indicate that the different climate scenarios could have a significant impact on the volume of water available in Lake Guiers.

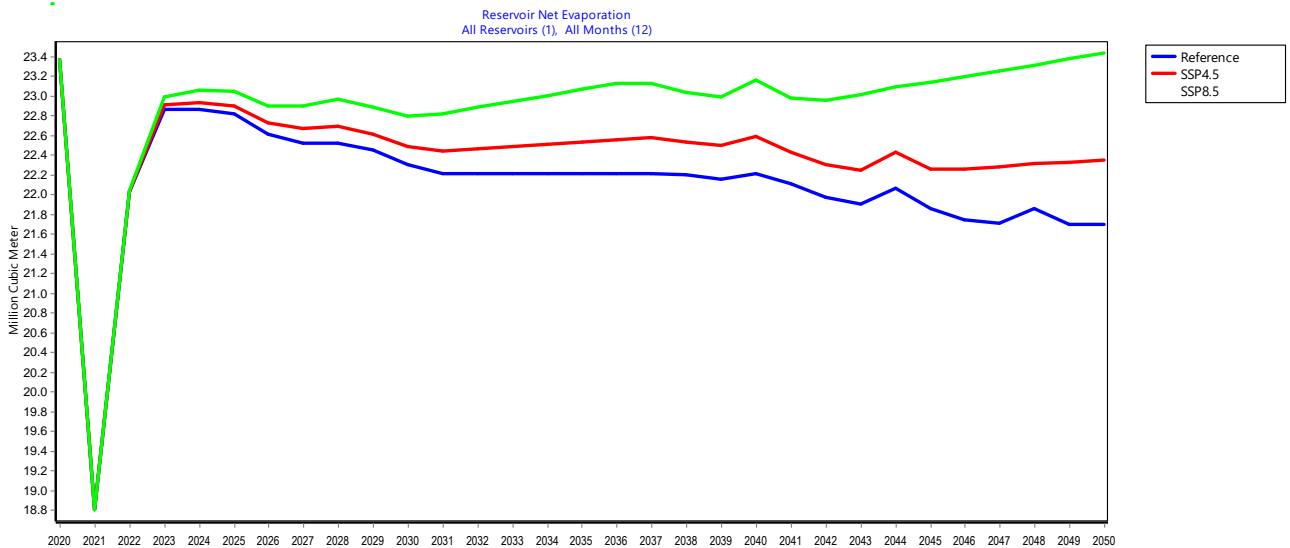


Figure 30: Annual net evaporation of Lake Guiers

4.6.2. Increased demand for water from extraction plants

This figure (Figure 31) illustrates changes in the storage volume of Lake Guiers between 2021 and 2050 according to three drinking water demand scenarios. The three scenarios initially present similar seasonal filling and emptying cycles, but their trajectories diverge considerably. The high-demand scenario (+10% for drinking water) shows a critical collapse from 2023-2024, reaching an irreversible structural deficit that stabilises at 149 million m³ from 2037. The inactive volume of the lake is set at 149 million m³. That is why the storage is not fully emptying to 0 m³. The medium-demand scenario (+5% for drinking water) remains in balance until 2034 before gradually deteriorating, collapsing from 2041 onwards and also stabilising at 149 million m³ in 2049. In contrast, the reference and low-demand scenarios (+2% for drinking water) maintain cyclical stability throughout the period, with constant fluctuations between 576 and 650 million m³, demonstrating their long-term viability.

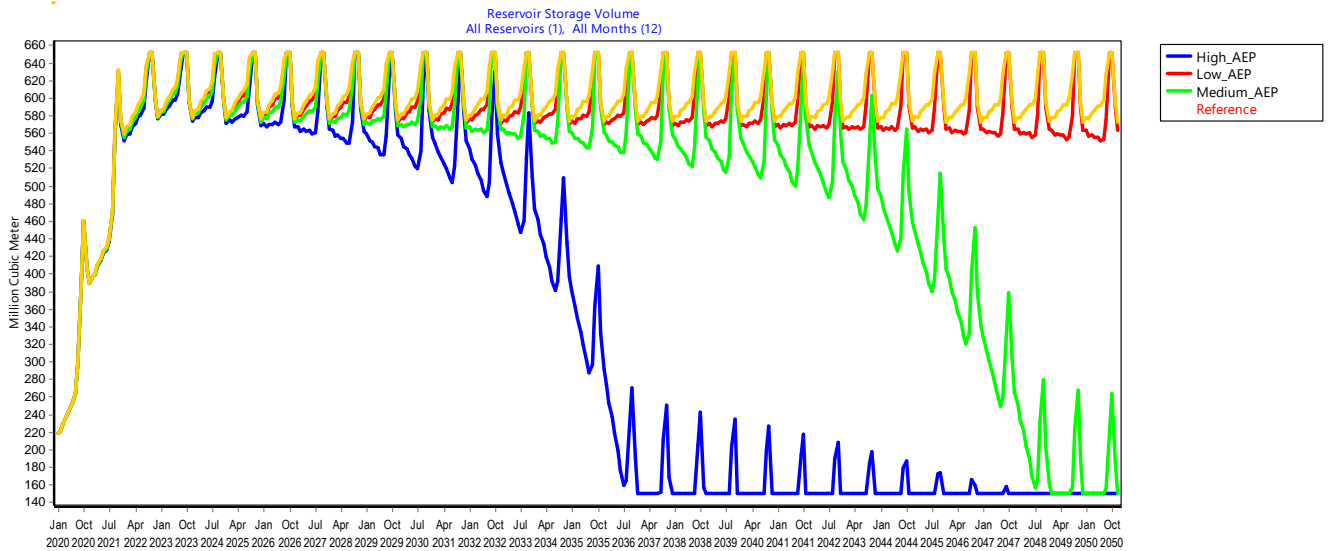


Figure 31: Monthly variation of the lake Guiers reservoir storage volume

The figure 32 illustrates the evolution of water supply deficits (unmet demand) according to the different drinking water demand scenarios. In the high-demand scenario, drinking water needs can no longer be met from 2036, with a deficit that worsens considerably to reach 1150 million m³ of unsupplied water by 2050. The medium-demand scenario allows sufficient supply to be maintained until 2048, before a deficit of 150 million m³ is recorded in 2050. The low-demand scenario, on the other hand, is fully sustainable, ensuring that all drinking water needs are met throughout the period 2021-2050, thus confirming its long-term.

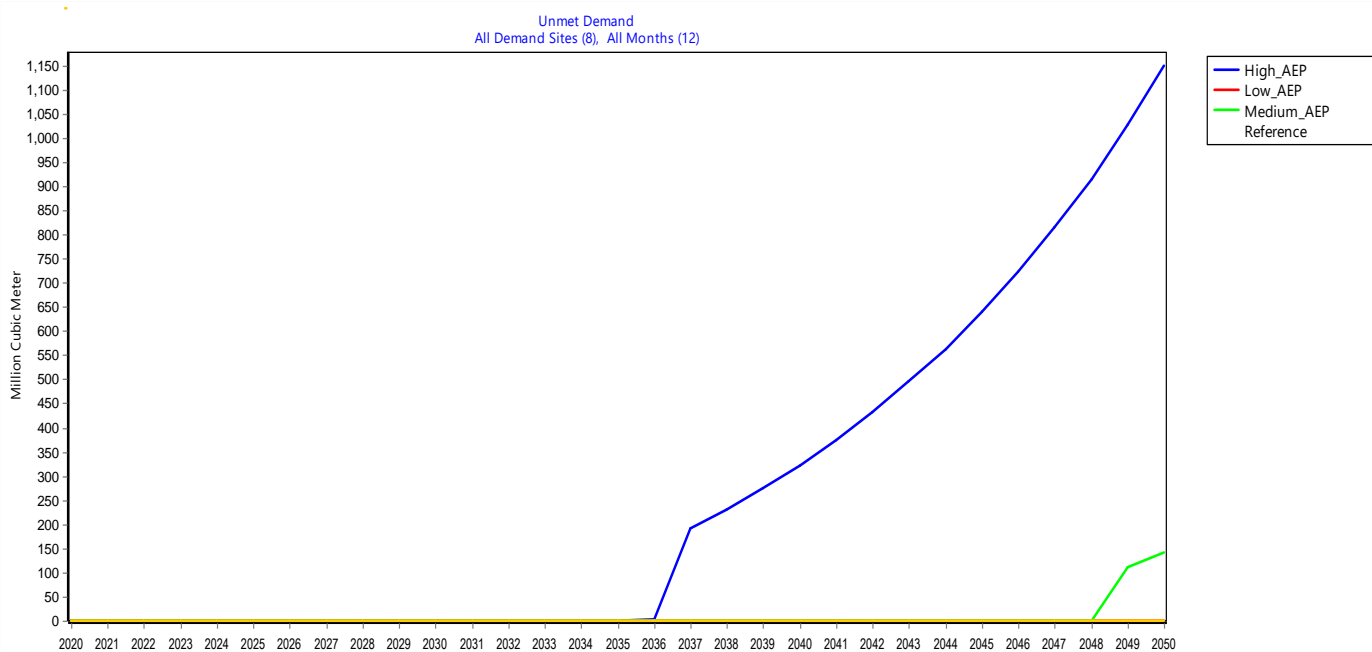


Figure 32: Unmet demand for water in Lake Guiers from 2021 to 2050 according to different drinking water demand scenarios

4.6.3. Increased demand for agriculture

Figure 33 shows changes in the storage volume of Lake Guiers from 2021 to 2050 under different agricultural demand scenarios. High agricultural demand (10%) causes a rapid decline in volume from 2023, leading to a total collapse and stabilisation at 149 million m³ from 2025. The medium demand (5%) scenario shows a gradual decline, reaching a critical level around 2028 before stabilising at around 149 million m³. Low demand (2%) also leads to a rapid reduction after 2025, stabilising at around 149 million m³ from 2037. In contrast, the reference scenario maintains stability, with regular oscillations between 576 and 650 million m³ throughout the period. These results indicate that an increase in agricultural demand could cause the lake to dry up critically in the long term.

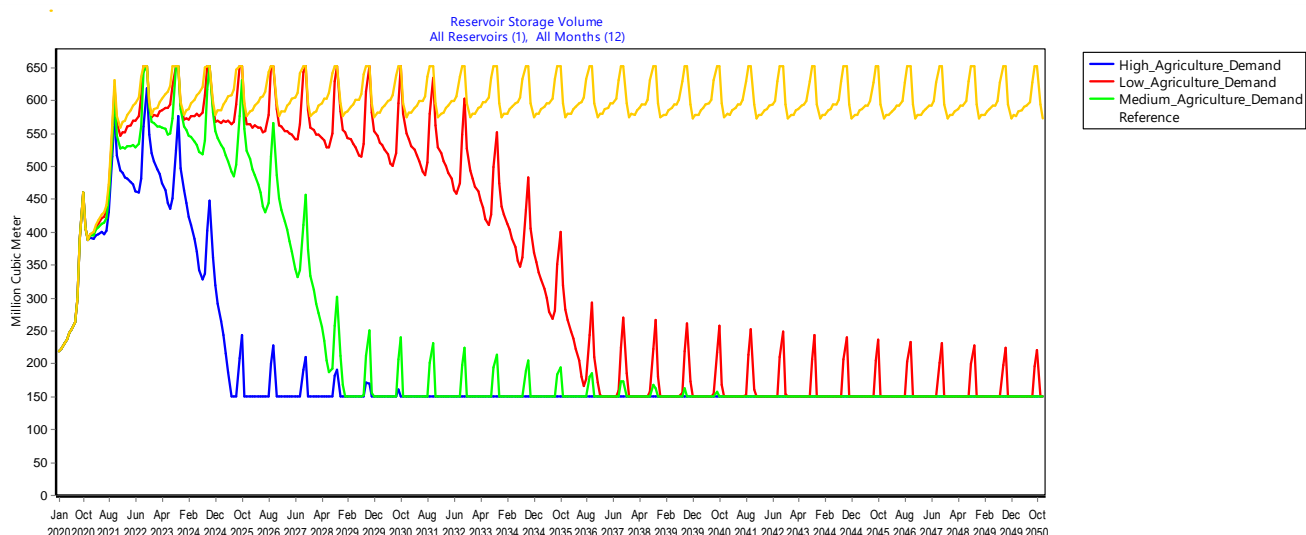


Figure 33: The storage volume of Lake Guiers from 2021 to 2050 under different agricultural demand scenarios

Figure 34 presents the unmet demand according to the same agricultural scenarios. The high agricultural demand scenario shows an exponential increase of the unmet demand from 2025, reaching around 10.5 billion m³ in 2050, revealing a growing inability to meet water needs. The medium-demand scenario also shows a gradual increase from 2028, reaching around 2 billion m³ in 2050. The low demand scenario shows moderate unmet demand from 2036, remaining below 0.5 billion m³ over the whole period. On the other hand, the reference scenario fully satisfies demand without showing a deficit.

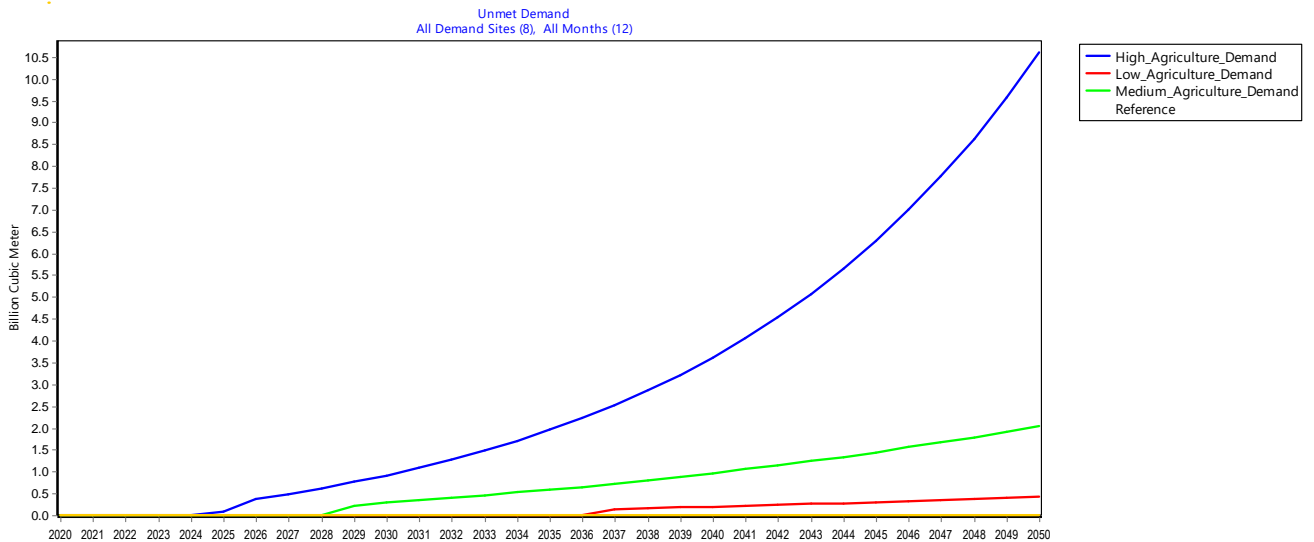


Figure 34: Unmet demand for water in Lake Guiers from 2021 to 2050 according to different agricultural demand scenarios

4.6.4. Senegal river inflow variation under climate change

Figure 35 depicts the evolution of the storage volume of Lake Guiers according to three scenarios of reduced inflows of water from the Senegal River.

The ‘Stop Flowing’ scenario simulates the total cessation of inflows, causing a rapid collapse in volume from 2024, reaching a critical level of 149 million m³. The SSP 8.5 scenario, with a 16% reduction in river flows in 2050, shows a gradual decline in volume from 2046, despite seasonal refilling cycles. The SSP 4.5 scenario, which is more moderate, with a reduction of 8%, shows a slight fall but maintains regular oscillations.

These results highlight the lake's strong dependence on inflows from the river and the importance of maintaining these flows to ensure its sustainability in the face of climate change.

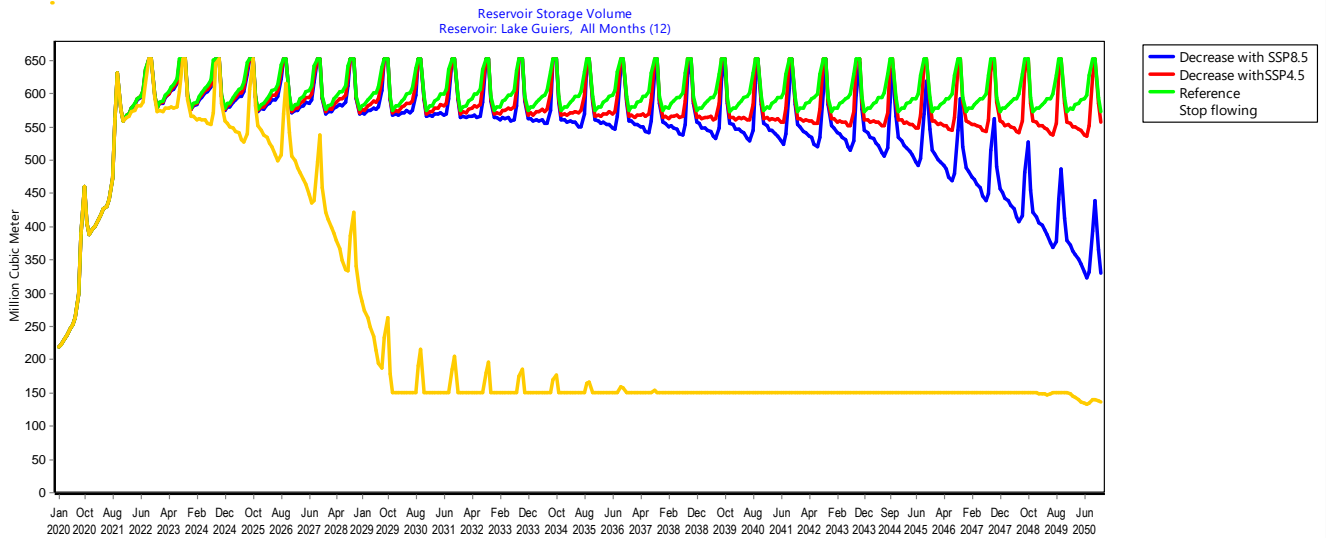


Figure 35: Evolution of the storage volume of Lake Guiers according to three scenarios of reduced inflows of water from the Senegal River

The unmet demand presented in Figure 36 highlights a deficit of 25 million m³ for the ‘Stop Flowing’ scenario, indicating the growing inability to meet the water needs of demand sites. This deficit gradually increases, reaching 966.95 million m³ in 2050, underlining the growing risks of shortages in the long term.

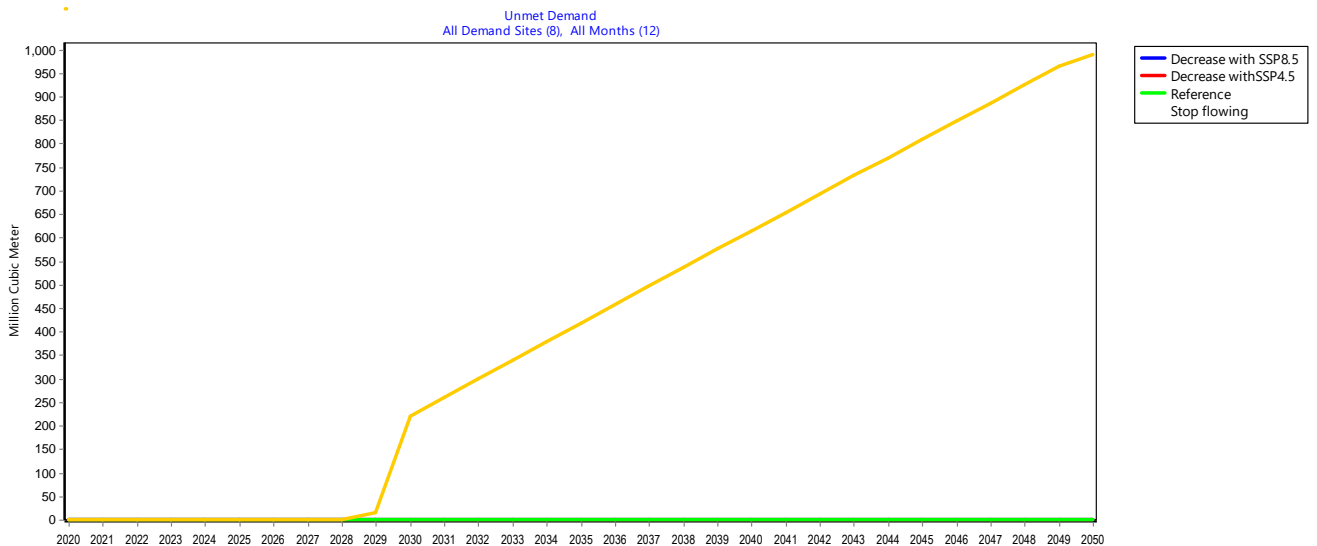


Figure 36: Unmet demand for water from 2021 to 2050, according to the scenarios of reduced water supply from the Senegal River

4.6.5. Future project scenarios (Grand Transfer_PREFERLO)

The inability of Lake Guiers to sustainably meet the water needs of the PREFERLO_Grand Transfer project is shown in Figure 37. A rapid decrease in the volume of the reservoir is observed from the beginning of 2021, until the lake reaches its inactive volume, set at 149 million m³. This critical threshold marks the point beyond which the lake can no longer ensure a viable water supply. Although inter-annual variations persist, particularly during the rainy season, they do not compensate for the overall depletion of resources.

This alarming situation is the result of annual withdrawals of around 556,237,370 m³ of water for the PREFERLO project, which aims to transfer water from Lake Guiers at Keur Momar Sarr to Vélingara Ferlo and Dahra. While this project pursues legitimate objectives of socio-economic development, ecosystem restoration and adaptation to climate change in the Ferlo agro-sylvo-pastoral zone, the results show that Lake Guiers, as per now, does not have sufficient capacity to support withdrawals on such a scale in a sustainable manner.

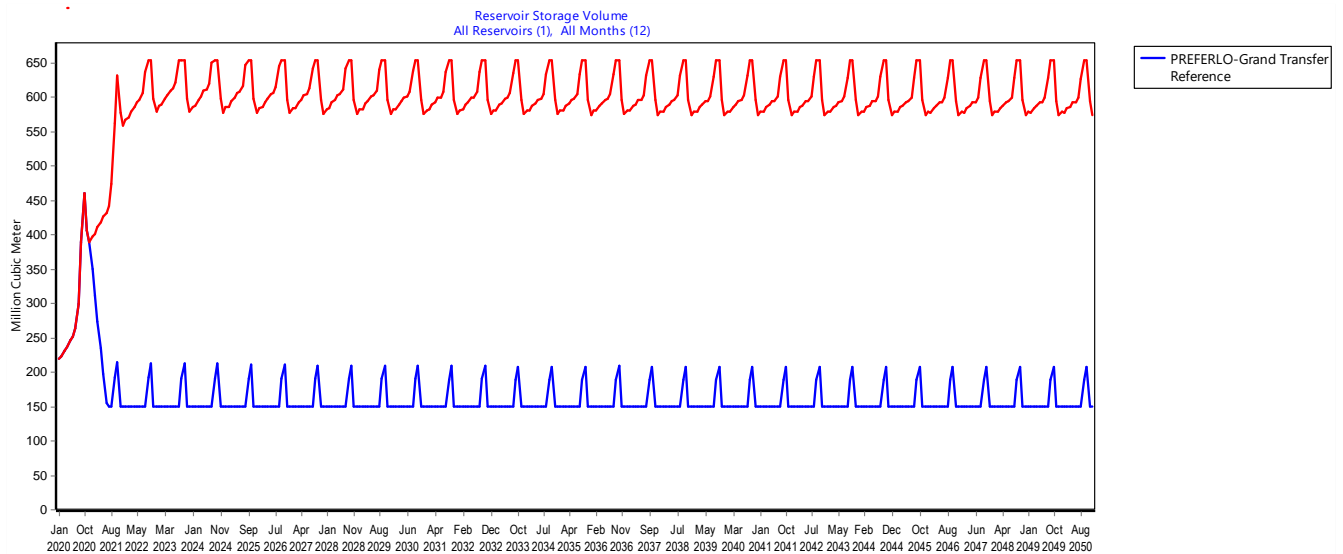


Figure 37: Evolution of the storage volume of Lake Guiers according to the future project

CHAPTER FIVE

5. DISCUSSION

5.1. State of water quality

As regards the results of physico-chemical analyses, the sites with the highest values requiring special attention are: Mbane and Bellel Mbaye. Overall, the results highlight a deterioration in raw water quality, influenced by natural factors such as post-rainfall run-off and the proliferation of aquatic plants, but also exacerbated by anthropogenic pressures (Cogels et al., 2002; Cogels & Gac, 1983; Diédhiou et al., 2019). Run-off from recent rains carries sediments, nutrients and pollutants from human and agricultural activities, increasing turbidity and concentrations of certain pollutants, particularly BOD5. In addition, the proliferation of aquatic plants, encouraged by excess nutrients, explains the variations in dissolved oxygen. These combined environmental and human pressures compromise not only water quality but also its ecological balance.

5.2. Evolution of head flows

A gradual decrease in flow is observed along the same axis, reflecting significant head losses. In the Lake Guiers area, head losses are particularly marked on the 17 km long Taouey canal, which links the lake to the Senegal River. A significant loss of 6.32 m³/s has been recorded, representing a daily volume loss of 546,048 m³. Several factors could explain this situation: clogging of the channel by aquatic vegetation, which reduces the flow capacity and generates turbulence that slows down the flow (Kamara, 2013); evaporation; and withdrawals by users (agribusiness, local farmers, water supply), which reduce the flows available downstream and accentuate water losses.

5.3. Agricultural water requirements

The significant water losses observed in the Lake Guiers basin are the result of several interdependent factors. Firstly, a lack of effective management of irrigation canals, leading to leaks and poor water distribution due to inadequate maintenance of the infrastructure. Secondly, the widespread absence of conservative irrigation systems, such as drip, sprinkler or pivot irrigation, and the low adoption of climate-smart farming practices, exacerbate these losses (Cisse, 2012). In addition, the clogging of canal-lake junctions by aquatic plants, observed in almost all the surrounding villages, is a major cause of wastage (Cisse, 2012). Finally, the dominant use of gravity-fed irrigation, combined with topographical constraints, exacerbates the situation: on the left bank (from Ngnith to KMS), the agricultural perimeters, far from the

lake and situated on high slopes, suffer increased losses, whereas on the right bank (Mbane, Temey, Diakhaye, Foss, Syer), the fields, close to the lake and situated on a similar relief, suffer fewer losses.

5.4. Impact of different scenarios on Lake Guiers storage

Lake Guiers is vulnerable to the combined effects of climate change and increased water abstraction. The SSP4.5 and SSP8.5 climate scenarios indicate increased evaporation, exacerbating this vulnerability. Sambou (2017) confirms that despite a potentially sufficient volume of water, shortages occur due to high evaporation and pumping for irrigation and urban water supply.

Combining the SSP8.5 scenarios with strong growth in demand (10%) accelerates the decline in lake volume: without climate change, significant declines would begin in 2029, but with SSP8.5, they would begin as early as 2026. Moderate growth in demand (2%) would make it possible to meet needs throughout the period studied, unlike the SSP8.5 scenarios with high demand (Figure 38). By this scenario, we can note the impact of climate change on decreasing water storage as it is also notified in different water resources (Dlamini et al., 2023; Opere et al., 2022; Touseef et al., 2021).

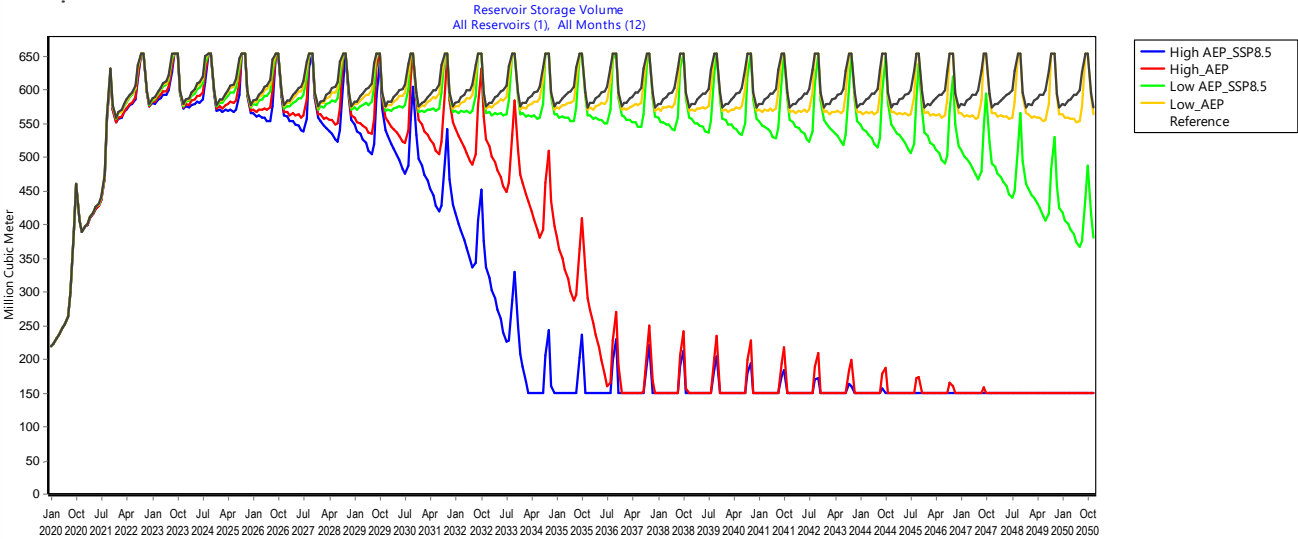


Figure 38: Lake Guiers storage volume variation under combined scenarios of drinking water demand and climate change SSP8.5

The high agricultural demand associated with the SSP8.5 scenarios would lead to a rapid collapse in volume from 2021, reaching 149 million m³ in 2025 (Figure 39). Reduced inflows from the Senegal River would further threaten the sustainability of this essential resource.

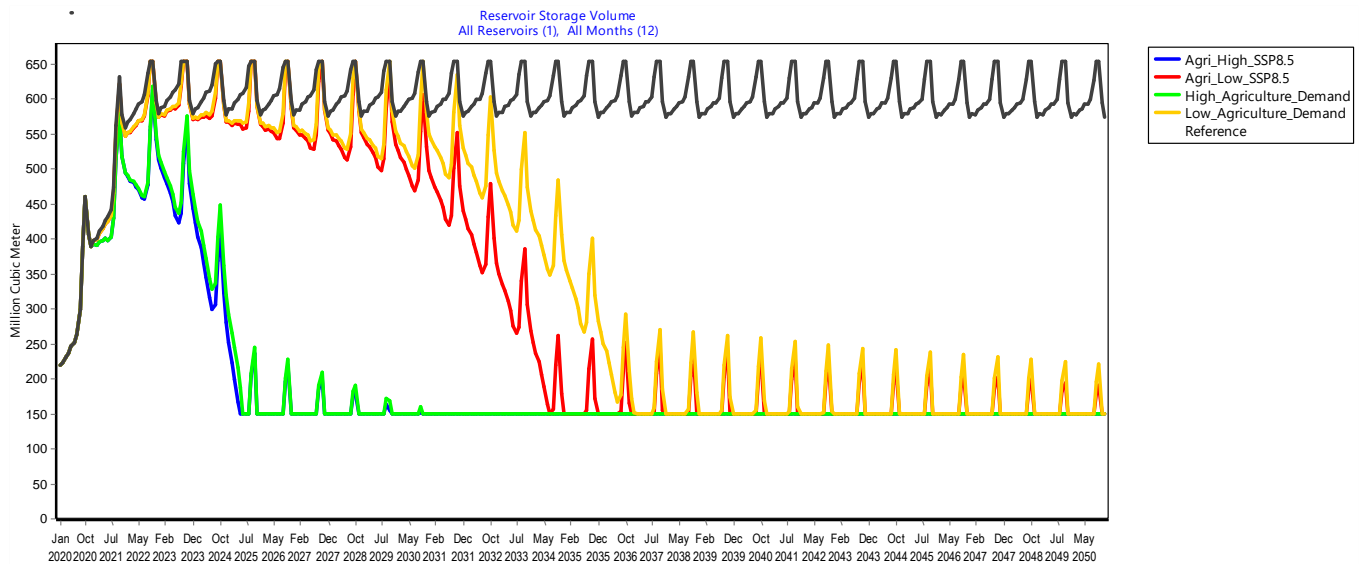


Figure 39: Lake Guiers storage volume variation under combined scenarios of demand and climate change SSP8.5

5.5. Limitations of Study

One of the main limitations of this study is the lack of precise data on interannual variability in the use of water resources. This uncertainty led to the incorporation of assumptions when validating the model, which may explain the drop in performance observed compared with the calibration. This approximation may affect the model's ability to reproduce flow fluctuations accurately, particularly for low and medium flows.

In addition, it was not possible to dynamically adjust the parameters related to water use due to the lack of up-to-date information. This limitation suggests the need for more in-depth data collection on water use practices and socio-economic changes to improve the robustness of future hydrological simulations.

CHAPTER SIX

6. CONCLUSION AND RECOMMENDATION

6.1. Conclusion

This study assessed the availability of water resources in Lake Guiers in the face of the combined effects of climate change and increasing human pressures, using the WEAP model as an analytical tool.

The results of the simulations reveal a significant vulnerability of Lake Guiers in the coming decades. The WEAP model, although showing excellent performance in the calibration phase (NSE=0.95, KGE=0.93), has limitations in the validation phase (NSE=0.46, KGE=0.47), suggesting a certain caution in the interpretation of long-term projections.

The SSP4.5 and SSP8.5 climate scenarios indicate an increase in net evaporation that could significantly reduce the lake's available volume by 2050. At the same time, the increase in demand for drinking water and agricultural water could put unsustainable pressure on this limited resource. A 10% increase in agricultural demand would lead to a critical collapse of the system as early as 2025, while a similar increase for drinking water would result in a structural deficit from 2037.

In addition to the quantitative aspects, analysis of the water quality revealed a worrying deterioration, particularly at the Mbane and Bellel Mbaye sites. This deterioration is the result both of natural factors such as post-rainfall run-off and the proliferation of aquatic plants, and of human pressures that increase turbidity and the concentrations of certain pollutants, particularly BOD5.

Field surveys also revealed significant water losses in the lake basin, estimated at 10,216,369.11 m³ per year, or around 33,496.29 m³ per day. These losses are attributable to poor management of the irrigation canals, the widespread absence of conservative irrigation systems, the obstruction of canal-lake junctions by aquatic plants, and the topographical constraints that affect the two shores of the lake differently.

The PREFERLO_Grand Transfer project, as currently dimensioned with annual withdrawals of around 556 million m³, proves to be incompatible with the lake's capacity, leading to a rapid drop in volume to the inactivity threshold (149 million m³).

This study provides a scientific basis for informing political decisions and guiding investment in hydraulic infrastructure, in order to ensure sustainable management of Lake Guiers in the face of the challenges of climate change and the region's socio-economic development.

6.2. Recommendation

Following this study, a number of recommendations can be made to ensure the sustainable management of Lake Guiers and the viability of the projects that depend on it, in particular PREFERLO_Grand Transfer and agriculture expansions. It is essential to develop new retention basins to capture the excess water from the Senegal River currently discharged into the Atlantic Ocean via the Diama dam, thus providing an alternative source for the PREFERLO project. At the same time, in-depth hydrological studies need to be carried out on the dynamics between the Senegal River and Lake Guiers, particularly upstream of the Richard-Toll works and before the Taouey, to optimise water transfers. Modernising irrigation systems to use more economical technologies (drip irrigation, sprinkler irrigation) and implementing a management plan to prevent the proliferation of aquatic plants that obstruct canal-lake junctions are also essential to reduce significant water losses. Finally, an integrated real-time monitoring system for water quantity and quality will enable adaptive management in the face of seasonal variations and long-term trends. Implementing these recommendations will require a collaborative approach involving public authorities, research bodies, users and technical and financial partners.

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