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Ismaghil GOUSMANE ANISLOUM

TITLE:

ASSESSING WATER-FOOD CLIMATE NEXUS USING GIS: CASE STUDY OF DARGOL BASIN IN NIGER RIVER MIDSTREAM

Defended on 15/04/2025 Before the Following Committee:

Chair	HADDOUCHE Driss	Prof.	University of Tlemen, Algeria
Supervisor	IBRAHIM Boubacar	Dr	Abdou Moumouni University, Niger
External Examiner	Tewodros Tena	Dr	BGR, Zambia.
Internal Examiner	Radia GHERISSI	Dr	University Centre of Maghnia, Algeria

DECLARATION

Signature: Date: 14/02/2025

Name: Gousmane Anisloum Ismaghil

Reg No: PAUWES/2023/MWP11

Signature: Date:

Name: Dr Ibrahim Boubacar

West African Sciences Service Centre of Climate Change and Adaptation Land Use (WASCAL)

Signature:

Name:

DEDICATION

I dedicate this work to my tow late grandmothers; to my parents and all those who believed on me.

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Glory and praise be to Almighty ALLAH (SWT) for granting me the health and strength to complete this end-of-studies project.

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ABSTRACT

The Sahel region is experiencing significant challenges related to water resources due to both natural and anthropogenic factors. This study examines the water resource management challenges in the Dargol Basin of the Niger River midstream, with a particular focus on the Water-Food-Climate (WFC) nexus. A thorough understanding of the intricate interconnections within this nexus is imperative for developing enhanced water management strategies and optimising agricultural productivity in the region. The study involved analysing the individual components of the WFC nexus- water, food, and climate- before employing the Principal Component Analysis test to assess their interlinkages. The findings underscore the pivotal role of water in agricultural productivity and food security, while concurrently highlighting the deleterious impacts of climate change on water availability. The results indicate that the water resources experienced spatiotemporal variability and changes. The food analysis results show a significant decrease in crop production while cash crops increased substantially. However, the Mann-Kendall and Pettitt tests reveal no statistically significant change point in the rainfall dataset from 1992 to 2022. The PCA analysis indicates a strong positive correlation between soil moisture and rainfall, while temperature is not correlated with rainfall and soil moisture. Cash crop yield and relative humidity (RH) are also positively correlated. In light of these findings, policy recommendations are proposed to enhance sustainable agricultural productivity, optimise water resource management, and strengthen resilience to climate change impacts in the Dargol Basin.

Keys words: Water Management, Food Security, Dargol Basin, Climate Change, Resilience

RESUME

La région du Sahel est confrontée à d'importants défis liés aux ressources en eau en raison de facteurs naturels et anthropogéniques. Cette étude examine les défis liés à la gestion des ressources en eau dans le bassin de Dargol, au milieu du fleuve Niger, en mettant l'accent sur le lien entre l'eau, l'alimentation et le climat (WFC). Une compréhension approfondie des interconnexions complexes au sein de ce lien est impérative pour développer des stratégies de gestion de l'eau améliorées et optimiser la productivité agricole dans la région. L'étude a consisté à analyser les différentes composantes du lien WFC - l'eau, la nourriture et le climat - avant d'utiliser le test de l'analyse en composantes principales pour évaluer leurs liens. Les résultats soulignent le rôle essentiel de l'eau dans la productivité agricole et la sécurité alimentaire, tout en mettant en évidence les effets délétères du changement climatique sur la disponibilité de l'eau. Les résultats indiquent que les ressources en eau ont connu une variabilité et des changements spatio-temporels. Les résultats de l'analyse alimentaire montrent une diminution significative de la production agricole alors que les cultures de rente ont augmenté de manière substantielle. Cependant, les tests de Mann-Kendall et de Pettitt ne révèlent aucun point de changement statistiquement significatif dans l'ensemble des données pluviométriques entre 1992 et 2022. L'analyse ACP indique une forte corrélation positive entre l'humidité du sol et les précipitations, tandis que la température n'est pas corrélée avec les précipitations et l'humidité du sol. Le rendement des cultures commerciales et l'humidité relative (HR) sont également positivement corrélés. À la lumière de ces résultats, des recommandations politiques sont proposées pour améliorer la productivité agricole durable, optimiser la gestion des ressources en eau et renforcer la résilience aux impacts du changement climatique dans le bassin du Dargol.

Mots clés : Gestion de l'eau, sécurité alimentaire, bassin du Dargol, changement climatique, résilience

ACRONYM

CCY	Cash Crop Yield
GFWS	Global Food and Water System
GIS	Geographical Information System
LCA	Life Cycle Assessment
MACA	Multivariate Adaptive Constructed Analogs
MLR	Multi Linear Regression
NWSAS	North Western Sahara Aquifer System
PCA	Principal Component Analysis
R	Rainfall
RH	Relative Humidity
SCY	Subsistence Crop Yield
SM	Soil Moisture
SSA	Sub-Saharan Africa
SWAP	Soil Water Atmosphere Plant
SWAT	Soil and Water Assessment Tool
T	Temperature
WEAP	Water Evaluation And Planning System
WEF	Water Energy Food
WEFN	Water-Energy-Food Nexis
WF	Water-Food
WFC	Water-Food-Climate

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CHAPTER I : INTRODUCTION

1.1 Background of the study

Water and food are the most important elements for human survival after oxygen. Water is an essential resource for both daily life and economic activities. Although 71% of the Earth's surface is covered by water, 97.5% of it is saltwater in oceans (Mishra & Dubey, 2015). Seventy per cent of freshwater is locked in polar ice, 29% is groundwater, and only 1% is easily accessible for human use. Water resources are unevenly distributed across time and space. For example, China has 7% of the planet's renewable water reserves, but 22% of the world's population, while Canada, home to around 0.5% of the world's population, possesses 9% of the world's water reserves (David B., 2002). The irrigation sector is the dominant global water-use sector, accounting for 70% of global water withdrawals and 90% of global water consumption (Laubenstein, 2021). Irrigated land produces around 40% of all the food we consume and represents an estimated 20% of agricultural land about 300 million hectares globally forming the backbone of many economies.

However, these two closely linked resources, water and food (WF), face threats from a common phenomenon. The first major threat is population growth. A rising population demands more clean water for drinking, sanitation, agriculture, and industry. Over the past 100 years, global water demand has increased by 600% (Wada et al., 2015). Additionally, population growth contributes to heightened water contamination. In many countries, water scarcity is exacerbated by water pollution (Liyanage & Yamada, 2017). Industrial discharges, sewage, and runoff from urban areas contaminate water bodies, impacting both water quality and availability. It is estimated that 300 to 400 megatons of industrial waste are released into water bodies annually (Boretti & Rosa, 2019). Water pollution affects nearly every river across Africa, Asia, and Latin America. In regions with limited water resources, population growth intensifies water stress. Less than 3% of the world's water resources are freshwater, and they are becoming increasingly scarce. Many populations risk losing sustainable access to clean and sufficient water, a situation expected to worsen in the coming decades. By 2050, global water demand for all uses will likely increase by 20% to 30% (Burek et al., 2016). Water scarcity is becoming a critical issue that affects ecosystems, livelihoods, and irrigation supplies. Furthermore, the expansion of urban areas due to population growth reduces the amount of land available for agriculture, which in turn decreases agricultural production and soil quality,

leading to food insecurity. Population growth is one of the most critical factors elevating the level of food insecurity (Molotoks et al., 2021). Future global food demand is anticipated to rise by 70% by 2050, with a doubling in developing countries, while currently, 690 million people endure daily hunger, two-thirds of whom reside in rural areas (FAO et al., 2020; Laborde et al., 2020).

The second threat is climate change. Climate change has multiple impacts on WF in the form of the diminishing amount of water for agriculture, decreasing water quality and changing biodiversity and ecosystems, which altogether eventually risk food security. Climate change manifests itself in two ways: progressive movements away from stable climatic conditions and climate-related extremes. Therefore, by altering rainfall patterns climate change affects water supplies for agriculture. Agriculture is primarily and heavily dependent on climate as factors such as rainfall, sunshine hours, temperature, relative humidity, and drought duration influence crop production (Alam et al., 2011). In sub-Saharan Africa (SSA), 95% of the cultivated land is under rainfed agriculture (Biazin et al., 2012). Climate change may affect groundwater resources due to the expected changes in rainfall and evapotranspiration and spatio-temporal distribution of these important water balance components. It is argued that Global warming will reduce rainfall and crop production, leading to loss of arable land, increased water stress, reduced crop yields (Islam, 2022). Climate change is a major threat to global food security (Atiqul Haq et al., 2021). In addition, increased rainfall will lead to higher levels of water flow, increased risk of flooding and reduced levels of groundwater recharge (Şen, 2021). Climate-related catastrophes have tripled since the 1980s (Munich Re, 2020). The International Disaster Database EM-DAT recorded a 340% increase in deaths from storms between 2022 and 2023, driven in large part by the devastating loss of life in Libya from the floods that resulted from Storm Daniel in September (EM-DAT, 2023). According to a new analysis from Save the Children, at least 12,000 people lost their lives due to floods, wildfires, cyclones, storms, and landslides globally in 2023. Rising temperatures due to global warming result in higher evaporation and soil erosion, diminishing the amount of water body and increasing water scarcity and demand for irrigation water. The Aral Sea, once the world's fourth largest inland water, is experiencing a rapid loss of 88% of its area and 92% of its water volume since the 1960s (Yang et al., 2020). The same goes for Lake Tchad, it has diminished by 90% since the 1960s due to overuse and climate change effects (Olowoyeye & Kanwar, 2023).

The Sahel region is characterized by highly variable rainfall patterns, both temporally and spatially, which have been exacerbated by a nearly 30% reduction in rainfall at the end of the 20th century (Aboubacar et al., 2023). This decline has led to recurrent droughts, such as those experienced in 1974 and 1984, which significantly affected the region (Mounkaila, 2002). The vulnerability of rural populations has intensified, as their primary subsistence activity rain-fed agriculture, depends on a single, unpredictable annual rainy season (Sultan et al., 2015). In Niger, this challenge is compounded by land degradation, which affects over 100,000 hectares of arable land annually, amidst growing demand for agricultural and forestry products. Over the last few decades, desertification, drought and erratic rainfall have become critical and widely discussed challenges for Niger (Wildemeersch et al., 2015).

In addition to climatic hazards, human activities are playing an increasingly significant role in exacerbating resource pressures. Niger's population grew from 5.1 million in 1977 to 17.1 million in 2012, with four out of five individuals residing in rural areas (INS, 2015). This demographic expansion has driven a rise in essential needs, such as food, energy, and housing. Given the reliance of agriculture on erratic climatic conditions, rural populations increasingly turn to natural resources to meet their basic needs (Aboubacar et al., 2023).

1.2 Statement of the problems

West African countries, including Niger, are facing the dual challenges of rapid demographic growth and environmental sustainability. The region's population is expected to nearly triple between 1990 and 2030, reaching 516 million people (United Nations, 2015). In Niger, the population growth rate of 3.7% per year makes it one of the fastest-growing populations in the world, with an estimated 24.46 million inhabitants in 2022 (INS, 2022). This rapid demographic expansion has intensified the demand for water, food, and arable land, making it increasingly difficult to meet these needs while maintaining environmental sustainability (World Bank, 2016).

Over recent decades, Niger has experienced significant degradation of its natural resources, particularly land. Natural forest cover declined from 16 million hectares in 1982 to 5 million hectares in 2006, with over 100,000 hectares of new land brought under cultivation each year (Mahamadou et al., 2023). This expansion, however, often conversion of arable land into less productive uses (Slegers & Stroosnijder, 2008).

Niger's economy is heavily reliant on agriculture, which contributes approximately 40% of the country's GDP (World Bank, 2020). However, the sector is highly vulnerable to the country's arid and semi-arid conditions, with annual rainfall ranging from 100 to 700 mm (Wouterse, 2017). Since the 1960s, declining rainfall has led to recurrent droughts, such as those in 1966–1967, 1973–1974, and 1983–1984 (Bharwani, 2011). Between 2000 and 2009, average rainfall was 8% below normal levels, and in 2020, severe flooding affected more than 1.5 million people (FAO, 2020). These climatic challenges, coupled with desertification, locust infestations, and declining soil productivity, threaten agricultural stability and food security. In regions like Tillabéri, food insecurity has reached critical levels (IPC Phase 3), with low-income households depleting cereal stocks and facing restricted access to agricultural sites (FEWS NET, 2024).

Despite efforts to combat land degradation and improve resource management, progress has been limited. National initiatives to restore degraded land have achieved less than 45,000 hectares annually, far below the planned target of 229,000 hectares (Mahamadou et al., 2023). Forest formations continue to suffer significant anthropogenic pressure, undermining restoration efforts. The persistent challenges of rapid population growth, environmental degradation, and climate change necessitate an integrated approach to address the water-food-climate nexus in Niger, particularly in vulnerable regions like the Dargol Basin.

1.3 RESEARCH QUESTIONS AND WORKING HYPOTHESIS

1.3.1 RESEARCH QUESTIONS

- How do the characteristics, dynamics, and vulnerabilities of the water, food, and climate sectors manifest within the Dargol basin?
- What are the key interlinkages and dependencies between water, food, and climate in the context of resource security within the Dargol basin?
- What practical recommendations can be made to improve the management of the water-food-climate nexus?

1.3.2 THE WORKING HYPOTHESIS

- The water, food, and climate sectors in the Dargol basin exhibit distinct characteristics, dynamics, and vulnerabilities that are influenced by factors such as topography, land use patterns, agricultural practices, and climatic

conditions patterns and interactions of water, food, and climate variables in the study area.

- The Dargol basin's water, food, and climate sectors are all interrelated, with climatic patterns influencing water availability, agricultural productivity, and food security, while land use impacts demand and quality.
- Implementing an integrated management approach that considers the interdependencies between water, food, and climate sectors can enhance the resilience of the WFC nexus in the Dargol basin. This may involve a combination of strategies such as water conservation measures, sustainable agricultural practices (e.g., precision agriculture, crop diversification), climate-smart technologies, and participatory decision-making processes involving local stakeholders.

1.4 OBJECTIVES OF RESEARCH

1.4.1 General Objective

The main objective of this study is to assess the Water-Food climate nexus using GIS-based in the Dargol basin.

1.4.2 Specific Objectives

The following specific objectives structure the present study:

- Describe the different sectors of the WFC nexus, with a focus on their characteristics, dynamics, and respective vulnerabilities.
- Evaluate the complex interconnection between water food and climate, by identifying the mechanisms through which disruption in one of the sectors can impact the others.
- Define some recommendations based on the analysis results to enhance the management and resilience of systems related to the water-food-climate nexus, highlighting risk mitigation measures and sustainable practices.

1.5 RELEVANCE OF STUDY

The study aims to provide a comprehensive understanding of the intricate relationships between the critical elements of water, food, and climate, which is crucial for informed decision-making and sustainable resource management. The study will use GIS to spatially analyse the

interactions between water resources, agricultural yield, and climate variability in order to identify dynamics, vulnerabilities, and opportunities for intervention. It will also use the Principal Component Analysis (PCA) test and Multi Linear Regression to identify the mechanisms through which one sector can impact the others.

The findings from this research will contribute to the existing body of knowledge on the complex interactions between water, food, and climate in the context of a developing region. The insights gained will inform policymakers, development agencies, and local communities in their efforts to address the pressing issues of water availability, agricultural yield, and climate resilience. Furthermore, the relevance of this study extends beyond the Mead-stream Niger basin, as the methodologies and findings can be adapted and applied to other regions facing similar challenges.

1.6 Scope of the Study

The Water-Food (WF) Nexus is a multifaceted concept increasingly employed to facilitate the comprehensive study and management of global water and food resource systems (Lubis et al., 2018). This nexus underscores the critical interdependencies between these resources, emphasizing the need for quantitative models to evaluate and optimize their use effectively. This complexity has also led to developing various models to enhance understanding and address the challenges within the WF Nexus. Figure 1 shows the importance of the WF Nexus relevance. This research aims to assess the impact of climate variability on water and crop yield in the Dargol Basin. It specifically analyses key climate variables such as rainfall, temperature, and relative humidity, and their influence on the yields and production of both cash and subsistence crops. Principal Component Analysis (PCA) is applied to explore interrelationships within the water-food-climate nexus.

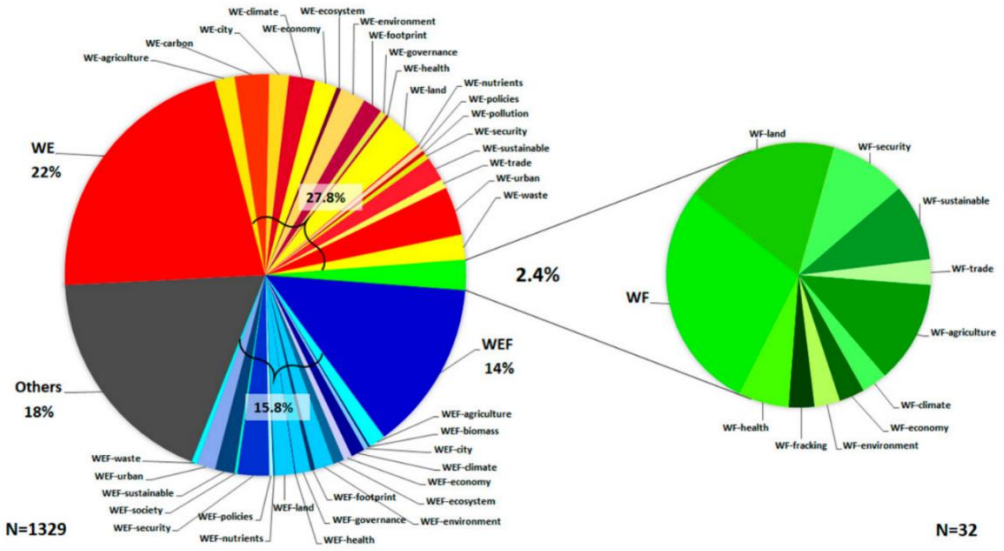

Figure 1: Water-Food Scops

1.7 Thesis Structure

The thesis is divided into five chapters and supplementary materials. Chapter one includes an introduction, problem statement, objectives, and significance of the study. The second chapter reviews relevant literature and discusses the study's assumptions. The third chapter covers methodology, explaining how the research was conducted step by step, from data collection to analysis and the software used. Chapter four presents results and discussion, detailing the outcomes of all activities conducted in the methodology. Chapter five concludes with recommendations, followed by bibliographic references and annexes.

CHAPTER II: LITERATURE REVIEW

The nexus has emerged as an important concept in integrated water management. Supported by various water organisations, including the World Economic Forum, the concept was promoted at several water conferences, especially the 6th World Water Forum. Many papers have been written on the concept, interactions, and sustainable use of resources after the launch of the WEF Nexus in Bonn (Corona-López et al., 2021). Thus, WEF's nexus concept rapidly expands in the academic literature and policy settings (Dl et al., 2016). The nexus approach seeks to identify trade-offs and synergies of water, energy, and food systems, internalise social and environmental impacts, and guide the development of cross-sectoral policies (Albrecht et al., 2018). The WEF nexus can improve policy coherence in decision-making processes on water, energy and food nexus (Weitz et al., 2017), as well as climate change adaptation (Rasul & Sharma, 2016). Further, The WEF nexus is essential for climate change adaptation, as it enables the understanding and management of complex interactions between water, energy, and food systems under changing climatic conditions (D'Odorico et al., 2018). However, the role of the WFE nexus in addressing the competing demands of adaptation and development has not yet been fully recognized (Khacheba et al., 2018). Most adaptation plans, including the National Adaptation Programmes of Action (NAPAs) focus generally on sectoral, and have been prepared to meet sectoral goals. The WEF Nexus convenience has been controversial (J et al., 2019), and several criticisms and questions are being asked about the nexus approach, such as: Does the nexus have any real influence on water management, or is it merely a 'trendy concept'? How can governance issues be integrated into this concept? Despite these criticisms, all authors agree on the approach's value for decision-making, policy creation, and resource management integration (Kaddoura & El Khatib, 2017; Rosales-Asensio et al., 2020).

2.1 Nexus approach

'Nexus thinking' emphasizes the inherent links among water, energy, and food resource systems and aims to overcome single-sector approaches to resource governance (Albrecht et al., 2018; Biggs et al., 2015; World Economic Forum, 2011). The Nexus approach employs an interdisciplinary strategy to optimize synergies, minimize trade-offs in resource management, improve resource-use efficiency, and include social and environmental implications (Kurian, 2017). The Nexus method fosters sustainability by addressing stress through metrics, highlighting the interconnection of sectors to achieve Water-Energy-Food (WEF) security

efficiently. The WEF nexus functions both as an analytical tool and as a policy discourse (Keskinen et al., 2016). However, the nexus has remained largely in the conceptual domain (Smajgl et al., 2016). As a conceptual framework, the nexus approach is used to better understand WEF interlinkages to promote coherence in policymaking and enhance sustainability.

This method is increasingly acknowledged as vital for managing the conflicting needs of these resources, especially for climate change adaptation and sustainable development. However, analytical methods within the nexus approach continue to evolve, promoting the development of tools that align with nexus thinking and address the complexity of multi-sectoral resource interactions.

2.2 Methods and tools for Nexus assessment

Nexus analyses are often carried out at regional or national levels, based on available data or national-level policy goals or metrics (Miralles-Wilhelm, 2016). To understand the complex relationships, interactions, and feedback among water, energy, and food sectors, the nexus analysis uses quantitative and/or qualitative methods (Endo et al., 2015). The quantitative methods are the most widely used, with 70% of research using largely quantitative approaches (Albrecht et al., 2018). Among quantitative methods, the physical models, benefit-cost analysis (BCA), and management models are used to study the nexus. Physical models, for example, are often used to predict the influence of a variety of factors on a complex system, they use mathematical formalizations to simulate a biological or ecological system. Integrated physical models can simulate the balance between water, energy and food production. Qualitative methods are generally used to describe the WEF nexus in the region of interest, design appropriate analytical models, and guide research to address policy needs (Endo et al., 2015). Qualitative methods can also offer important contributions to the design and implementation of resource-use policies that are socially and politically feasible (Albrecht et al., 2018). This method includes primary research methods such as questionnaire surveys and secondary research methods such as ontology engineering and integrated maps.

(Endo et al., 2015) emphasize the importance of developing nexus methodologies by integrating multiple approaches, as this facilitates a more comprehensive and nuanced understanding of nexus interactions. Interdisciplinary research methods play a crucial role in this process by

unifying diverse variables, visualizing complex problems, evaluating multifaceted issues, and simulating interconnected systems. Such methods also support participatory design, iterative analysis, and policy evaluation, fostering inclusive and adaptive decision-making processes. For example, some studies integrate policy analysis with trade-off analysis or combine policy analysis with water balance modelling (Scott, 2011). Other approaches merge hydrological modelling with spatial demographic analysis and participatory scenario planning (Keskinen et al., 2016), demonstrating the versatility and effectiveness of interdisciplinary frameworks in addressing nexus challenges.

The WEF nexus tools are being developed at an increasing rate, driven by the WEF nexus concept's growing traction in international policy and research, including the iconic World Economic Forum Water Initiative (World Economic Forum, 2011) and the Bonn 2011 Conference on The WEF Security Nexus Solutions for the Green Economy (Hoff, 2011). The year 2020 marked the highest number of newly developed WEF nexus tools, including NEST, iWEF, and WEF Nexus Index. However, some available tools are in code format, which can undermine their applicability by users without programming skills. A good majority (70%) lack key capabilities such as geospatial features and transferability in spatial scale and geographic scope (Taguta et al., 2022). Only 30% of the tools are applicable at local scales.

2.3 GIS Applications in Assessing the Nexus

In recent years, Geographical Information System (GIS) technology has been widely used for assessing and mapping in several disciplines incorporating data from innovative techniques like satellite remote sensing and LiDAR images. The use of such methods, which are becoming openly available, provides a range of site-specific information (Almulla et al., 2020). This extends to the nexus studies and integrated resource planning. However, the use of GIS data and its associated analytical tools is still in its early stages. (Korkovelos et al., 2019). GIS is a computer-based tool for spatial decision-making that aids in accurately assessing distributed WEF resources, hence accomplishing economic and environmental (Taguta et al., 2022). Thus, A GIS-based approach offers a bird’s eye view and mapping for analysis of WEF resources and their spatial relationships, which can help identify hotspots, synergies, and trade-offs with the possibility of exploring the impacts of interventions and transfer of good practices and technology (Fernandes Torres et al., 2019; Lin et al., 2019).

(Azzam et al., 2023) developed Water Energy Food nexus (WEF) framework based on Geographic Information Systems. The framework and model are presented as effective tools for stakeholders to design scenarios and obtain quantitative and spatial information about the WEF nexus. The framework is intended to support decision-making processes by providing insights into the complex interactions between water, energy, and food systems, particularly in the context of agricultural productivity and sustainability. Additionally, (Almulla et al., 2020), used the GIS-based model to estimate irrigation water and energy requirements across the North Western Sahara Aquifer System (NWSAS). By mapping and analysing the spatial distribution of resources, GIS supports decision-making processes to optimise resource use and ensure sustainability. It identified the location and extent of irrigated croplands, calculated the water needed for different crops, and determined the electricity required for pumping groundwater.

GIS provides a powerful tool for visualizing, analysing, and integrating various data layers to assess the complex relationships within the nexus. It gives a deeper geographical detail of the WEF nexus profile in research locations (Eldrandaly, 2007).

2.4 Statistical analysis

Statistical analyses are also used to study the relationship of nexus. Statistical analyses such as Principal Component Analysis (PCA) have been employed to reduce the dimensionality of complex datasets, allowing researchers to identify key factors influencing water availability, agricultural productivity, and climate variability. For instance, studies have utilized PCA to uncover patterns in how climate variables affect water resources and food security (Saed et al., 2024), highlighting the intricate relationships within the nexus. By integrating PCA and regression techniques, researchers can effectively assess trade-offs and synergies among water, food, and climate systems, providing valuable insights for sustainable resource management and policy development (He et al., 2024). Additionally, multiple regression analysis has been widely used to quantify the relationships between these factors, enabling researchers to model the impacts of climate change on water supply and food production. This integrated approach not only deepens our understanding of the nexus but also supports decision-making processes aimed at enhancing resilience to climate change and ensuring food security.

2.5 Water-Food-climate Nexus

Over the past two decades, the WEFN approach has strengthened the synergy between nexus sectors and sustainable water use (Bieber et al., 2017). However, in recent years, the uncertainty about securing access to essential resources has made the Water and Food nexus a crucial issue for the scientific communities (Ahmadzadeh et al., 2015a). Due to the emerging water and food availability challenges, the WF nexus is key to achieving the SDGs including SDGs 2, 3, 6, and 13 directly linked with the WF nexus. The WF Nexus is a complex concept used for studying and managing global resource systems, promoting the development of various models to better understand its scope (Mortada et al., 2018; Zhang et al., 2018). The WF Nexus evaluation models are helpful to predict future scenarios considering the shortage and demand of both resources.

The significance of the WF Nexus is important, although few documents quantify it (Corona-López et al., 2021). The WF nexus is a complex concept that is often used in the comprehensive analysis and management of global resource systems (Lubis et al., 2018). Using WF nexus tools is essential to support assessments, policy implementation and resource management by helping anticipate future resource scarcity and demand.

A few studies have been carried out in different places (Lubis et al., 2018; Romeiko, 2019; Sinnathamby et al., 2017), using various tool to assess water food climate change including Life Cycle Assessment (LCA) (Cellura et al., 2012), Common Agricultural Policy Regional Impact (CAPRI), Global Food and Water System (GFWS) (Blanco et al., 2012), Soil and Water Assessment Tool (SWAT) (Ahmadzadeh et al., 2015b), Water Evaluation And Planning system (WEAP) (Schneider et al., 2019), and Soil Water Atmosphere Plant (SWAP) (Jiang et al., 2016). Some studies also have been carried out before in the Niger River basin but Several focused on the Upper Niger Basin and the Inner Niger Delta (Bazilian et al., 2011; Liersch et al., 2013). In the upper Niger basin (Aich et al., 2013) evaluated the impacts of climate change on streamflow and identified adaptation options with the Soil and Water Integrated Model (Liersch et al., 2013) used the same model to assess crop production and ecosystem vulnerability under climate change and human activities in the Inner Niger Delta.

2.6 Methods used in the climate change impacts on Water-Food

Studies investigating the influence of climate change on Water-Food nexus mainly focused on how climate change may impact water availability for irrigation, soil moisture and crop yield. Gao et al. (2023) reviewed peer-reviewed journal articles on the subject of climate change that were published related to Water-Food, between 2017 and 2022, 45 articles were found. 53% of the Water-Food nexus studies (24 of 45) used statistical methods, 64% (29 of 45) used physics-based modelling methods and 9% (4 of 45) used operation optimisation methods. Furthermore, Most Water-Food studies utilised multiple methods or coupled models from different disciplines. (Aliyari et al., 2021) employed the coupled SWAT-MODFLOW modelling framework as a hydrological simulator to assess water resources and agricultural productivity in the South Platte River Basin, Colorado. The model was forced using outputs from five CMIP5 climate models, downscaled via the Multivariate Adaptive Constructed Analogs (MACA) method, under two Representative Concentration Pathways (RCP4.5 and RCP8.5). (Pulighe et al., 2021) use a restructured and advanced version of the Soil and Water Assessment Tool (SWAT+) to assess the impacts of climate change on the water balance of a Mediterranean watershed.

2.7 Challenges and gaps

The Water-Food-Climate (WFC) Nexus presents significant challenges and gaps that hinder its effective analysis and implementation. At its core, the nexus demands multidisciplinary dialogue, integrating complex system methodologies capable of quantifying resource interrelationships with policy analysis tools that promote coherence and integration. However, practical application requires transdisciplinary collaboration among stakeholders in water, food, and energy management, which often encounters barriers due to differing perspectives and the underrepresentation of social science-driven assessments. The lack of standardized frameworks further exacerbates these challenges, as the absence of universally accepted methodologies results in inconsistencies in research approaches and findings. Additionally, limited access to high-resolution, reliable, and comprehensive datasets for water, food, and climate variables constrains the ability to develop robust models and analyses.

2.8 Conclusion

The Water-Food-Climate (WFC) Nexus represents a critical framework for understanding and managing the interconnected challenges of resource sustainability in the face of climate

change. Over the past two decades, the nexus approach has gained prominence as a tool for promoting synergies and addressing trade-offs between water, food, and climate systems. By fostering interdisciplinary and transdisciplinary collaboration, the nexus aims to integrate scientific, social, and policy dimensions into a cohesive strategy for sustainable resource management. However, despite its potential, significant challenges and gaps remain in its application and analysis.

Advances in quantitative and qualitative methodologies, including GIS and modelling tools, offer promising avenues for addressing these gaps. However, these tools must be accessible and adaptable to diverse contexts to ensure their utility. Moving forward, the nexus approach requires stronger institutional frameworks, enhanced data systems, and innovative governance models to bridge disciplinary divides and foster sustainable resource management.

In conclusion, the Water-Food-Climate (WFC) Nexus serves as a crucial framework for tackling global sustainability challenges. However, unlocking its full potential requires fostering collaborative, interdisciplinary approaches and establishing robust, inclusive frameworks that emphasize equity, resilience, and the interconnected nature of resource systems.

CHAPTER III : METHODOLOGY

3.1 Study area

The Dargol is one of the main tributaries of the River Niger in the Sahel region and spans an area of approximately 7,300 km2 (Abdou, 2016). This transboundary river lies between Burkina Faso (24%) and Niger (76%). It originates near the Niger-Burkina Faso border in the Dori highlands of Burkina Faso, flowing through the towns of Tera, Dargol, and Kakassi before merging with the Niger River (Figure 2). The study area is geographically situated between 0°20' and 1°40' East longitude and 13°30' and 14°40' North latitude, within the region commonly referred to as Liptako-Gourma.

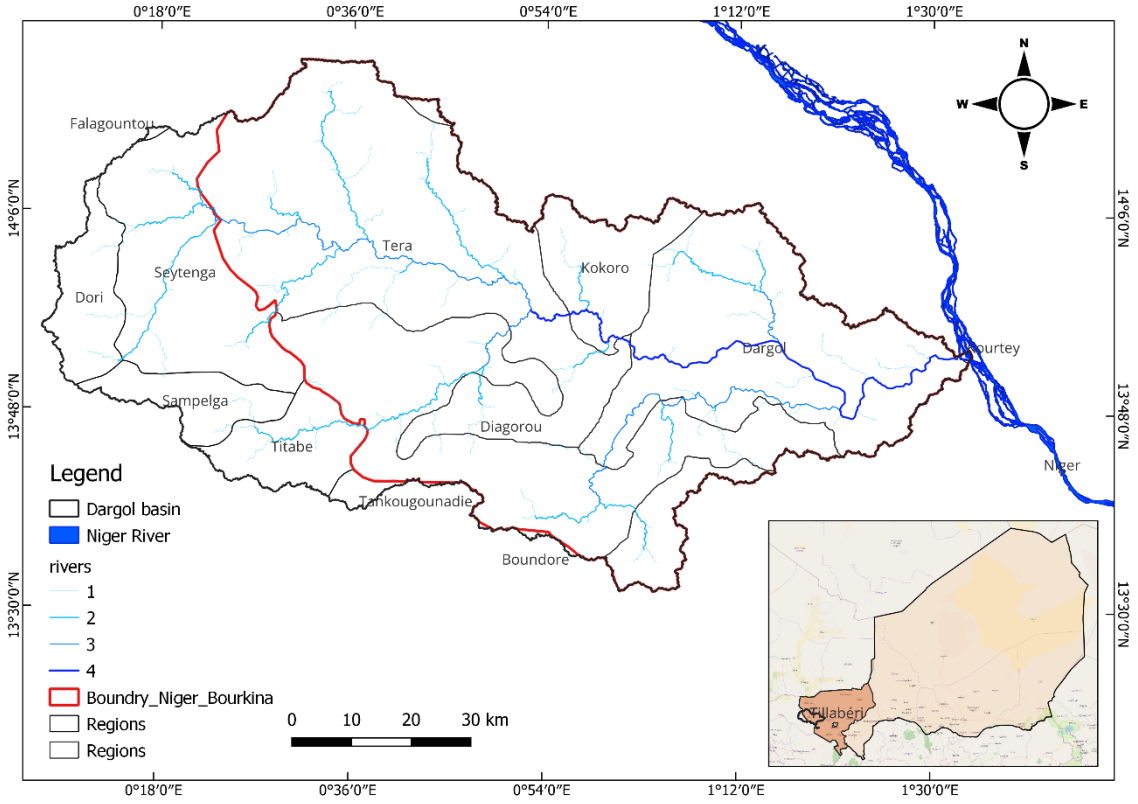

Figure 2: Location of the Dargol basin.

3.1.2 Humans Asset

The population of the Dargol basin was estimated at 466,739 in 2014 (INS, 2014). The basin spans eight departments, including Tara, Dargol, Kokoro, and Diagorou in Niger, as well as Dori, Seytanga, Sampelga, and Titabe in Burkina Faso (Figure 3). Among these, the Diori and Dargol departments are the most densely populated, each housing between 150,000 and

200,000 inhabitants. The annual population growth rate in the basin is 3.9%, surpassing the 3.2% growth rate recorded in the region (INS, 2012).

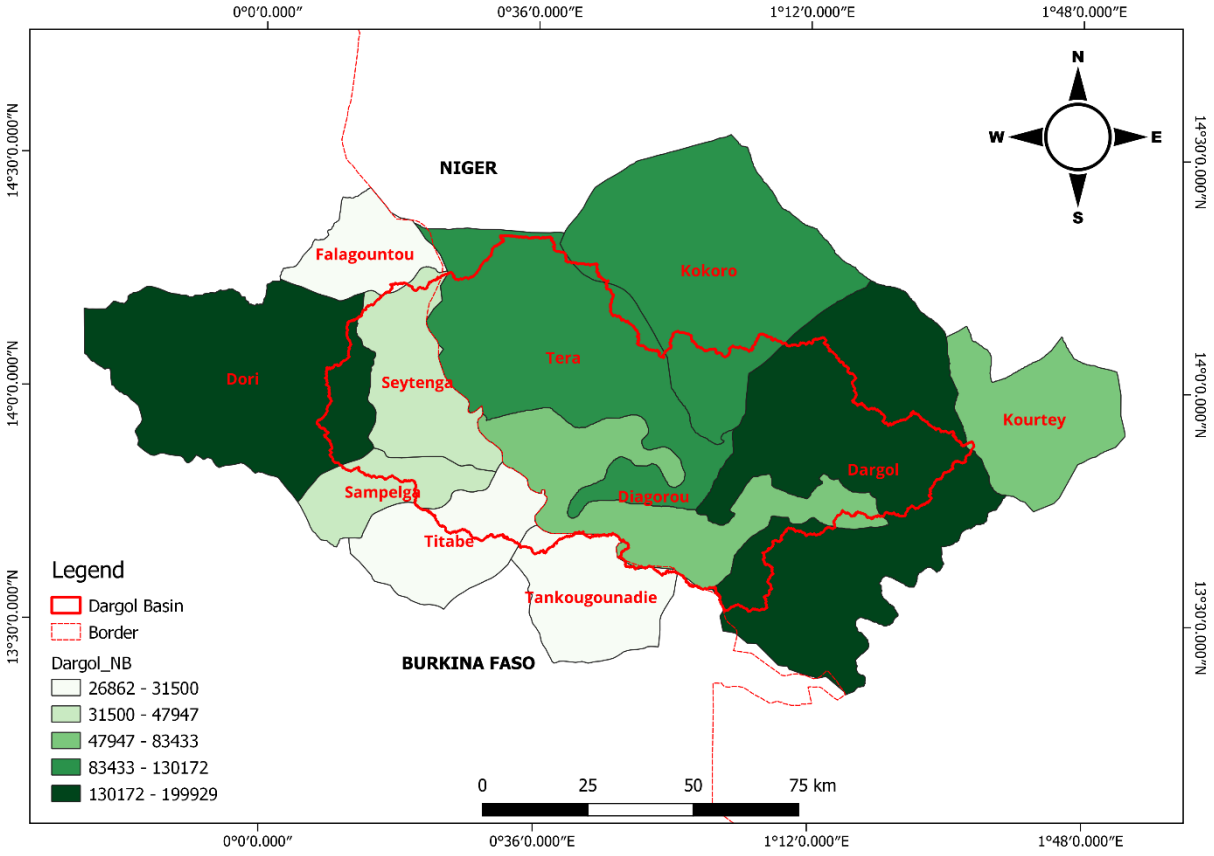

Figure 3: Map of the density of the population.

3.1.3 Economic Asset

Despite significant challenges faced by the agricultural sector in recent decades, including rainfall variability, soil degradation, and persistently low yields, agriculture remains the primary economic activity in the region, employing approximately 94% of the population. The region's arable land is estimated at 635,000 hectares (DRA/T, 2013). Rain-fed agriculture dominates, with key crops including millet, sorghum, cowpea, groundnut, and sesame, while irrigated farming supports the cultivation of lettuce, onion, cassava, cabbage, and tomato through market gardening practices. Livestock farming represents the second most important economic activity, primarily practised by the Fulani and Tuareg communities. The livestock population is estimated at 2,020,148 head (DRE/T, 2014), consisting of cattle, sheep, goats, donkeys, camels, and horses.

Beyond agriculture and livestock, the region possesses significant yet underexploited economic diversification potential. Forestry-related activities, such as timber marketing, honey production, and the collection of non-timber forest products, present promising opportunities. Although currently limited, handicrafts hold potential for expansion, particularly in toolmaking, jewellery production, pottery, and blanket weaving. Additionally, artisanal gold mining is an important economic activity within the basin, with sites such as Komabangou operating under administrative supervision. Collectively, these sectors underscore the region's economic diversity and its potential for sustainable development.

3.1.4 Relief

The relief of the Dargol catchment is characterized by the juxtaposition of various geodynamic units, the main ones being gently sloping dunes, lateritic hills and plateaux, shallows and valleys, glacis, and basement outcrops. Altitudes in the catchment range from 193 m to 363 m (Figure 4), with a corresponding median of 285 m. The plateaux, composed of clayey sandstones that lie unconformably on the crystalline basement, overlook long glacis intersected either by rocky outcrops or by dune ridges, primarily oriented east-west. The catchment's morphological features also include granite domes to the north, greenstone hills to the south, and quartz vein mounds interspersed throughout. Sandy dune ridges extend north of the 14° parallel, often over tabular surfaces such as lateritic plateaux and glacis. These landforms are incised by valleys (koris), which are typically dry but channel water into depressions (ponds) during the rainy season, contributing to the area's hydrological dynamics.

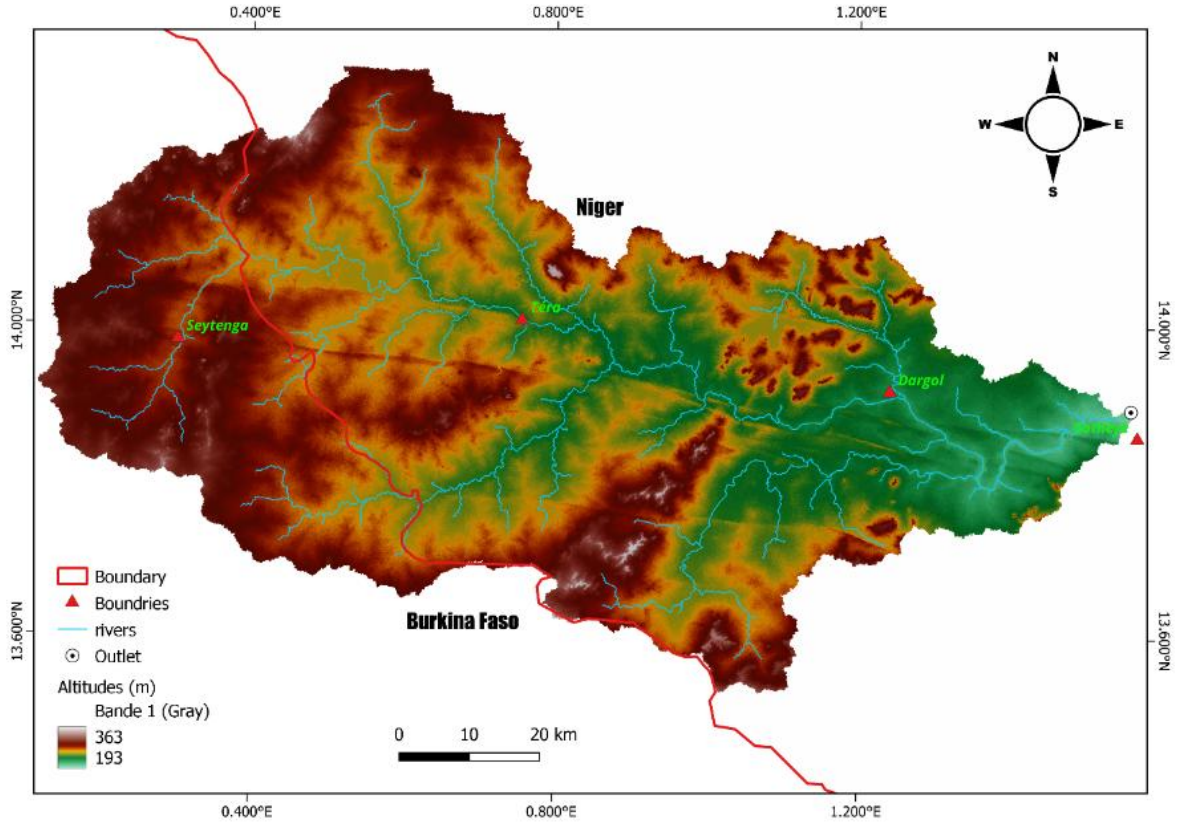

Figure 4: Relief map of the Dargol basin.

3.1.5 Geology and Hydrogeology

The Niger Liptako, which covers most of the Dargol catchment area, corresponds to the north-eastern edge of the Dorsale de Man (MHA, 2019). This region is characterised by granitic massifs and greenstone belts, forming a succession of furrows and batholiths. The Liptako basement consists of a varied complex of Precambrian metamorphic and igneous rocks, representing the eastern end of the Dorsale de Man. Its lithology is extremely diverse, including migmatites, amphibolites, granitoids, schists, greywackes, quartzites, gneisses, dolerites and diorites. This geological diversity gives the region a unique structural and morphological richness.

Most of the Liptako is underlain by a Precambrian basement composed of crystalline and metamorphic rocks. The aquifers in this region are mainly discontinuous and their productivity depends on the thickness and nature of the altered zone (regolith) and the presence of fractures. The Liptako has two main types of groundwater: surface aquifers in River Niger beds and deep

aquifers in fractures in crystalline and crystallophyllous rocks, both of which are rarely exploited (Babaye, 2012).

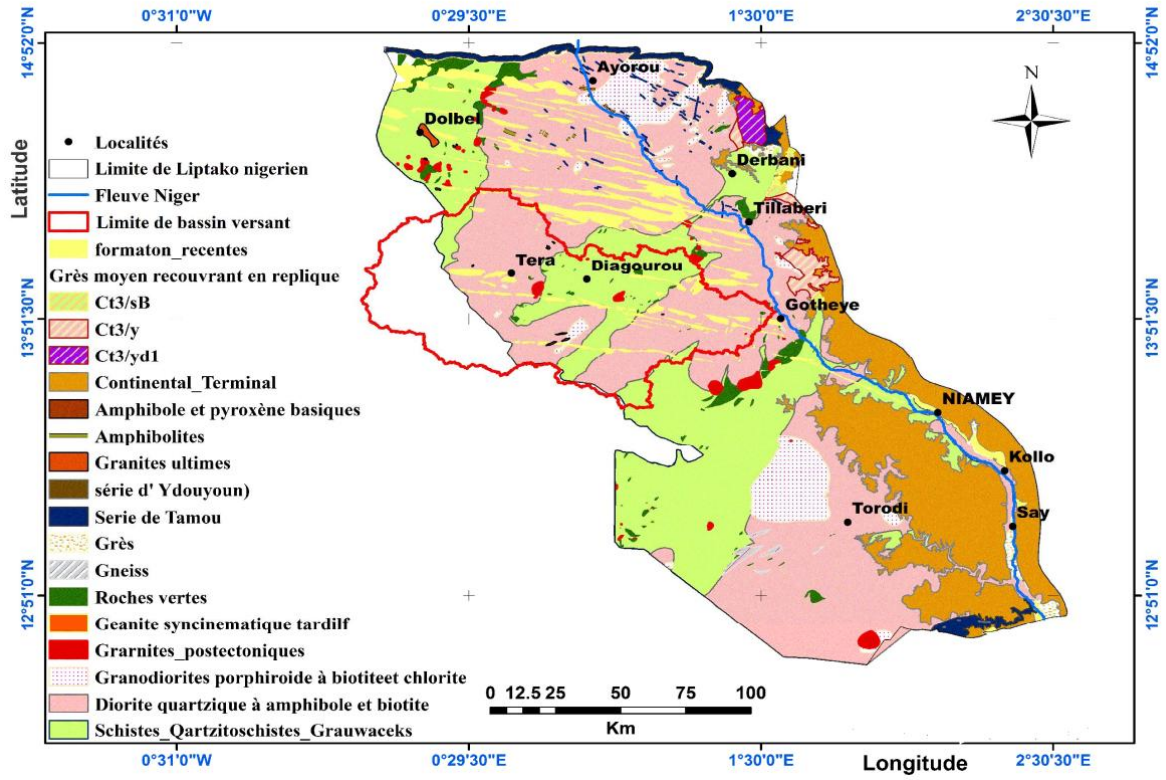

Figure 5: Geological situation of the Dargol catchment area (MHA, 2019)

3.1.6 Climate

The climate in the Dargol basin is Sahelian, characterized by a distinct bimodal seasonal pattern. A dry season from October to May and a rainy season from June to October. The average annual rainfall calculated at the Téra rainfall station over the period 1999 to 2008 is 409mm (MHA, 2019). July and August are the wettest months of the year, accounting for more than 60% of annual rainfall.

The temperatures range from 15°C to 43°C, with an annual average of 29°C. The lowest temperatures are recorded in July-August and December-January in winter ("cold" season), while the highest values are recorded in April-May (hot season). During the dry season, temperatures peak at up to 43°C in the shade.

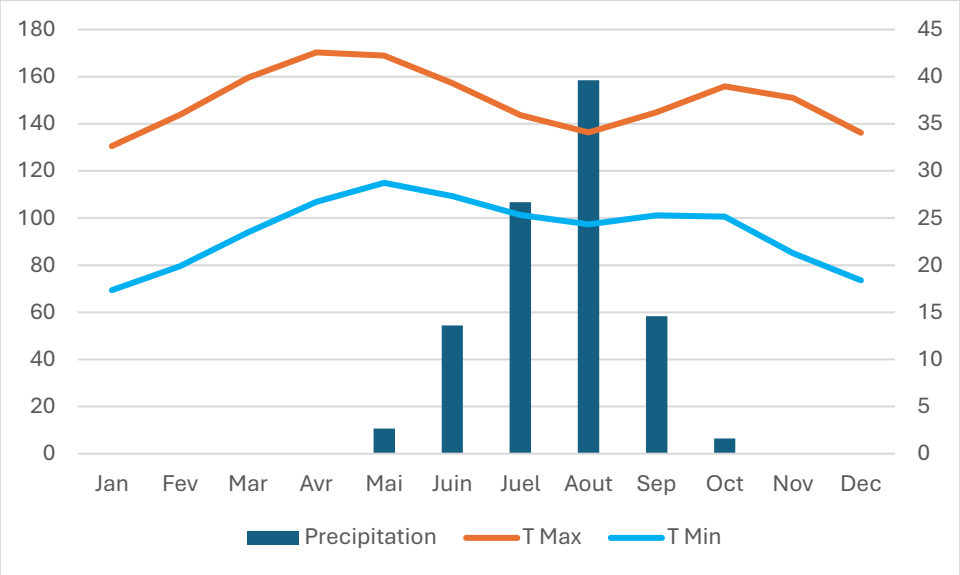

Figure 6: Ombrothermic Diagram of Tillaberi Station

3.1.7 Insecurity

Since 2015, the Tera area has suffered a series of attacks and bombings carried out by Groups d' Opposition Armé (GOA) affiliated to Jihadists, in particular JNIM, EIGS and Al-Qaeda, who operate in the tri-border area (Mali-Niger and Burkina). Between January and December 2022, the Niger Protection Cluster recorded 80 protection incidents in the Tillaberi region, classified as targeted murders, assassinations, attacks and physical assaults (CIVIC, 2023). Between January and June 2024, Tillabéri saw the arrival of 2,396 Malian refugees and 7,700 Burkinabe asylum seekers, bringing the number of new arrivals to 10,096 people (UNHCR, 2024). The attacks mainly targeted the authorities and defence forces, although they also illegally taxed civilians, extorted their property and took their battles and crops, but since 2021 the GOA have started to target civilians - the number of GOA attacks on civilians increased by 52% between 2021 and 2022 (CIVIC, 2023).

3.2 Data Collection

3.2.1 Spatial Data

We used Satellite images that have already undergone Level 2 processing from the USGS Earth Explorer website for Landsat 5 TM+ 1990 and Landsat 8 OLI for 2022 (https://earthexplorer.usgs.gov/).

The SRTM (Shuttle Radar Topography Mission) database (30x30 resolution) from the USGS Earthexplorer website to create a digital elevation model (DEM) with a 1-arc second, slop, and hydrographic network.

We downloaded FAO Soil Classification data, for the Soil map.

3.2.2 Meteorological Data

From DMN (Direction Météorologique Nationale), we found daily data from 1992 to 2022 for the meteorological station of Tera Gothey and Tillaberie, for the parameters; Precipitation, Max and Min temperature, and Max and Min Relative Humidity for Tillaberi's Station and only Precipitation for Tera and Gothey.

Table 1: Weather Stations localisation

Station	Long	Lat
Gothey	1.58	13.82
Tera	0.82	14.03
Tillaberi	1.45	14.2

3.2.3 Hydrometric data

The Niger Basin Authority has provided us with a series of hydrometric data for flow and head at the Kakassi station.

3.2.4 Agricultural data

We collected agricultural data from the Tillabery Regional Directorate of Agriculture and the Tillabéry Regional Directorate of Rural Engineering during the field reconnaissance mission.

3.2.5 Field mission

A site survey was organised from 23 to 25 December 2024. This mission enabled us not only to assess the geomorphology of the basin, land use and erosion dynamics, but also to collect relevant data by touring institutions such as the Regional Directorate of Agriculture, the Regional Directorate of Rural Engineering, the Directorate of Hydraulics and Sanitation, etc., and also to talk to some of the main players about their perceptions of the environmental and climatic dynamics in the basins.

Figure 7: Images taken during the field mission

3.2.6 Software

In the context of this study, data processing was made possible by several software programs.

- We used Hec-HMS for watershed delineation and hydrographic features calculation.
- QGIS 3.28 was used for, Satellite image processing, Land Use and Land Cover (LULC) classification, editing and cartographic presentation of various processes during this study.
- Rstudio was used for climate data analysis.
- Microsoft Office (Excel, Word) was used for data processing, creating diagrams, and writing the report.

3.3 Data Analysis and Processing

3.3.1 Lande Use

In Niger, the land use classification adopted by the Ministry in Charge of the Environment (MHE/LC, 2006) distinguishes six main themes: vegetation, the crop-fallow mosaic, hydrography, bare soil, dwellings and the road network. Land use in the Dargol basin is characterised by a diversity of natural and man-made formations.

- waterbody, such as ponds and reservoirs
- Scrubland or shrubby formations that develop on glacis and dunes.
- The steppe, whether grassy or shrubby, consists of discontinuous vegetation often associated with trees and shrubs.

- Riparian belts form forested strips along the hydrographic network, and
- bare surfaces such as eroded glacis, gravel beaches.

To do Land Use Land Cover classification we downloaded Landsat 5 TM for 1990 and Landsat 8 OLI for 2022. Then I used the SCP automatic classification Plugin in QGIS to make a LU/LC map.

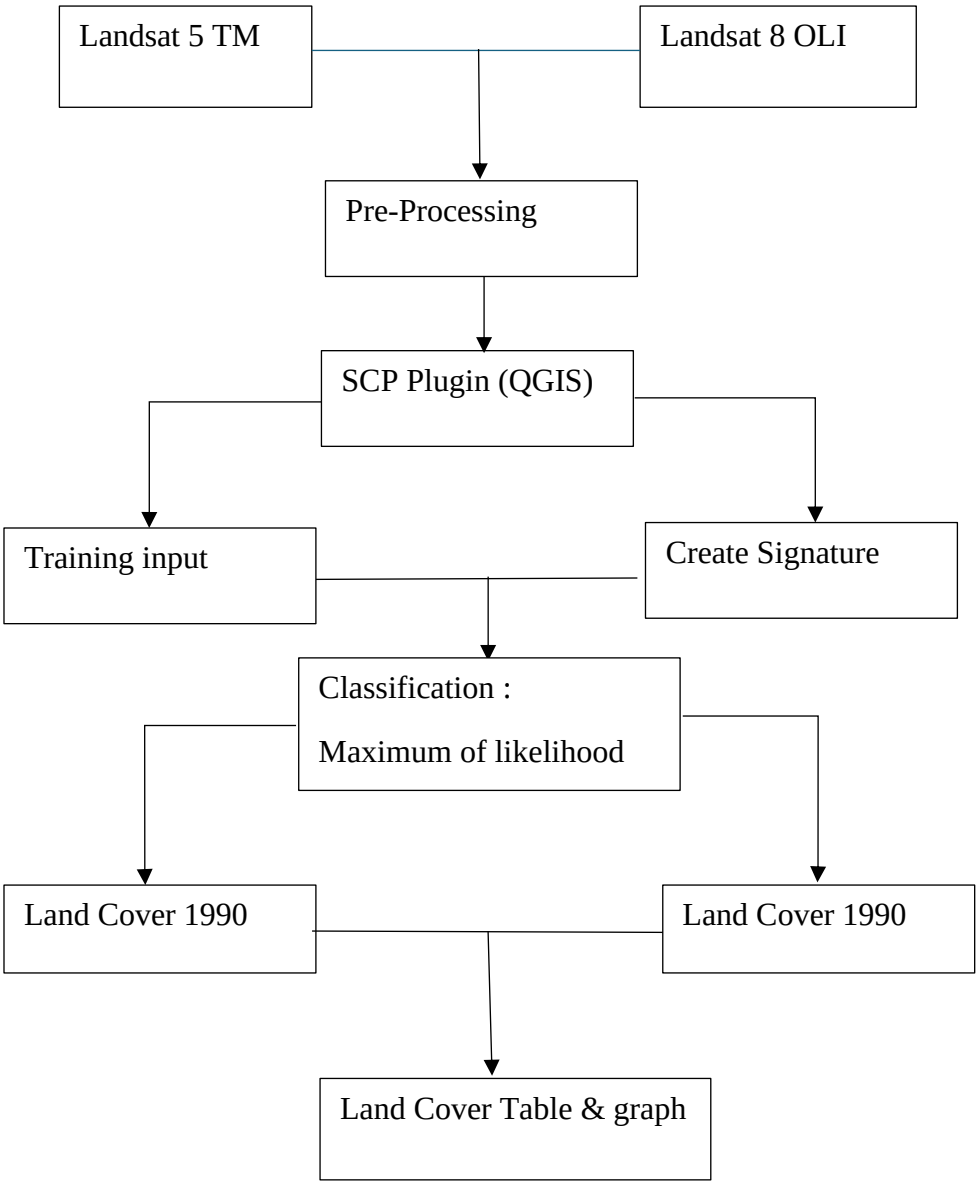

Figure 8:Flowshat of the Land Use/ Land Cover classification methodology.

3.3.2 Weather Data Processing

We used RStudio and excel to analyse the climate data trend and anomaly and conduct the multi-regression linear analysis.

3.3.3 Agriculture

The Niger's Agricultural classified crops according to their type and use. The main rainfed crops are dominated by cereals (millet, sorghum, rice, maize, fonio) and cash crops (cowpeas, groundnuts, voandzou, sesame, sorrel, cotton, market gardening). Staple crops are grown for self-consumption, in particular pearl millet, which clearly dominates the others (46% of the total area), sorghum (18%) and cowpea (32%) (GIZ 2022). These three crops alone occupy almost 95% of cultivated land and are often grown in combination. In irrigated areas, rice and wheat are the main crops grown in hydro-agricultural schemes (AHA), along with cash crops such as onions, tomatoes, cabbage, chillies, peppers and potatoes.

In the case of this study, we focused our analysis on under-rainfall subsistence crops Millet and Sorghum and under-rainfall cash crops Cowpea and Groundnut. The agricultural analysis involves calculating the water needs of crops and studying the dynamic of production and yield over a given period.

Agricultural yield = Total Quantity of Agricultural Production / Cultivated Area

3.3.4 Water-Food-Climate Analysis

We used Principal Component Analysis (PCA) as a potent method for analysing and visualizing multidimensional data within the context of the Water-Food-Climate Nexus. By applying PCA, we can identify patterns and relationships among the variables, which can help in understanding how different factors interact within the Water-Food-Climate nexus (He et al., 2024). It offers a complementary approach to existing methodologies and proves invaluable for delving into the intricate interactions among these three pivotal elements. We confirmed the results by applying Multiple Linear Regression (MLR). MLR was used at the same time to assess the influence of climate variability and change on water resources and crop yield. Linear regression analysis is a parametric tool and one of the most widely used methods to detect a pattern in data series (Aswad et al., 2020).

Table 2: Principal Component Analysis (PCA) Steps

Steps	Formula / Concept	Explanation
Data Standardisation	$Z = \frac{X - \mu}{\sigma}$	Ensure all data are numeric and without missing values. PCA does not work with categorical variables.
Compute Covariance or Correlation Matrix	Cov(X,Y)=N/1∑(Xi−X¯)(Yi−Y¯)	The covariance matrix measures relationships between variables. If variables have different units, use a correlation matrix instead
Compute Eigenvalues and Eigenvectors	$det(A - \lambda I) = 0$	Eigenvalues (λ\lambdaλ) indicate the variance explained by each principal component (PC). Eigenvectors define the new axes.
Select Principal Components (PCs)	$Explained\ Variance = \frac{\gamma_i}{\sum \gamma}$	Keep the first components that explain 80-90% of the total variance. The Scree plot helps determine the optimal number of PCs.
Project Data onto New Components	$Z = X \cdot W$	Data are transformed into the new space of principal components (PCs).

3.4 Hydrological characteristics of the catchment area

3.4.1 Surface and Perimeter

The surface area and perimeter of the catchment were determined using QGis software. The surface area of the Dargol catchment is A= 7,319.3 km², with a corresponding perimeter of P= 828.94 km.

3.4.2 Shape coefficients

A catchment's shape influences the hydrograph's shape at its outlet. Catchments with a compact shape drain water more quickly than those with an elongated shape. There are various morphological indices that can be used to characterise the environment. The most widely used is the Gravelius compactness index (Kc or KG).

$$K_C = 0.28\frac{P}{\sqrt{A}}$$

For the Dargol, Kc = 2.7, indicating an elongated catchment.

3.4.3 Hypsometric Curve

The Dargol hypsometric curve (Figure 9) shows that most of the basin is comprised of lowlands transitioning into hills and highlands in smaller sections. The curve starts steeply, indicating that a significant portion of the basin's area is at lower elevations (220–260 m). The basin is predominantly composed of low to mid-elevation areas, as evidenced by the gentler slope in the middle range of the curve. It then becomes more gradual in the mid-range (260–320 m), suggesting a relatively even distribution of land in these elevations. The curve steepens sharply toward the higher elevations (above 380 m), indicating that a small percentage of the basin's area lies in these elevated regions.

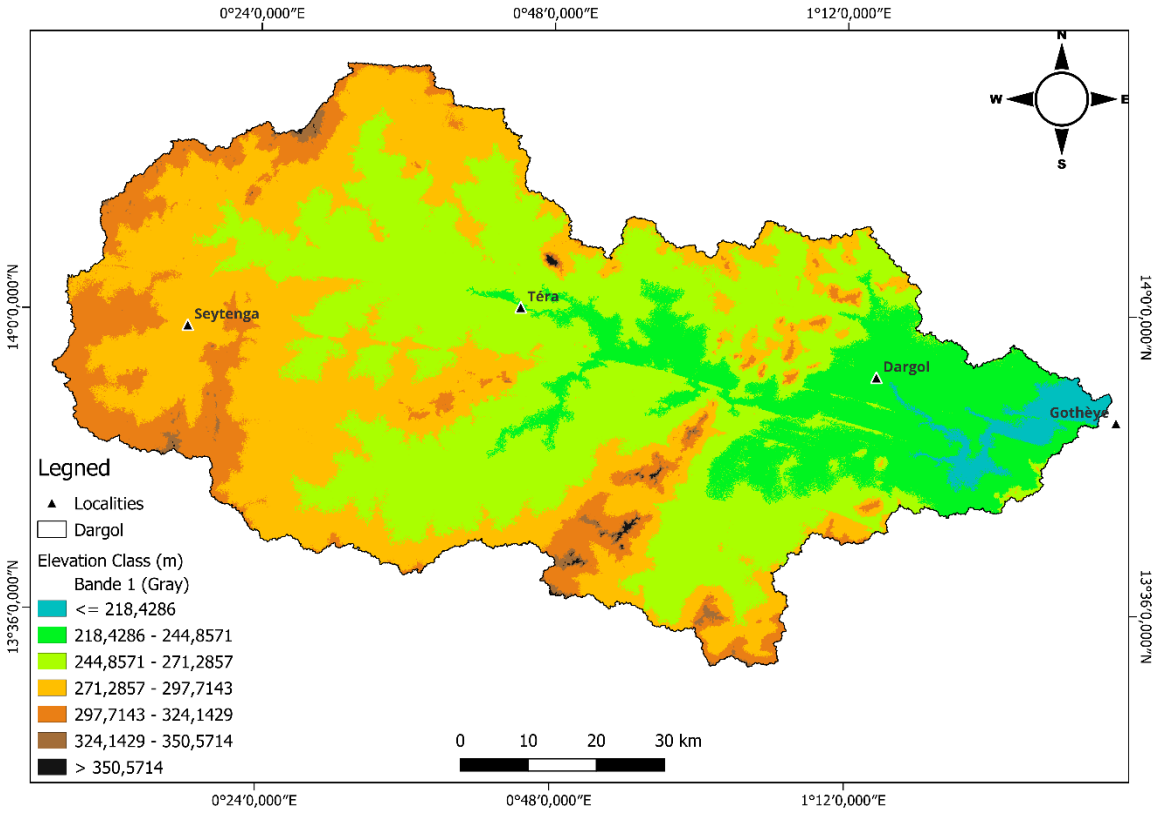

Figure 9: Hypsometric map

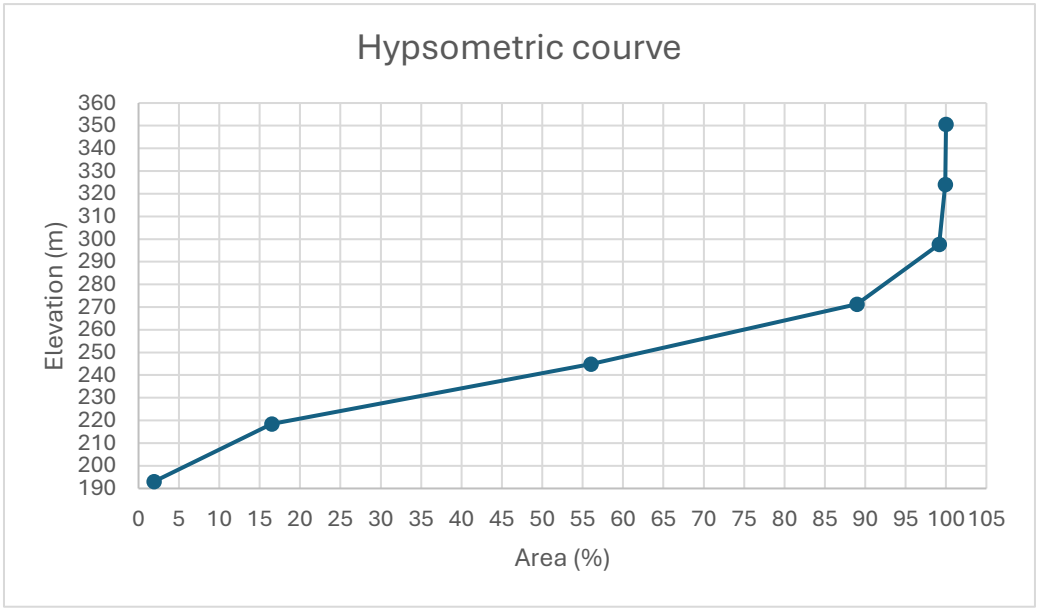

Figure 10: Hypsometric curve

3.4.4 Average slop

The average slope of the catchment is determined by the next relation.

$$I_m = \frac{l * D_t}{A}$$

The average slope of the Dargol basin is $I_m = 0.813 = 81.3\%$

3.4.5 Catchment slope indices

Hi	Hi-1	Hi-Hi-1	A	VA*(Hi-Hi-1)
363	350.57	12.43	7.70	9.78
350.57	324.14	26.43	53.30	37.53
324.14	297.71	26.43	746.29	140.44
297.71	271.29	26.43	2410.84	252.42
271.29	244.86	26.43	2892.79	276.50
244.86	218.43	26.43	1069.96	168.16
218.43	193	25.43	138.48	59.34
	944.17			
L	282.9			
Ip	3.3			

3.4.6 Specific gradient

$$D_S = I_g * \sqrt{A} = \frac{D}{L} * \sqrt{A} = D * \sqrt{\frac{l}{L}}$$

H 5%	H 95 %	D (m)	L (m)	L (m)	Ds
198	277	79	282.9	61.92	36.9595

3.4.7 River network

The hydrographic network includes a temporary watercourse (the Dargol), the largest of whose tributaries is the Tilim. In addition to this river, there is a string of semi-permanent pools and artificial water reservoirs, of which only the Téra (Niger) and Seytenga (Burkina) dam are permanent.

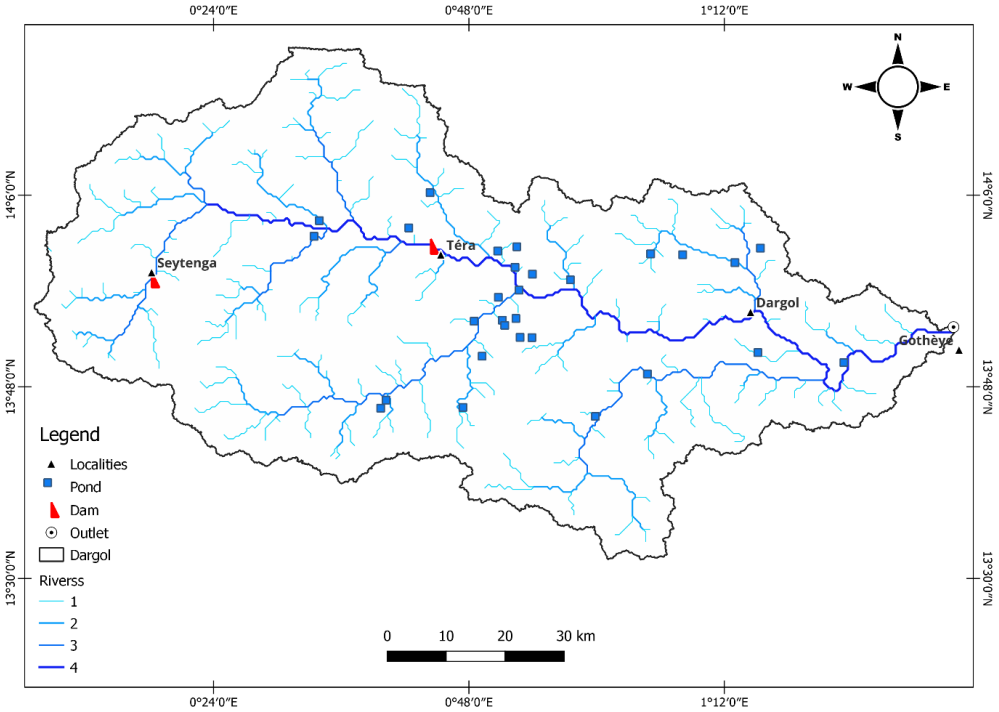

Figure 11: River Network map.

3.5 Conclusion

The Dargol basin is a transboundary watershed shared between Niger and Burkina Faso, playing a crucial role int the region's hydrology, agriculture and socio-economic activities. The region has a Sahelian climate receiving an average annual rainfall of 409mm and the temperature range from 15°C to 43°C. Agriculture and farming dominate the local economy employing over 90% of the population. The methodology of this study involves satellite data collection, land use/land cover mapping, agricultural and climate analysis and MLR model to identify the mechanisms through which one sector can impact the others.

CHAPTER IV: RESULTS AND DISCUSSION

4.1 Results

4.1.1 Water Analysis

4.1.1.1 Dynamic of LULC

Maps based on LANDSAT-5 and LANDSAT-8 satellite images (taken from September 1990 and 2022) show significant changes in land use in the basin (Figure 12). These changes mainly concern vegetation (riparian corde, steppes and bush), the crop-fallow mosaic, and bare areas, highlighting the evolution of landscapes under the effects of human activities and climatic conditions.

There has been a sharp reduction in riparian cord. Its surface area has fallen from 37.67% in 1990 to 20.84% in 2022. Bushland has declined by around 5% over the same period. This significant decline in vegetation can be attributed to the decline in rainfall, the expansion of cultivated areas and the increase in wood harvesting for domestic use. On the other hand, the crop-fallow mosaic shows a sharp increase in surface area, from 15% of the surface area of the basin in 1990 to 34.16% in 2022. There has also been an increase in bare land, to the detriment of vegetation due to rock outcropping. This has risen from 36.3% to 38.88%, an increase of 2.58%. Finally, the bare surface and water bodies also showed a small rise in surface area.

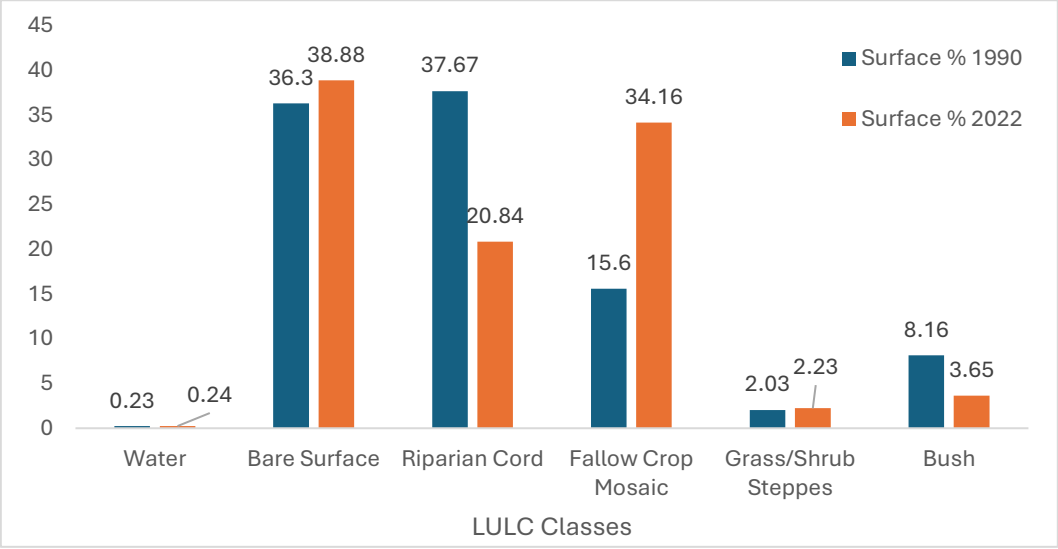

Figure 12: Land use dynamics between 1990 and 2022 in the Dargol catchment.

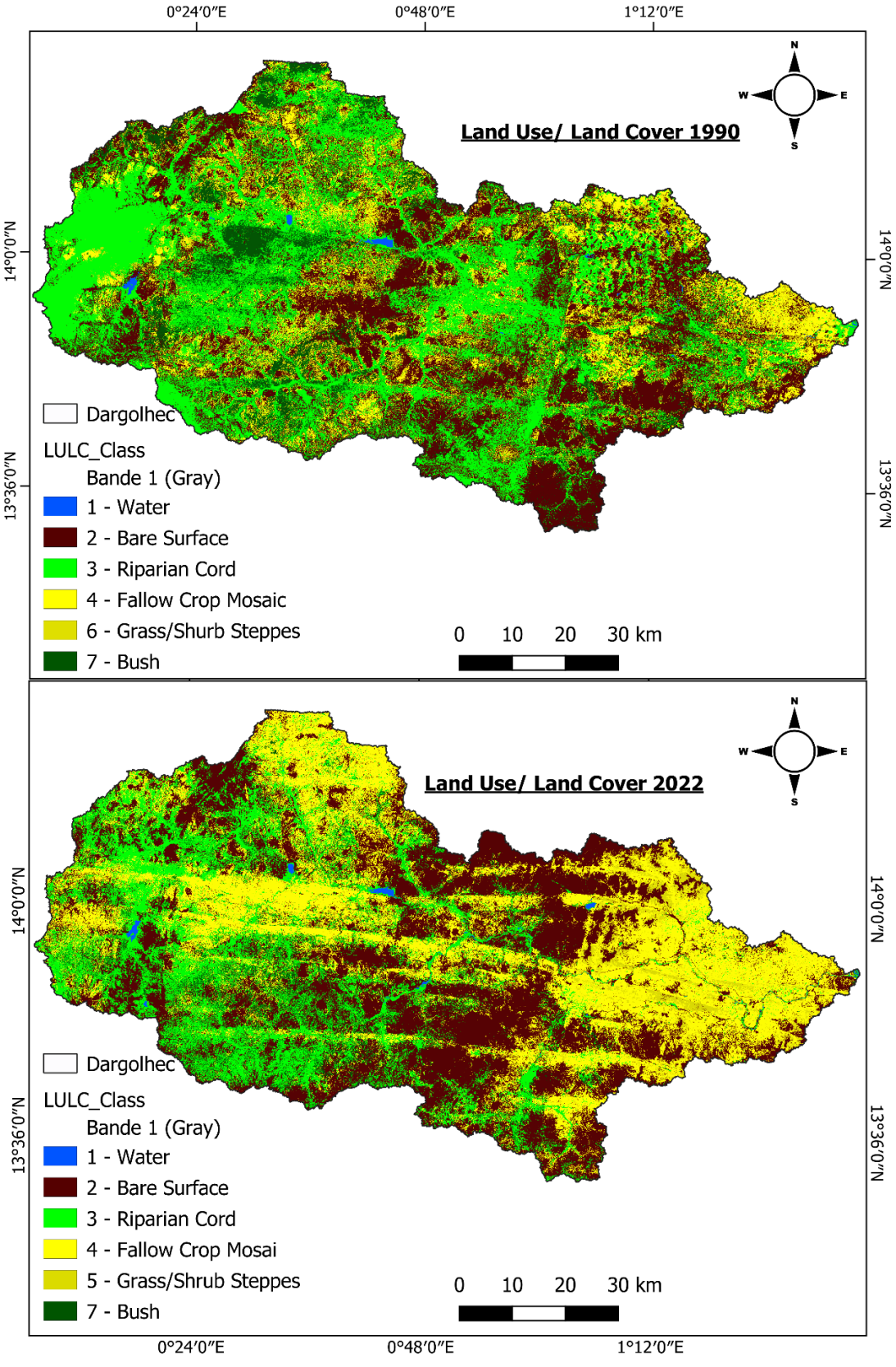

Figure 13: LULC Map 1990-2022

4.1.1.2 Water level

The hydrogram of water head (in blue) and river flow (in red) for the Kakassi gauging station provided by the Niger Basin Authority (NBA) shows the daily variation in flow and water head for the period 1957 to 2020. The hydrogram of water level (blue) and river flow (red) for the Kakassi gauging station, provided by the Niger Basin Authority (NBA), illustrates the daily variation in flow and water level from 1957 to 2020. The figure reveals a clear increase in water levels during the period between 1980 and 1990, with the lowest levels reaching around 100 cm at the beginning of that decade, while the river flow remains low. Both flow and water level peaked in 1990, with the river reaching a discharge of over 300 m³/s and a height exceeding 450 cm. This peak reflects a period of intense rainfall and elevated flood risk. Following this peak, the data indicate a general increase in both flow and water level trends, suggesting a possible resurgence in rainfall or other contributing hydrological changes in the region. Finaly, From the 2010s we can notice that the river base flow is greater than 0 m3/s, the river is permanently flowing over the period.

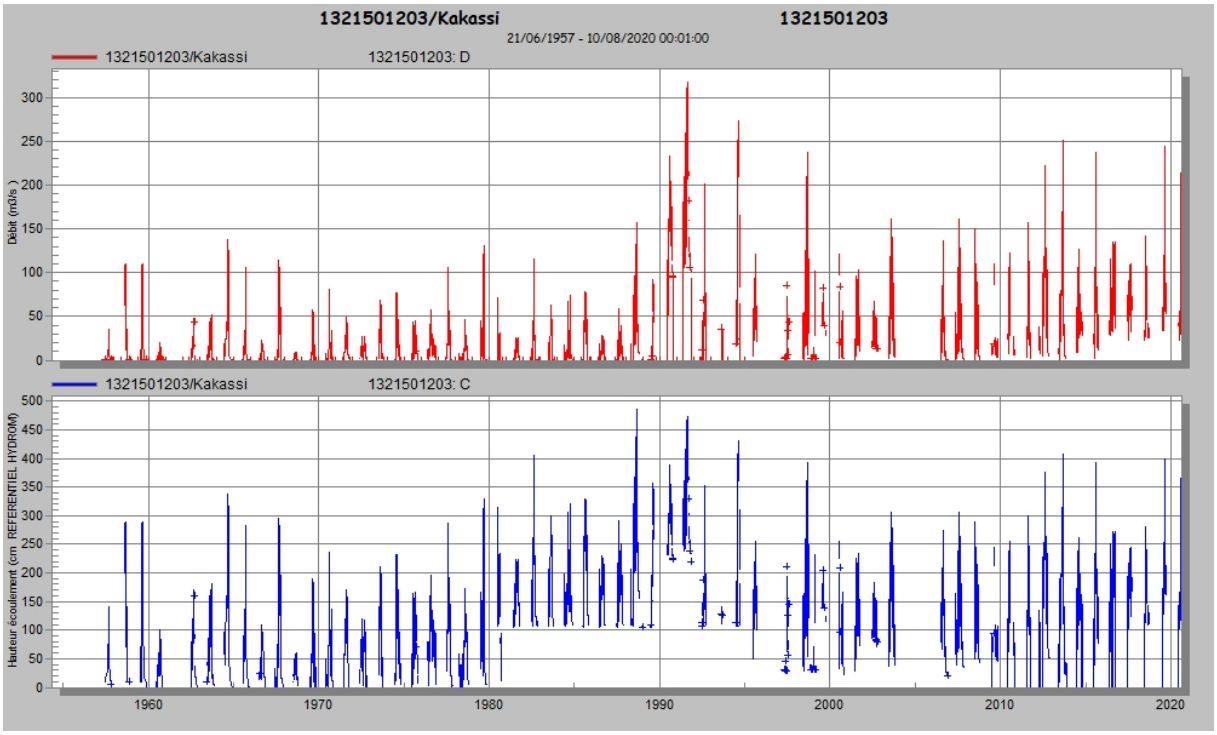

Figure 14: Dragole river flow's Hydrogram 1997-2020

4.1.2 Food Production Analysis

In the Dargol Basin, food production is primarily rain-fed, supplemented by limited irrigation along watercourses. The key crops can be classified into two main categories: subsistence crops include cereals like millet and sorghum, which dominate due to their resilience to semi-arid conditions, and cash crops such as cowpeas and groundnuts.

The (Figure 15) represents the average agricultural production in the region (Tera and Gothey) from 2012 to 2021. Millet dominates production, accounting for 52%, reflecting its importance as a staple food crop. Cowpea follows with 26%, underscoring its dual role in food security and soil fertility improvement, sorghum contributes 20%. Groundnut, at just 2%, represents a smaller share, cultivated for economic purposes or as a complementary crop.

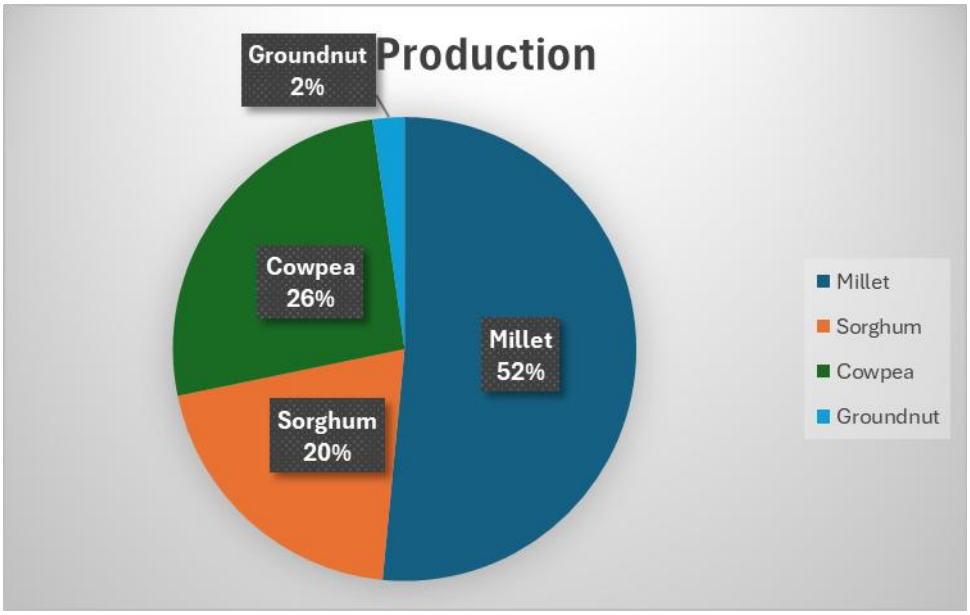

Figure 15: Distribution of the average production2012-2021.

This distribution illustrates the predominance of cereals in the agricultural system, shaped by climatic and dietary needs, while also highlighting the limited diversification in crop production.

Evaluation of the yield

The trends of production and yield for cash crops (cowpeas and groundnuts) and subsistence crops (millet and sorghum) in the Dargol Basin from 2012 to 2021 show a dynamic crop yield.

For subsistence crops, millet production is consistently higher than sorghum, both crops reached peak production in 2016 and 2017, followed by a gradual decline. Yields of millet and sorghum also exhibit a similar pattern. The figure shows a decline in yield from 2012 to 2015 before peaking at 1098 in 2016 and then decreasing again to 2021 with a peak in 2020.

For cash crops, cowpea production has shown a generally increasing trend, peaking in 2018 before slightly declining, whereas groundnut production remains significantly lower throughout the period. The yield of groundnuts has been more variable, reaching its highest levels between 2015 and 2020 before dropping sharply in 2021. In contrast, cowpea yield followed a fluctuating trend, with a peak in 2018 before declining. This pattern suggests that cowpeas are more dominant as a cash crop in the region, with more stable production levels, while groundnuts, though cultivated, have lower production volumes and yield fluctuations, possibly due to climatic or market constraints.

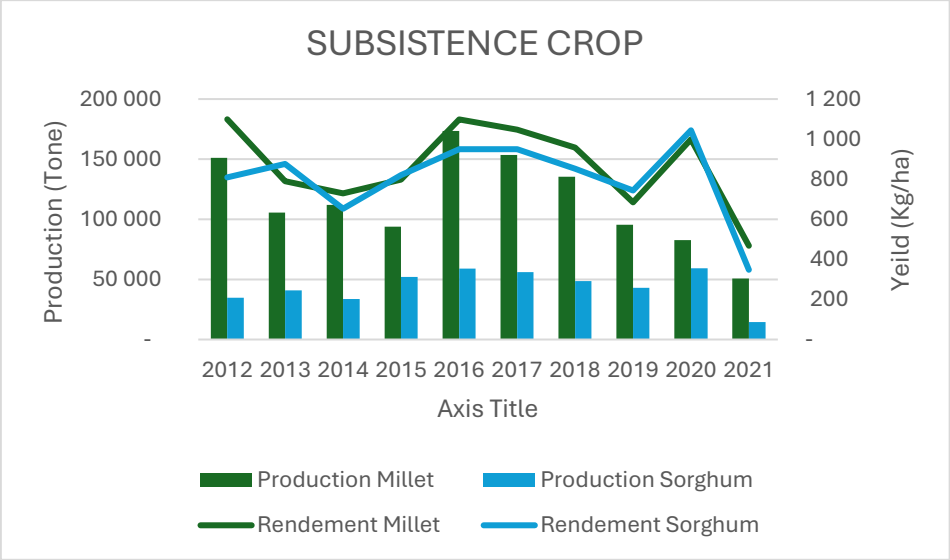

Figure 16: Evolution of the production and yield of subsistence crops from 2012-2021.

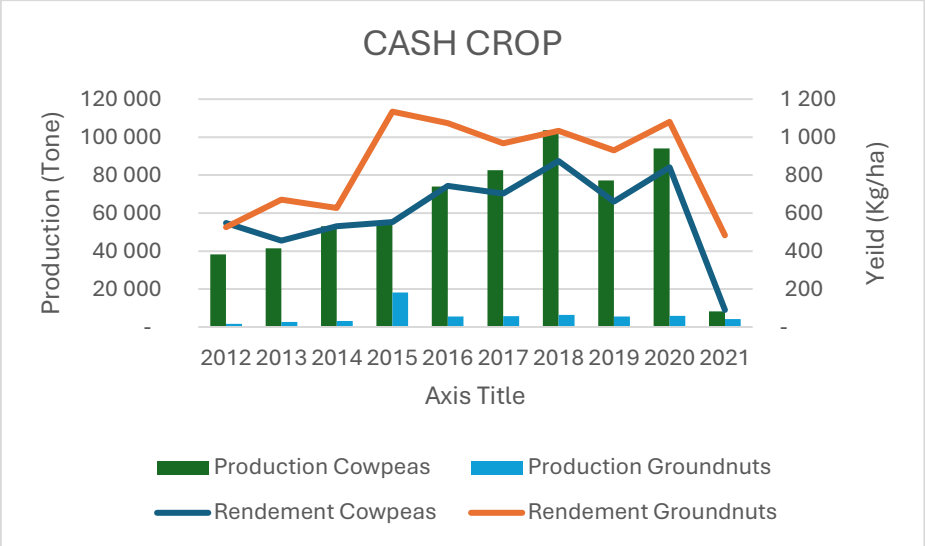

Figure 17: Evolution of the production and yield of cash crops from 2012-2021.

4.1.3 Climate Analysis

4.1.3.1 Seasonal Analysis

The seasonal analysis of rainfall was conducted for two distinct stations Upstream (Tera) and Downstream (Gothey) from 1992 to 2022 (Figure 18). The results reveal a considerable seasonal pattern. The rainy season, which spans from May to September but can go until October for certain years, with August being the wettest month 163 mm per month for Gothey and 132 mm per month for Tera. The dry season extends from September/October to April. It is interesting to note that the Gothey station, from this location, receives more water than the Tera station.

This seasonal precipitation analysis highlights a regularity in the region's climate pattern. It provides crucial information for water resources management, agriculture planning and author sectors dependent.

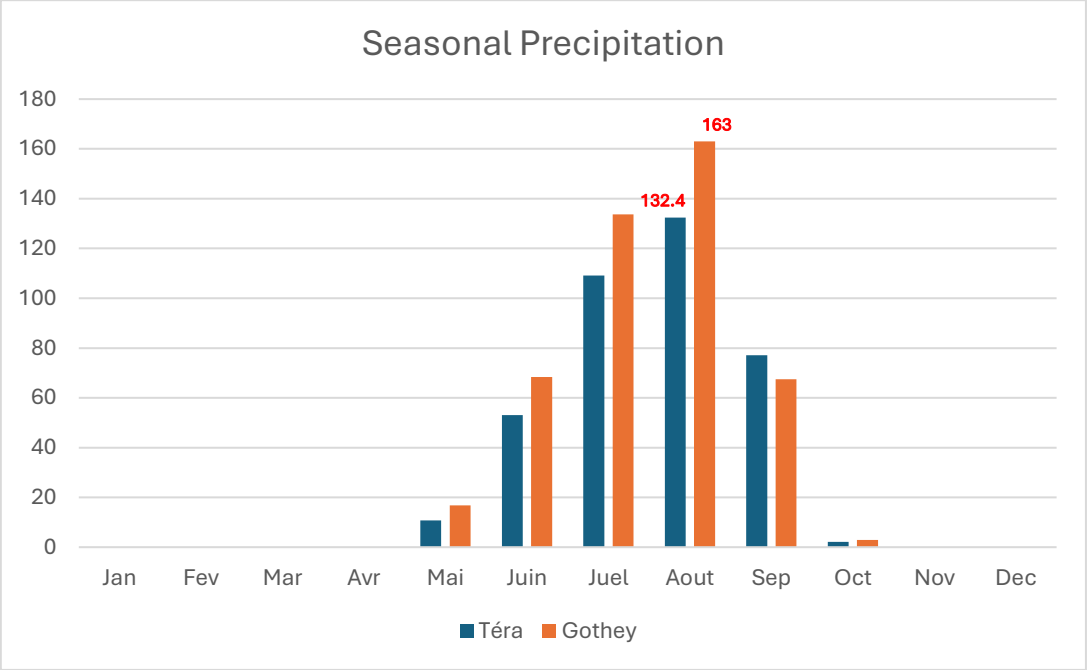

Figure 18: Seasonal Precipitation

4.1.3.2 Inter-Annual Analysis

The inter-annual precipitation analysis for the period 1992 to 2022 for the stations of Tera and Gothey and Tillaberi gives an average prospective precipitation of 444.78 mm, 453.79 mm and 433.34mm respectively. The highest precipitation recorded is 970.8 mm at the Tera station in 2021, corresponding to the devastating floods that hit the region in 2019, and the lowest is 253.2

mm.

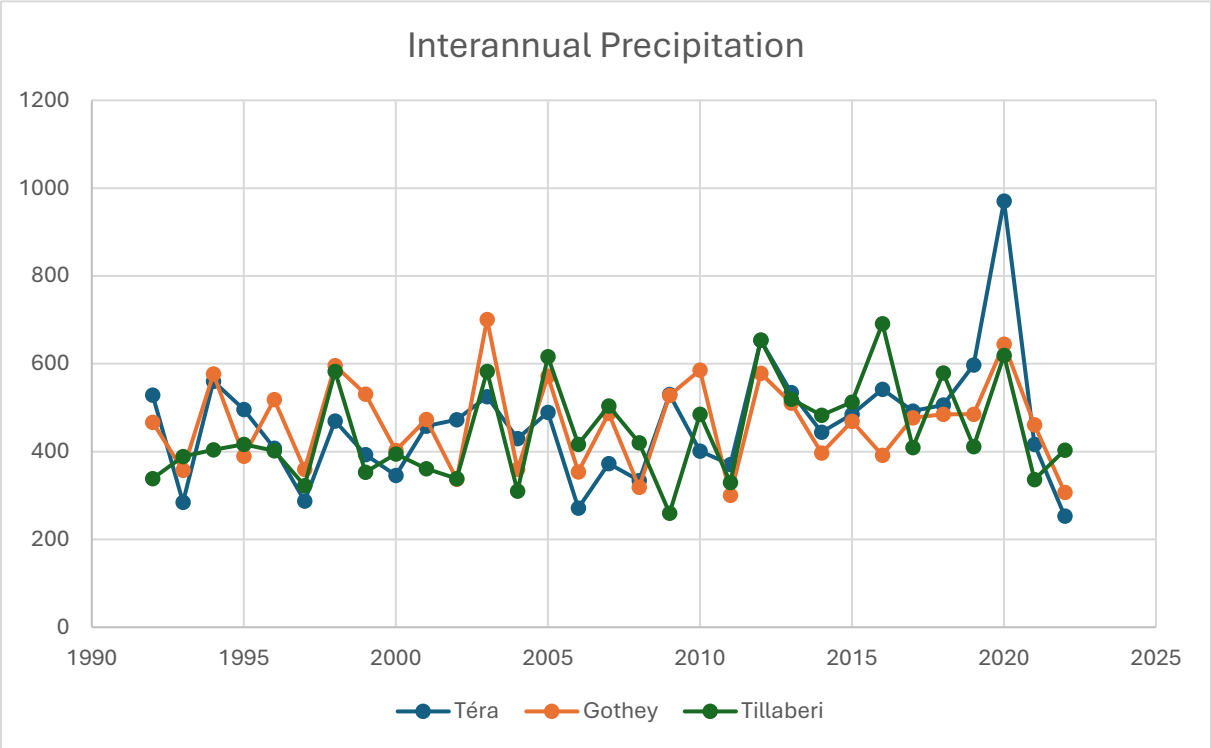

Figure 19: Inter-annual precipitation 1992-2022.

4.1.3.3 Trend Analysis and Anomaly

The Mann-Kendall trend test applied to the rainfall dataset from 1992 et 2022 for Tera and Tillaberi indicates a weak positive trend for the annual rainfall. The P-value 0.8784 and 0.1028 of Tera and Tillaberi respectively greater than 0.05 indicates insufficient evidence to reject the null hypothesis, the trend is not statistically significant. This means we cannot confidently conclude that there is a trend in Tillaberi and Tera' rainfall series. To do so, we compiled Pettit test, the result shows no statistically significant change point in the data.

Table 3: Mannkendall test summary

	Tillaberi	Tera
P-Value	0.10275	0.8784
Tau	0.209	-2.0215

This implies that while there may be a slight increase in rainfall, it could be due to random variation rather than a consistent underlying trend. The lack of statistical significance highlights the importance of considering other factors, such as variability, extreme events, and regional climatic drivers, rather than relying solely on a long-term trend.

This result also suggests that adaptive water management strategies should focus on addressing variability and extremes rather than assuming a predictable increase in rainfall over time.

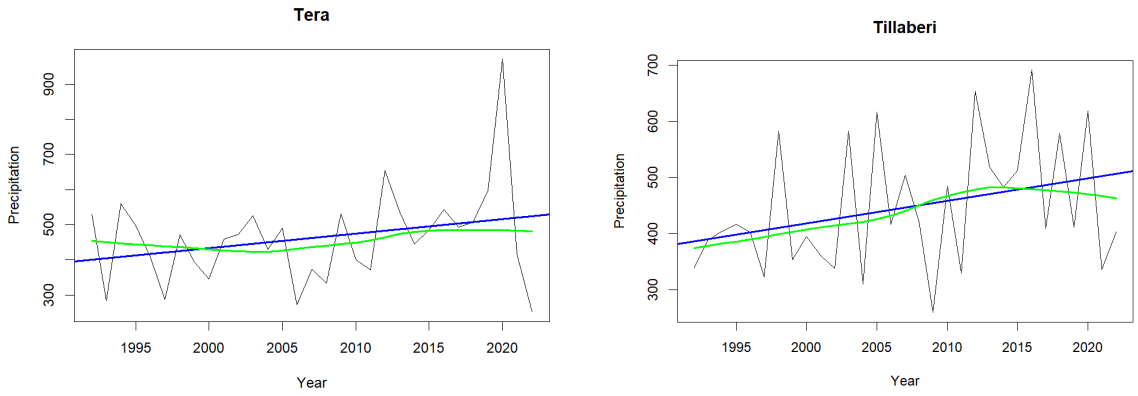

Figure 20: Precipitation tends.

4.1.3.4 Rainfall Anomaly

The analysis of the Annual Rainfall Anomaly Index (RAI) reveals significant rainfall variability over time, reflecting the region's susceptibility to climatic extremes exposure to both droughts and floods. The most striking feature of the graph is the exceptionally high positive anomaly around the most recent year, surpassing 11, which suggests an unprecedented wet year or extreme rainfall event. This anomaly far exceeds the other positive spikes in the dataset, indicating a potentially significant climatic event or an outlier in the rainfall record. Conversely, several years exhibit negative anomalies, with the deepest troughs reaching below -5, highlighting severe drought periods.

The RAI reflect the Dargol's vulnerability to both extreme wet and dry conditions, with the variability likely influenced by regional climatic drivers such as the Sahelian climate system or broader global phenomena.

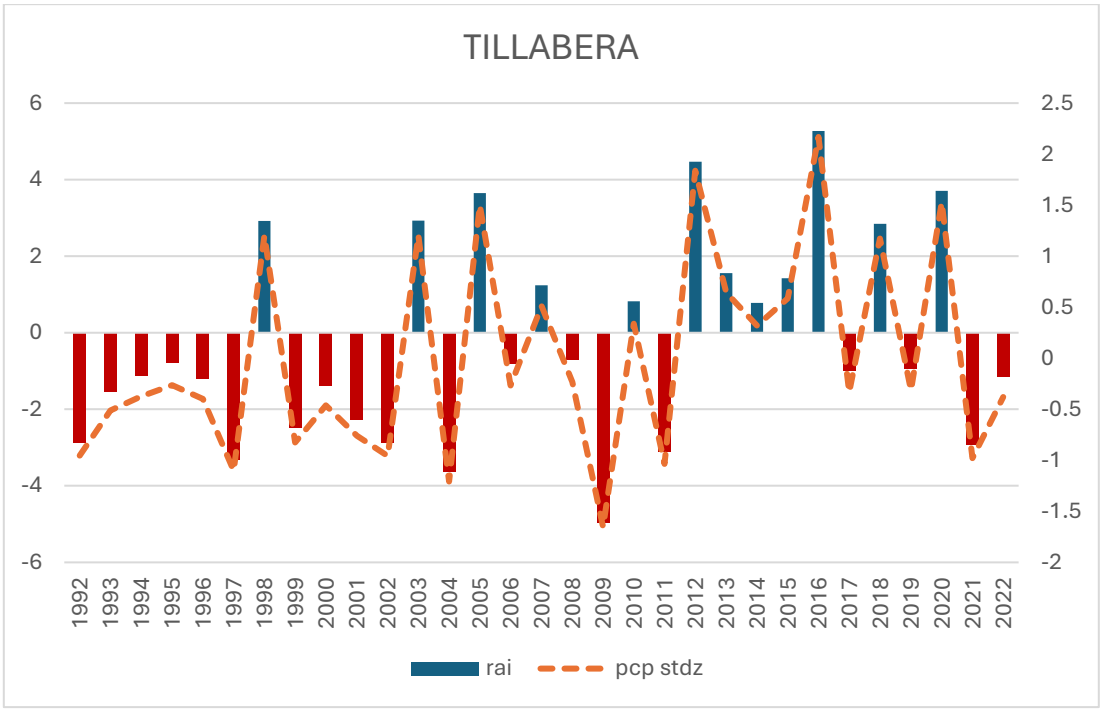

Figure 21: Tillaberi Rainfall Anomaly Index

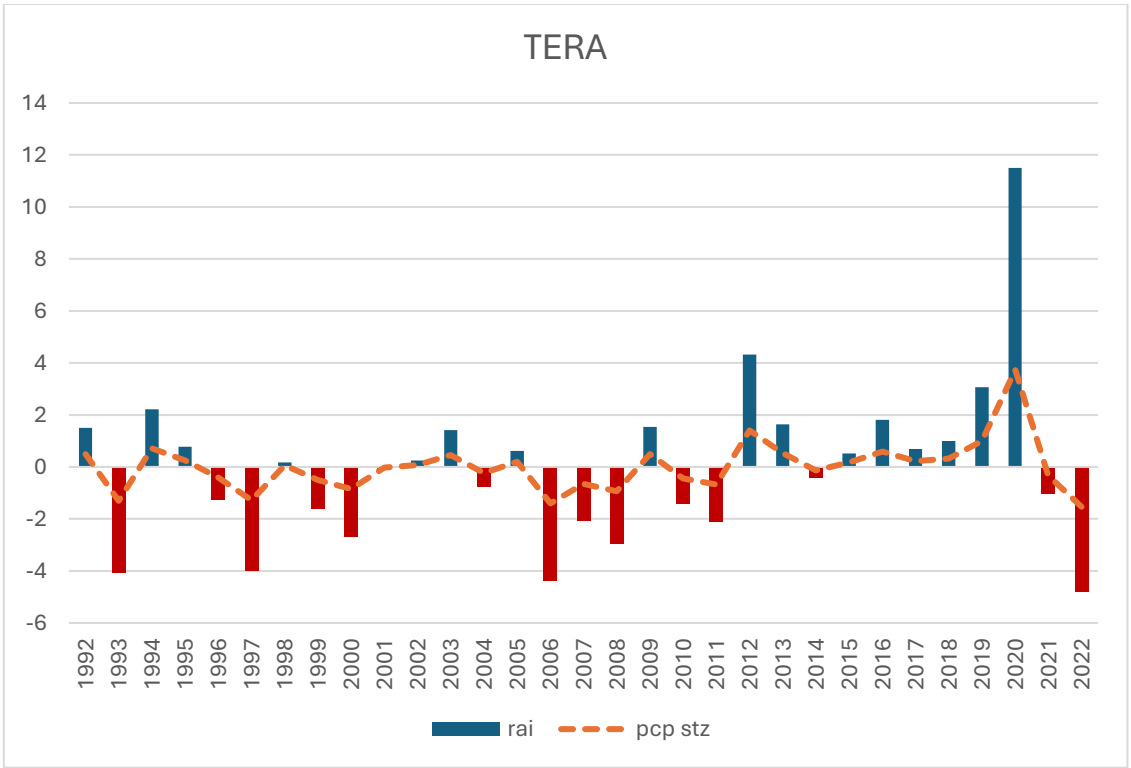

Figure 22: Tera Rainfall Anomaly Index

4.1.3.5 Temperature

The analysis of minimal and maximal temperatures of Tillabery's station shows a small trend of maximum temperature while the minimum temperature shows a sharp increase of 0.9°C. The increase of minimal temperature harms waterbodies and soil moisture leading to deficit of water requirement for plants in the soil to grow properly and an increase in the average temperature Figure 24.

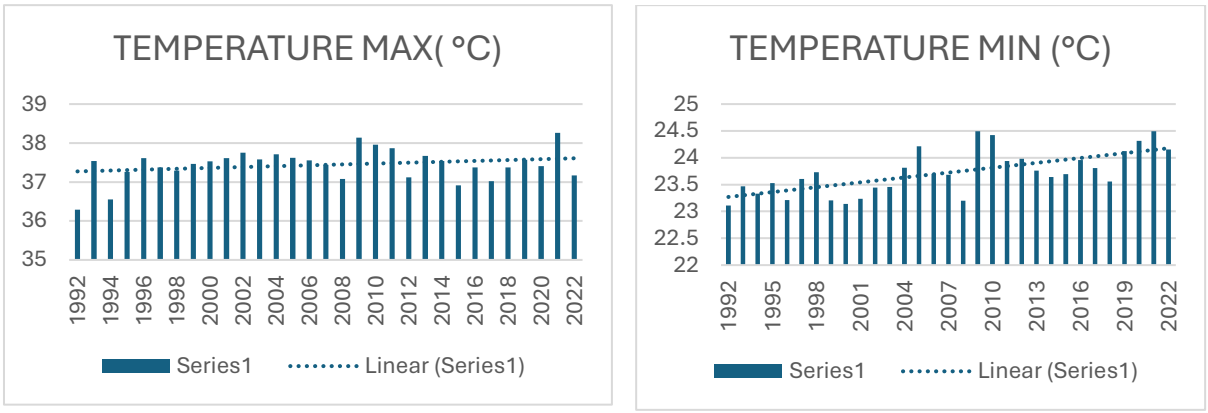

Figure 23; Max and Mind Temperature form 1992-2022.

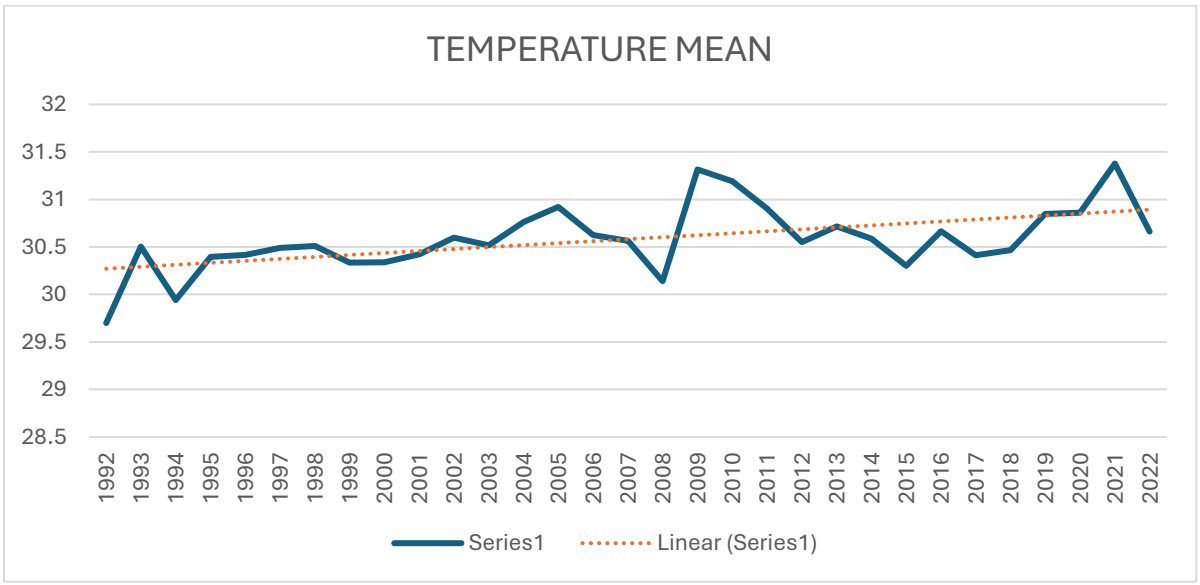

Figure 24: Annuel average Temperature 1992-2022

4.1.4 Water-Food-Climate nexus analysis

To explore the interconnection between Water, Food and Climate, a Principal Component Analysis (PCA) test was applied to the various variables comprising our WFC nexus system

over the period 2005 to 2020. The goal was to reduce the dimensionality of the dataset while identifying key variables that explain most of the variability in the system.

As for the variables, we used relative humidity (RH) and Soil Moisture (SM) to represent water, yields of cash crops (CCY) and yields of subsistence crops (SCY), to represent agricultural aspects and rainfall (R) and temperature (T) are served as variables to represent the climate component. The results obtained Figure 25 indicate that the original variables contribute to the first two principal components (Dim1 and Dim2), which together explain about 69.1% of the total variance in the dataset. Hence, the first component contains most of the information, shedding light on the trends in the relationships of the WFC Nexus in the Dargol region.

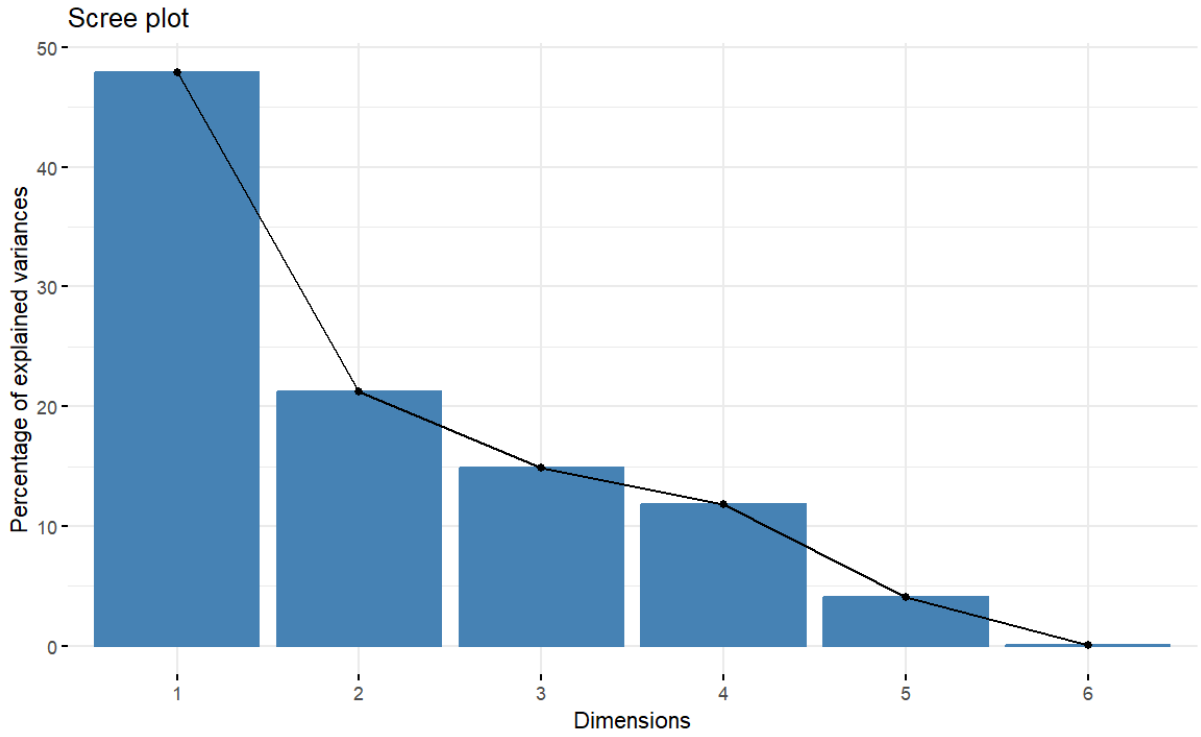

Figure 25: Principal Component Analysis results.

The PCA helps reduce the complexity of the dataset while retaining most of the information. Temperature, Cash Crop Yield, and Relative Humidity contribute strongly to the first principal component.

To better understand the predominant variable within the first trees components our analysis focused on the Table 4

Table 4: Eigenvectors

	PC1	PC2	PC3	PC4	PC5	PC6
RH	-0.550	0.206	0.125	-0.237	0.302	-0.702
SM	-0.544	0.232	0.145	-0.253	0.245	0.711
CCY	-0.331	0.304	-0.095	0.886	-0.066	0.005
SCY	-0.219	-0.586	-0.649	0.080	0.424	0.039
R	-0.488	-0.341	-0.061	-0.131	-0.790	-0.024
T	0.077	0.593	-0.728	-0.268	-0.202	-0.012

The table presents the loadings (or correlations) of each variable with the principal components. For instance, Relative Humidity (RH), Soil Moisture (SM), and Rainfall (R) all show strong negative loadings on PC1, indicating that they contribute significantly to this component. In contrast, Cash Crop Yield (CCY) and Temperature (T) are more strongly associated with PC2, particularly Temperature, which exhibits a high loading of 0.593.

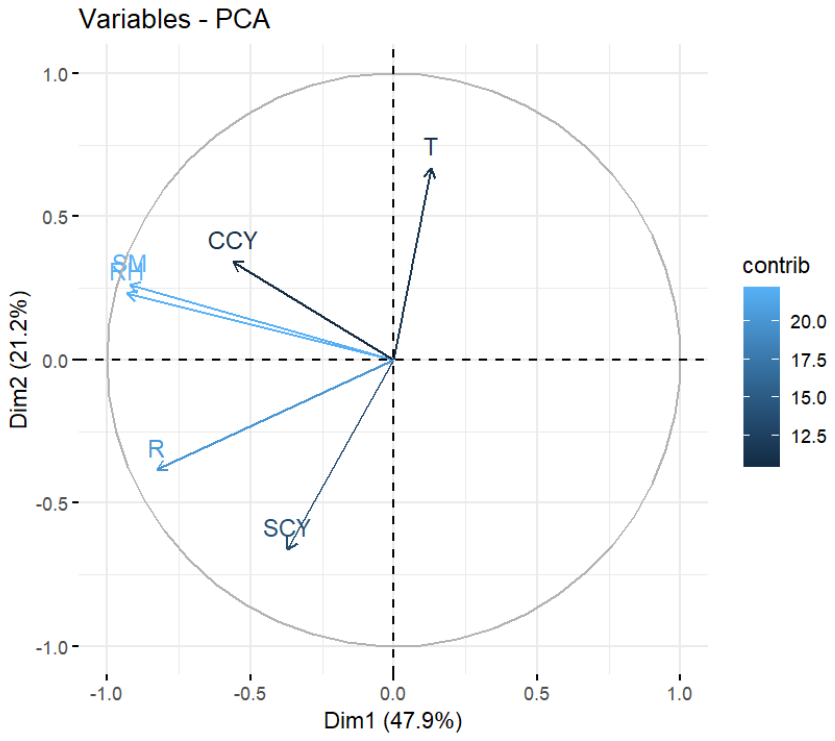

Figure 26: Correlation between the two first component.

Results and Discussion

The PCA results indicate that the first two principal components explain a significant portion of the variance, with Dim1 accounting for 47.9% and Dim2 for 21.2%, totalling 69.1%. Temperature (T) is strongly associated with Dim1, meaning it significantly influences variations in the dataset. Cash Crop Yield (CCY) and Relative Humidity (RH) show a strong positive correlation, indicating that cash crops likely benefit from higher humidity levels. Similarly, Soil Moisture (SM) and Rainfall (R) are closely aligned, which is expected as increased rainfall naturally contributes to higher soil moisture. In contrast, Subsistence Crop Yield (SCY) is negatively correlated with both SM and R, suggesting that excessive rainfall and soil moisture might not favour subsistence crops as much as cash crops. Temperature appears to have a minimal correlation with rainfall and soil moisture, indicating that its influence on these water-related variables is relatively independent.

The correlation matrix provides insights into the relationships between key climate and agricultural variables in the Dargol Basin. The strong positive correlation between relative humidity (RH) and soil moisture (SM) suggests that increased humidity helps retain soil moisture, likely by reducing evaporation. Similarly, the high correlation between cash crop yield (CCY) and subsistence crop yield (SCY) indicates that both types of crops respond similarly to climatic conditions, meaning favourable conditions benefit both. The moderate to high correlation between rainfall (R) and soil moisture (SM)/relative humidity (RH) confirms that higher precipitation increases moisture availability in the soil and the atmosphere. However, the negative correlation between temperature (T) and rainfall (R) implies that higher temperatures are linked to reduced rainfall, a pattern often observed in semi-arid regions where increased evaporation and shifting climatic patterns reduce precipitation. Lastly, the negative correlation between temperature (T) and crop yields (CCY, SCY) highlights the detrimental impact of higher temperatures on agricultural productivity, likely due to heat stress, increased evapotranspiration, and soil moisture depletion, which ultimately lower crop yields. These findings emphasize the vulnerability of the Dargol Basin's agricultural system to climate variability, particularly temperature increases and changing rainfall patterns.

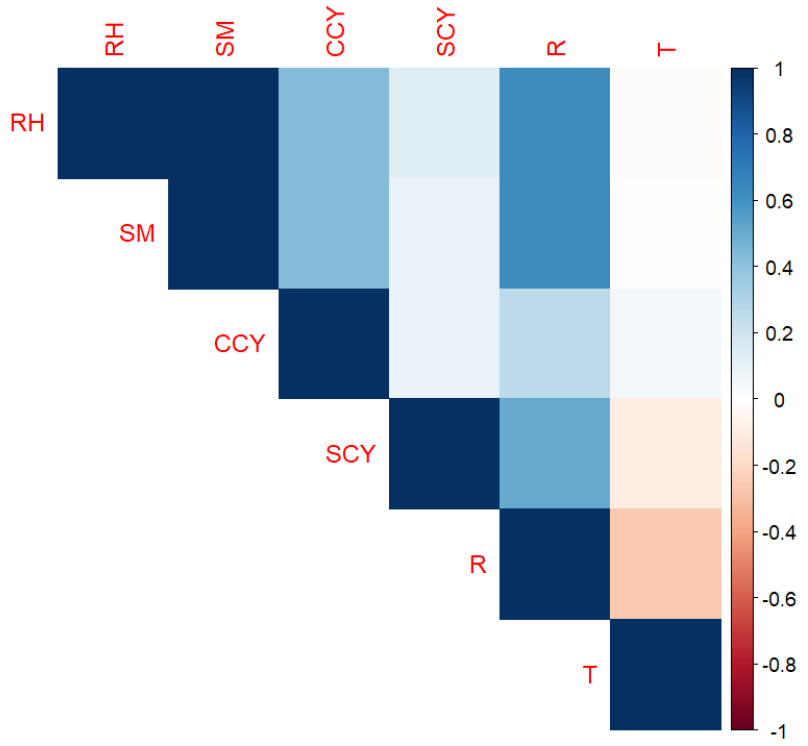

Figure 27: Multi- regression linear model.

4.2 Discussion of Results

Climate plays a pivotal role in the water cycle and water resources, while water management is critical in agriculture to optimise water resource utilization. Effective climate patterns analysis and water resources knowledge are essential for agriculture productivity and yield optimisation while preserving water resources.

The Dargol basin is highly dependent on climatic conditions for agricultural production. Observations and interviews carried out during the reconnaissance mission reveal that climatic variations significantly impact agricultural production and food security. At the start of the agricultural season, farmers are confronted with pockets of drought and violent winds that occur after sowing. These extreme conditions lead to rapid drying of the soil and the uprooting of young seedlings, making reseeding necessary. This increases production costs and jeopardises producers' food security. Faced with these difficulties, the government often steps in to supply improved seeds to enable farmers to start sowing again. However, this dependence on external aid poses a real challenge in terms of agricultural resilience. Another significant impact is the drought that occurs at the end of the season. Millet, the region's main crop, is often at a critical stage of bolting or heading when rainfall stops prematurely. This water shortage has dramatic

consequences for agricultural production, leading to major harvest shortfalls. In general, crops are sown in July, and the rains stop in September. If the seedlings planted at the end of July do not have time to complete their cycle before the rains stop, losses are inevitable.

One of the adaptation strategies observed among farmers is crop association. Unlike monoculture, which is still rare in the region, combining crops is widespread practice and is an adaptive response to climate change. Millet and cowpea are often combined in the same field. Cowpeas are sown a little later than millet, enabling farmers to diversify their production and reduce the risk of total losses. If millet fails, cowpeas can provide part of the harvest, offering a degree of food security. Other associated crops such as millet, cowpea and sorrel can also be found in the same field. Despite these strategies, some areas remain structurally deficient, even during surplus crop years. These deficits can be attributed to many factors, including late sowing and soil quality. In addition, the introduction of resilient crops, although effective, has not yet been fully adopted by all rural communities. Cassava and sweet potato, for example, are beginning to be gradually integrated into production systems, as they are better adapted to extreme climatic conditions.

CHAPTER V : CONCLUSION AND RECOMMENDATION

5.1.Conclusion

In conclusion, this master's thesis explores the complex interconnection of relationships between water management, food security, and climate change in the context of the Dargol basin. Through analysis, we underline the importance of these factors to ensure sustainability and resilience in the region. The study initially allowed us to examine separately the trends of the various elements that constitute the WFC nexus, namely water, food, and climate. This was followed by the evaluation of the WFC nexus using Principal Component Analysis (PCA). Finally, based on the conducted analyses, recommendations were made. First, it should be noted that water resources, studied through land use and trend and RAI analysis, showed spatiotemporal variability and changes in and around water resources. Regarding food, it should be mentioned that agricultural production continued to increase during the period from 2012 to 2020; however, the results show a decrease in substantial crop production while cash crops increased significantly, demonstrating adaptation to climate change and variability in the region. As for the climate, there is significant seasonal and interannual climatic variability in the region. The climate is characterized by a unimodal pattern with a single rainy season and a single dry season. The Mann-Kendall and Petti trend tests applied to the rainfall dataset from 1992 to 2022 for Tera and Tillaberi indicate a weak positive trend; the results show no statistically significant change point in the data. The rainfall anomaly shows that the region has experienced several droughts and rainfall deficits over the period from 1992 to 2022. The inextricable link between food security and climate variability is clear, highlighting the urgent need for adaptation strategies that account for the increasing unpredictability of weather patterns. Our findings underscore the fundamental principle that maintaining a stable food supply requires a comprehensive understanding of, and response to, evolving climate dynamics. The PCA facilitated an in-depth analysis of the interrelationships among the various variables representing the sectors within the water-food-climate (WFC) nexus. Our results reinforce the fundamental truth that ensuring a stable food supply depends on considering ever-changing climatic dynamics. Recognition of these interdependencies underscores the critical importance of policy design as a central component of sustainable resource management. To promote sustainable development, policies must be strategically formulated to ensure efficient water resource management, build resilience to climate change, and guarantee food security.

However, achieving this objective necessitates a collaborative and participatory approach, involving the active engagement of all relevant stakeholders within the Dargol Basin. This includes policymakers, local communities, farmers, water resource managers, and environmental organizations, whose collective efforts are essential for the development and implementation of effective strategies. The establishment of a more resilient and adaptive framework for sustainable water resource management, climate resilience, and long-term food security in the region is contingent upon the implementation of inclusive decision-making processes, the promotion of knowledge-sharing, and the integration of local expertise.

5.2.Recommendation

5.2.1 Water resources

Climate change introduces significant uncertainties, thereby challenging existing water resource management practices in the Dargol basin. The implementation strategies of the national water and sanitation policy are centred on the establishment of Hydrological Water Management Units (UGE), which serve as a structured framework for the planning, development, and sustainable utilization of water resources. The following recommendations are made to preserve water resources and natural resources and address climate variability within the Water-Food-Climate nexus.

- Conduct a detailed hydrological assessment of the Dargol Basin (by 2030) to quantify surface and groundwater potential, using remote sensing and field surveys. Responsible: Regional Directorate of Water Resources and local universities.
- Implement small-scale rainwater harvesting projects (2025–2030) in priority villages such as Kakassi and Gouthey for agro-sylvo-pastoral use, especially targeting areas with erratic rainfall.
- Rehabilitate and expand existing hydro-agricultural infrastructure (e.g., small dams, irrigation canals) in the midstream Dargol Basin (target: rehabilitate at least 3 structures by 2030), while promoting affordable borehole drilling with solar-powered pumps.
- Strengthen cooperation with neighboring basins through a sub-regional framework under AES (by 2028), focusing on data-sharing and flood/drought management for the Dargol River.

5.2.2 Agricultural Yields

To ensure food security and adapt to climate variability in the Dargol Basin:

- Introduce and scale up climate-smart crops, such as drought-resistant millet and sorghum varieties (target: 60% of cultivated area by 2030).
- Promote drip and sprinkler irrigation systems among farmers through subsidized schemes, aiming for at least 25% of farms equipped by 2030.
- Establish a pilot solar irrigation farm (by 2030) in Kakassi, showcasing mechanization (solar pumps, tillers) and providing a model for replication.
- Develop a training program on treated wastewater reuse for irrigation (start pilot sessions in Gouthey by 2025), aiming to irrigate 50 ha of crops with recycled water by 2030.

5.2.3 Climate adaptation

To strengthen climate resilience within the Dargol Basin:

- Promote agroforestry practices (e.g., integrating acacia and baobab trees with crops) on 500 ha by 2028 to protect soil and enhance water retention.
- Create community-led water management committees in each major village by 2030 to plan seasonal water use based on climate forecasts.
- Integrate climate data (rainfall forecasts, drought alerts) into farming calendars, disseminated through local radio programs and mobile SMS alerts, operational by 2025.
- Set up a revolving micro-credit fund (initial capital: $100,000 by 2025) accessible to small farmers for investing in resilient practices (irrigation kits, improved seeds).
- Organize annual farmer field schools (starting 2025) focused on adaptation techniques, such as conservation agriculture and water-saving practices.
- Strengthen local meteorological stations (e.g., update equipment at Tillabéri Meteorological Centre) and connect them to village early-warning systems by 2026.
- Encourage the adoption of farming practices that take climate predictions into account, such as selecting crops suited to local conditions.
- Improve water resource management to address climate variability, utilizing effective and sustainable irrigation practices.

These recommendations are tailored to the specific conditions of the Dargol Basin and aim to address the multifaceted challenges stemming from interconnections between water, food, and climate. They align with the promotion of sustainable and resilient agricultural practices within the Dargol Basin. By prioritising localised interventions, integrating climate and water management, and building local capacities, these recommendations seek to enhance the basin's resilience to climate change while securing food and water resources sustainably.

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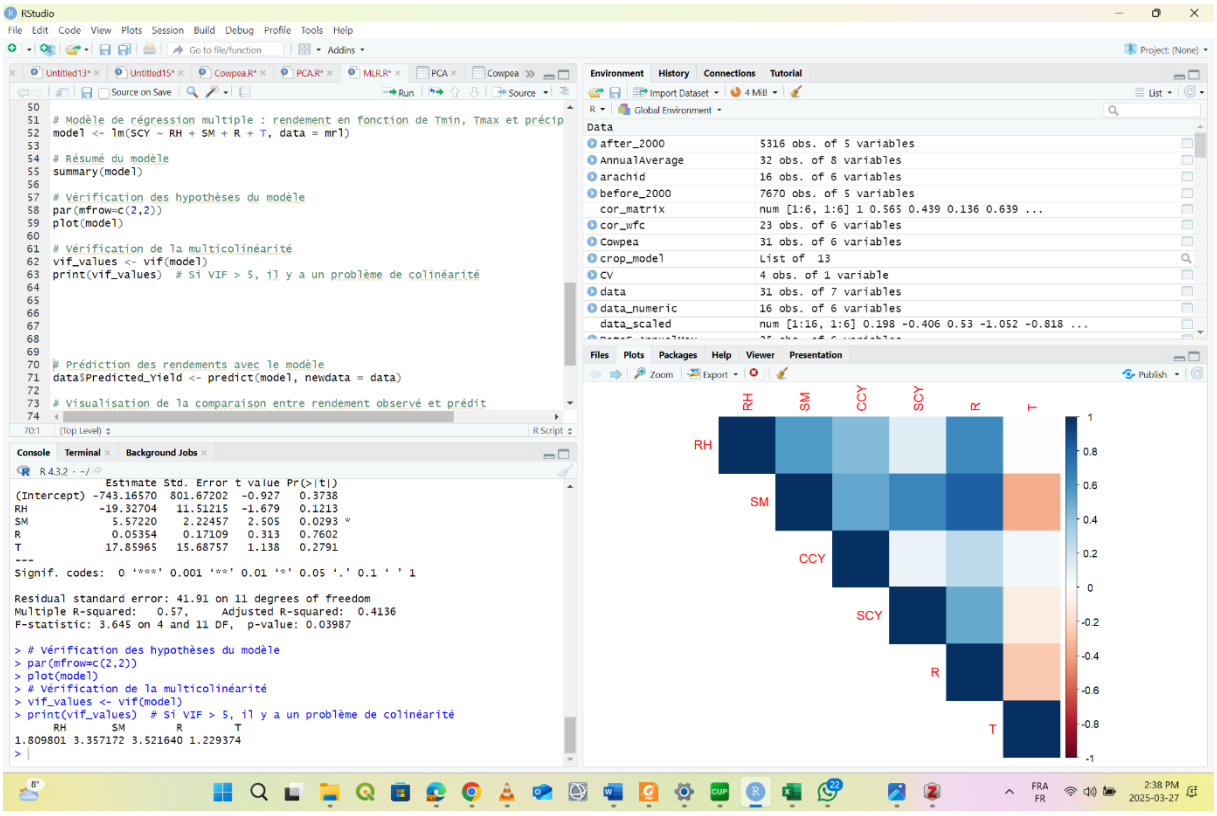
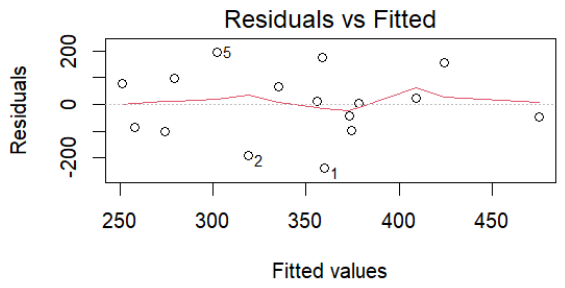
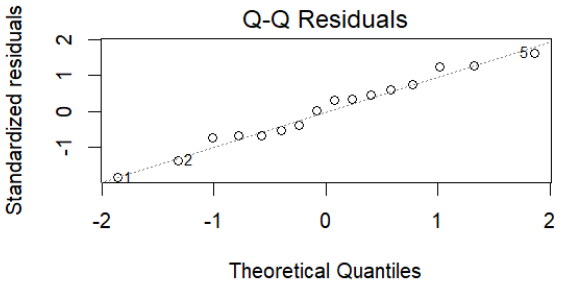
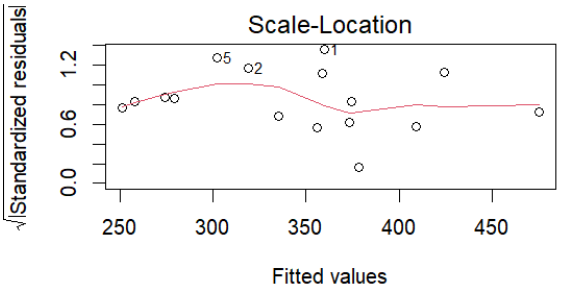
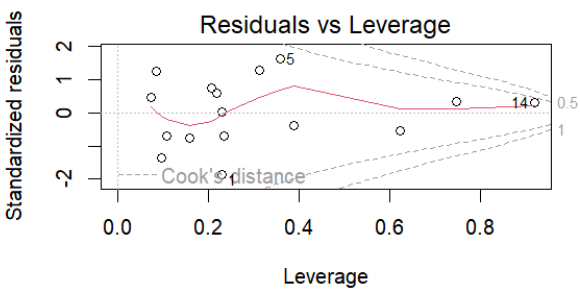
APANDIX


RStudio
# Modèle de régression multiple : rendement en fonction de Tmin, Tmax et précip
model <- lm(SCY ~ RH + SM + R + T, data = mrl)
# Résumé du modèle
summary(model)
# Vérification des hypothèses du modèle
par(mfrow=c(2,2))
plot(model)
# Vérification de la multicolinéarité
vif_values <- vif(model)
print(vif_values) # Si VIF > 5, il y a un problème de colinéarité
Prédiction des rendements avec le modèle
data$Predicted_Yield <- predict(model, newdata = data)
Visualisation de la comparaison entre rendement observé et prédit
Estimate Std. Error t value Pr(>|t|)
(Intercept) -743.16570 801.67202 -0.927 0.3738
RH -19.32704 11.51215 -1.679 0.1213
SM 5.57220 2.22457 2.505 0.0293 *
R 0.05354 0.17109 0.313 0.7602
T 17.85965 15.68757 1.138 0.2791
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 41.91 on 11 degrees of freedom
Multiple R-squared: 0.57, Adjusted R-squared: 0.4136
F-statistic: 3.645 on 4 and 11 DF, p-value: 0.03987
> # Vérification des hypothèses du modèle
> par(mfrow=c(2,2))
> plot(model)
> # Vérification de la multicolinéarité
> vif_values <- vif(model)
> print(vif_values) # Si VIF > 5, il y a un problème de colinéarité
RH SM R T
1.809801 3.357172 3.521640 1.229374
RH
SM
CCY
SCY
R
T


Residuals vs Fitted
Residuals
Fitted values

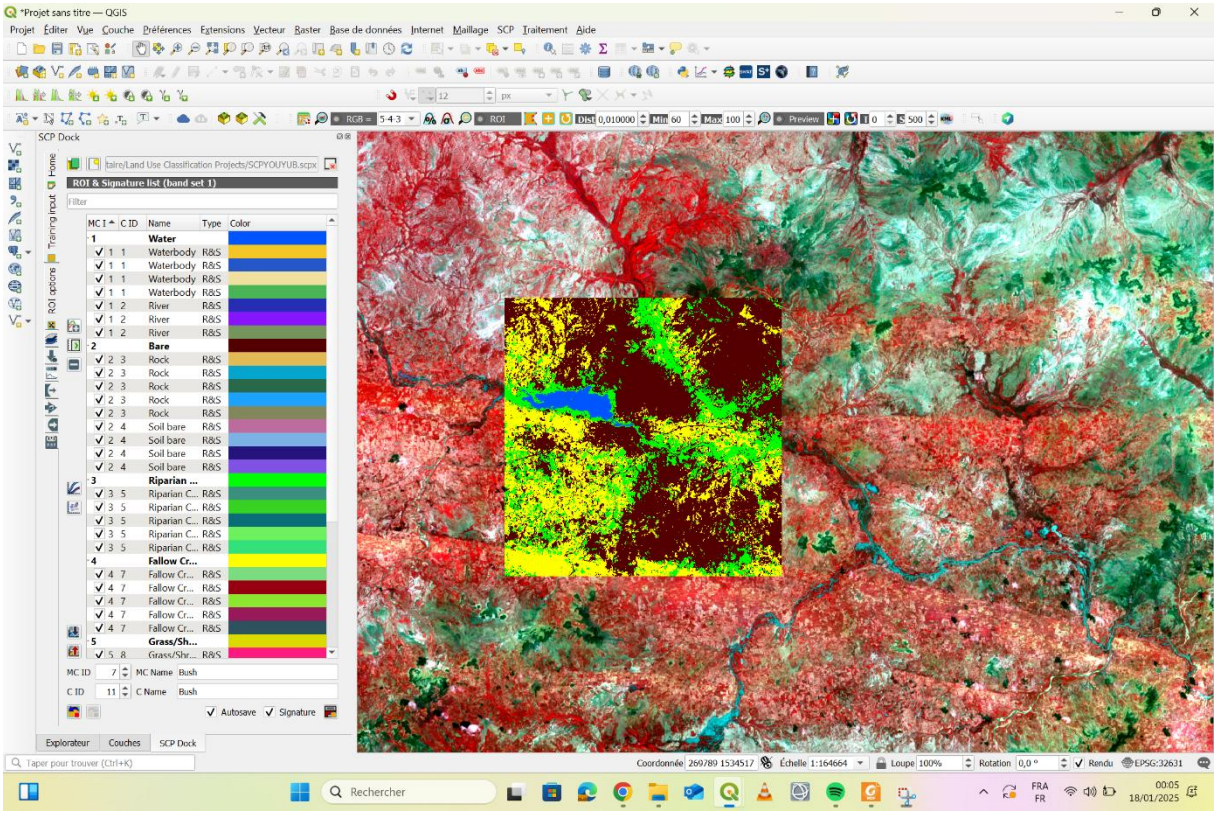

Q-Q Residuals
Standardized residuals
Theoretical Quantiles


Scale-Location
√|Standardized residuals|
Fitted values


Residuals vs Leverage
Standardized residuals
Cook's distance
Leverage


DRA
DRGR
DIRECTION REGIONALE DE L'AGRICULTURE
DIRECTION REGIONALE DU GENIE RURAL
DIRECTION REGIONALE DE L'ENVIRONNEMENT ET DE LA LUTTE CONTRE LA DESERTIFICATION


PGIP
PROJET DE GESTION INTEGREE DES PAYSAGES
UNITE D'APPUI REGIONALE DE
TILLABERI


*Projet sans titre — QGIS
Projet Éditer Vue Couche Préférences Extensions Vecteur Raster Base de données Internet Maillage SCP Traitement Aide
SCP Dock
ROI & Signature list (band set 1)
Water
Waterbody
River
Bare
Rock
Soil bare
Riparian ...
Fallow Cr...
Grass/Sh...
Bush
Autosave
Signature
Explorateur
Couches
SCP Dock
Rechercher