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Presented by

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TITLE:

EVALUATION AND OPTIMIZATION OF IRRIGATION TECHNIQUES TO REDUCE WATER LOSSES AND IMPROVE AGRICULTURAL PRODUCTIVITY: CASE OF DANOUNA IRRIGATION SCHEME IN CHAD

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

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DECLARATION AND RECOMMENDATION

DECLARATION

I declare that this research proposal is my original work and has not been submitted to any other University for the award of any degree.

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RECOMMENDATION

This research proposal has been submitted for examination with my approval as Supervisor.

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ABSTRACT

This study focused on the evaluation and optimization of irrigation techniques to reduce water losses and improve agricultural productivity in the Danouna irrigation scheme, located in the Hadjer Lamis region of Chad and benefiting from the water resources of the Chari-Logone River. The main aim of the study was to identify the inefficiencies of the current irrigation system in terms of rational water use and agricultural yield, and to propose solutions adapted to the local context for more sustainable management of the resource. The analysis carried out in the Danouna irrigation scheme, combining literature review, field surveys and measurements with simulations using CROPWAT model, revealed an over-irrigation of around 86% compared to the real needs of rice. This wastage was mainly due to an inappropriate irrigation schedule, a lack of tertiary canals and losses through deep percolation and infiltration in unlined secondary canals.

As far as agricultural productivity is concerned, despite these inefficiencies, the average yield observed in the Danouna perimeter is around 6 tons per hectare, which is still higher than the regional average but below optimum potential. Analysis of water productivity, estimated at around 0.27 kg/m³, points to considerable room for improvement through more rigorous irrigation management and more efficient farming practices. On this basis, the study proposed several avenues for optimization: a precise readjustment of the irrigation schedule according to the critical growth stages of the rice crop, the modernization of hydraulic infrastructures, notably through the rehabilitation of secondary canals and the much-needed construction of tertiary canals, and the adoption of better agricultural practices, including raising farmers' awareness of good irrigation practices.

This work has highlighted a number of methodological limitations, particularly with regard to data availability and reliability. As a result, further research integrating advanced tools such as soil moisture sensors or remote sensing is required. Specific recommendations were also made to ensure sustainable management of the Danouna irrigated perimeter.

Keywords : Irrigation, water management, optimisation, agricultural productivity, irrigation scheme, Danouna, rice cultivation, Hadjer Lamis, Chad.

RESUME

Cette étude a porté sur l'évaluation et l'optimisation des techniques d'irrigation afin de réduire les pertes d'eau et d'améliorer la productivité agricole dans le périmètre d'irrigation de Danouna, situé dans la région de Hadjer Lamis au Tchad et bénéficiant des ressources en eau du fleuve Chari-Logone. L'objectif principal de l'étude était d'identifier les inefficacités du système d'irrigation actuel en termes d'utilisation rationnelle de l'eau et de rendement agricole, et de proposer des solutions adaptées au contexte local pour une gestion plus durable de la ressource. L'analyse réalisée dans le périmètre irrigué de Danouna, combinant une revue de la littérature, des enquêtes de terrain et des mesures avec des simulations utilisant le modèle CROPWAT, a révélé une sur-irrigation d'environ 86% par rapport aux besoins réels du riz. Ce gaspillage était principalement dû à un calendrier d'irrigation inapproprié, à un manque de canaux tertiaires et à des pertes par percolation profonde et infiltration dans les canaux secondaires non revêtus.

En ce qui concerne la productivité agricole, malgré ces inefficacités, le rendement moyen observé dans le périmètre de Danouna est de l'ordre de 6 tonnes par hectare, ce qui reste supérieur à la moyenne régionale mais en deçà du potentiel optimal. L'analyse de la productivité de l'eau, estimée à environ 0,27 kg/m^3, laisse entrevoir une marge de progression importante par une gestion plus rigoureuse de l'irrigation et des pratiques culturales plus efficientes. Sur cette base, l'étude propose plusieurs pistes d'optimisation : un réajustement précis du calendrier d'irrigation en fonction des stades critiques de croissance de la culture du riz, la modernisation des infrastructures hydrauliques, notamment par la réhabilitation des canaux secondaires et la construction indispensable de canaux tertiaires, et l'adoption de meilleures pratiques agricoles, y compris la sensibilisation des agriculteurs aux bonnes pratiques d'irrigation.

Ce travail a mis en évidence un certain nombre de limites méthodologiques, notamment en ce qui concerne la disponibilité et la fiabilité des données. Par conséquent, des recherches supplémentaires intégrant des outils avancés tels que les capteurs d'humidité du sol ou la télédétection sont nécessaires. Des recommandations spécifiques ont également été formulées pour assurer une gestion durable du périmètre irrigué de Danouna.

Mots-clés : Irrigation, gestion de l'eau, optimisation, productivité agricole, périmètre irrigué, Danouna, riziculture, Hadjer Lamis, Tchad.

ملخص

ركزت هذه الدراسة على تقييم تقنيات الري وتحسينها من أجل تقليل الفاقد من المياه وتحسين الإنتاجية الزراعية في محيط الري في دانونا الواقع في منطقة حجير لميس في تشاد والمستفيد من الموارد المائية لنهر شاري لوغون. وكان الهدف الرئيسي للدراسة هو تحديد أوجه القصور في نظام الري الحالي من حيث الاستخدام الرشيد للمياه والمردود الزراعي، واقتراح حلول تتكيف مع السياق المحلي من أجل إدارة أكثر استدامة للمورد. وكشف التحليل الذي أجري في محيط دانونا المروي، والذي يجمع بين مراجعة الأدبيات والمسوحات والقياسات الميدانية وعمليات المحاكاة باستخدام نموذج CROPWAT، عن الإفراط في الري بنسبة 86% تقريباً مقارنة بالاحتياجات الفعلية للأرز. ويعزى ذلك بشكل رئيسي إلى عدم ملاءمة جدولة الري ونقص القنوات الثلاثية والفاقد من خلال الترشيح العميق والترشح في القنوات الثانوية غير المبطنة.

أما فيما يتعلق بالإنتاجية الزراعية، فعلى الرغم من أوجه القصور هذه، فإن متوسط الغلة الملحوظة في محيط الدانونة يبلغ حوالي 6 أطنان للهكتار الواحد، وهو ما يزال أعلى من المتوسط الإقليمي، ولكنه أقل من الإمكانات المثلى. ويشير تحليل إنتاجية المياه، المقدرة بحوالي 0.27 كيلوغرام/متر مكعب، إلى وجود مجال كبير للتحسين من خلال إدارة أكثر صرامة للري وممارسات زراعية أكثر كفاءة. وعلى هذا الأساس، تقترح الدراسة عدة سبل للتحسين : إعادة ضبط دقيق لتقويم الري وفقاً لمراحل النمو الحرجة لمحصول الأرز، وتحديث البنى التحتية الهيدروليكية، ولا سيما من خلال إعادة تأهيل القنوات الثانوية والتشييد الضروري للقنوات الثلاثية، واعتماد ممارسات زراعية أفضل، بما في ذلك توعية المزارعين بممارسات الري الجيدة.

وقد سلط هذا العمل الضوء على عدد من القيود المنهجية، لا سيما فيما يتعلق بتوافر البيانات وموثوقيتها. ونتيجة لذلك، يلزم إجراء المزيد من البحوث التي تتضمن أدوات متقدمة مثل أجهزة استشعار رطوبة التربة أو الاستشعار عن بعد. كما تم تقديم توصيات محددة لضمان الإدارة المستدامة لمحيط الدونة المروي.

الكلمات المفتاحية : الري، إدارة المياه، الاستغلال الأمثل، الإنتاجية الزراعية، محيط دانونا المروي، زراعة الأرز، حاجر لميس، تشاد

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LIST OF SYMBOLS

ANAM – Agence Nationale de la Météorologie
AW – Available Water
BADEA – Banque Arabe pour le Développement Économique en Afrique
BMP - Best Management Practice
CR - Capillary Rise
CU – Uniformity Coefficient
CWR – Crop Water Requirement
D10 - 10% finer particle diameter (m)
D30 - 30% finer particle diameter (m)
D60 - 60% finer particle diameter (m)
DGGRHA – Direction Générale du Génie Rural et de l'Hydraulique Agricole
DIS – Danouna Irrigation Scheme
Dj - Representative grain diameter for sediment size fraction j
DP - Deep Percolation
ea - mean actual vapor pressure
es - saturation vapour pressure
ET - Evapotranspiration
Etc - Actual Crop Evapotranspiration
Eto - Reference Crop Evapotranspiration
ETp - Potential Evapotranspiration
ETr - reference Evapotranspiration
FAO – Food and Agriculture Organization
FC - Field Capacity
fw - an average fraction of soil surface wetted by irrigation or precipitation
g - Acceleration due to gravity (m/s2)
GDP - Goss Domestic Product
GPS – Global Positioning System
h - Depth of flow
ID – Irrigation duration
IWMI –International Water Management Institute
Kc - crop coefficient
LCBC – Lake Chad Basin Commission

NIB - National Irrigation Board
PDA – Plan Directeur Agricole
PDRICL2 – Projet du Développement de la Riziculture Irriguée
Peff - Effective Rainfall
PET - Potential Evapotranspiration
PM - Penman-Monteith
PVC – Polyvinyle chloride
RAW – Readily Available Water
Rd – Root depth
SDG – Sustainable Development Goals
SODELAC – Société des Eaux du Lac
SRA - Strategy for Revitalization of Agriculture
SRI– System de Riziculture Intense
SWISSAID – Aide Suisse
UN – United Nation
UNDP – United Nations Development Program

UNFCCC - United Nations Framework Convention on Climate Change
USDA S.C. – United States Department of Agriculture - Soil Conservation
WEC – Water and Environment Centre
WFP –World Food Program
WHC - water holding capacity
WP – Water Productivity
WUAs– Water User Associations

Y – yield

ƒ- Water density (kg/m3)
v - Kinematic viscosity
(es – ea) : saturation vapour pressure deficit

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CHAPTER ONE

1. INTRODUCTION

This chapter introduces and outlines the focus of the study, beginning with an overview of the background and context surrounding the evaluation and optimization of irrigation techniques at the Danouna Irrigation Scheme (DIS) in Chad. It highlights the challenges associated with water scarcity and inefficient irrigation practices and explores opportunities for enhancing water management to reduce losses and improve crop yields. The chapter also outlines the problem statement, research objectives, justification, research questions, and working hypotheses, thereby establishing the framework for sustainable agricultural development in the region.

1.1. Research background

Agriculture plays a central role in Chad's economy, accounting for approximately 23% of GDP, of which 20% comes from food production and 3% from cash crops. The sector is the driving force behind the country's development, directly supporting the livelihoods of nearly 88% of households, the majority of whom practice subsistence farming on small farms(Hasdiana, 2018). Food crops such as millet, sorghum, maize and rice provide food for the population, while cash crops, including cotton, sugarcane, peanuts and sesame, contribute significantly to export earnings. However, despite considerable agricultural potential; only 13% of arable land out of a potential 39 million hectares is exploited; weak infrastructure and the predominance of traditional farming practices limit the overall performance of the sector(*Analyse Des Contraintes et Opportunités Pour Le Développement Du Sous-Secteur Agricole*, 2022).

Chadian agricultural productivity has a lot of potential, but it is still lower than that of other nations with comparable agroclimatic conditions. About 43 billion cubic meters of renewable water found in rivers, lakes, floodplains, and rainfall are found in Chad; the Chari-Logone alone offers 300,000 hectares that can be exploited in the winter season and 150,000 hectares that can be exploited in the off-season, these resources are especially susceptible to changes in the climate(IFAD, 2023). Furthermore, because of ineffective management, non-renewable aquifers which are estimated to be between 260 and 540 billion cubic meters remain underutilized. Low productivity is a result of this circumstance, which restricts the best use of water for agriculture(En & Et, n.d.).

Although the country has vast areas that can potentially be irrigated (5.6 million hectares of all arable land), actual irrigation covers only about 43,000 hectares, highlighting the deficit in suitable water infrastructure(No, 2019a). This sector, which is essential for food security, could be developed on a large scale (4 to 8 thousand hectares) and on a small scale (53 to 288 thousand hectares), generating important economic benefits. Faced with irregular rainfall in the recent years and a population growth expected to reach 27 million by 2050 irrigation is therefore an essential solution to address climate variability, characterized by irregular rainfall and periods of intense drought, by ensuring a regular supply of water to crops(Xie, n.d.).

An in-depth analysis of Chad's agricultural situation is provided by the General Directorate of Rural Engineering and Agricultural Hydraulics (DGGRHA) of the Ministry of Agriculture, represented by its DGA Mr. Guiradoum Nandingar. It emphasizes the significance of the four main crops: corn, rice, sorghum, and millet which dictate how cultivated areas are organized. Due mostly to inadequate water management and restricted mobilization of production components, this analysis indicates that present rice yields in hydro-agricultural initiatives are approximately 2.5 t/ha, a level deemed insufficient. As part of its goals for food security, the Ministry in charge of agriculture wants to maximize the utilization of water, equipment, and inputs while strengthening cooperative capacities in order to reach an average output of 7 t/ha.

Chad's agricultural production methods, which are centered on small-scale subsistence farms, are still essentially extensive and ineffective. In terms of irrigation, the most popular gravity systems, which have an efficiency of 70 to 80% and an average construction cost of 15 million CFA francs per hectare, present considerable water losses of up to 20 to 40% in the absence of proper canal lining(IRENA & FAO, 2021). These results highlight how urgent it is to update and enhance irrigation infrastructure in order to enhance water management, which will boost agricultural output and the sector's sustainability in Chad.

In the national context where the Chadian government seeks to strengthen food security and stimulate agricultural development, a strategic initiative has been launched to develop rice agriculture (PDRI-CL2). The very ambitious Rice Development Project in the Chari-Logone Plain II (PDRI-Cl2) aims to rehabilitate and develop seven (07) irrigated areas, totaling 350 hectares, based on the abundant water resources of the Chari-Logone River. The capacity of the river, which supplies these areas with a maximum required flow of 1.05 m^3/s, is largely higher than the needs of the facilities, which represents an opportunity to optimize water use(R. D. U. Tchad et al., 2022).

The Danouna irrigation scheme, which is an integral part of these seven (07) areas managed by PDRI-CL2, perfectly illustrates the current challenges: despite access to an abundant water source along the Chari-Logone River, the Danouna irrigation scheme system, which is a system with total water control, still presents inefficiencies in terms of water management. Thus, the study and optimization of the Danouna irrigation system, based on soil, topographic, socio-economic and environmental data, are essential to improve water efficiency and increase agricultural productivity.

In the difficult agro-hydric context of Chad in general and the village of Danouna in the province of Hadjer Lamis in particular, the assessment and optimization of the Danouna irrigation scheme is crucial as a strategic solution, turning water challenges into opportunities for sustainable development along with improved food security

1.1. Objectives

1.1.1. Main objective

The main objective of this study is to evaluate and improve the irrigation system used in Chad's Danouna Irrigation Scheme in order to minimize water loss, boost agricultural output, and guarantee the sustainable use of water resources.

1.1.2. Specific Objectives

- To evaluate the effectiveness of the current irrigation system at the Danouna Irrigation Scheme by analyzing its water consumption patterns, distribution efficiency, and overall impact on crop yields.
- To quantify water losses within the system by measuring losses due to evaporation, uncontrolled infiltration, and inefficient management practices, thereby identifying the primary sources of inefficiency.
- To propose optimization strategies for the Danouna irrigation system, taking into account local socioeconomic and environmental constraints, in order to minimize water losses and maximize agricultural productivity.

1.2. Problem Statement

The primary source of income for about 78% of the rural population in Chad, a Sahelian nation with severe economic and environmental limitations, is subsistence farming(adelphi, 2018). Due to reliance on rain-fed agriculture, which is characterized by erratic rainfall and rising climate variability in recent years, agricultural productivity is still at risk in this setting. The agricultural sector's contribution to national food security is limited since only a small percentage of arable land is utilized, despite the area's significant natural potential. Thus, the growth of irrigated agriculture seems to be a crucial tactic for raising food production and stimulating the economy.

The Danouna region, integrated into an ambitious project (PDRI-CL2) for the development of 07 irrigated areas in the Hadjer Lamis province totaling 350 hectares, including 20 hectares for the village of Danouna, occupies a strategic place in rice production in Chad. Although the Danouna irrigation scheme benefits from a significant water supply from the Chari-Logone River with an average flow estimated at 1.05 m^3/s, the current system remains characterized by significant technical inefficiencies(R. D. U. Tchad et al., 2022). The use of traditional irrigation techniques, particularly without adequate lining of secondary canals, leads to significant water losses through infiltration of up to 20 to 40%, which results in poor management of water resources that can be used to irrigate more hectares and increase the rice yield in the region.

For example, Lake Chad, which is mainly fed by this river, has lost more than 90% of its volume since the 1960s(Olowoyeye & Kanwar, 2023), illustrating the impact of prolonged droughts and unpredictable floods. These fluctuations compromise the average flow required for irrigated areas and threaten the sustainability of water supply, thus affecting the ability of the agricultural sector to achieve its productivity and food security objectives. Given these challenges, it appears essential to conduct a thorough assessment of the existing irrigation system in Danouna in order to identify sources of inefficiency and propose appropriate optimization strategies. The objective of this research is to formulate technical and organizational solutions aimed at reducing water losses, improving agricultural yields and promoting sustainable water resource management.

1.3. Justification of the study

Optimizing irrigation systems is crucial to improve agricultural productivity and ensure food security, particularly in Sahelian regions such as Chad. According to the World Bank and Food and Agriculture Organization (FAO), irrigated agriculture, although representing only 20% of cultivated land, contributes to 40% of global food production, highlighting its strategic importance. In Chad, traditional irrigation systems often have inefficiencies, such as significant water losses due to unlined canals and outdated techniques. These limitations hamper efforts to increase agricultural production and improve food security.

The evaluation and improvement of irrigation systems, like the one in Danouna Irrigation Scheme, are crucial in this regard. It is feasible to lower water losses, raise agricultural yields, and support sustainable water resource management by locating inefficient practices and suggesting modified solutions. In addition to helping the agricultural sector become more resilient to climate problems, this strategy will also aid in Chad's socioeconomic development.

Chad is particularly vulnerable to climate change, with projections indicating increasing temperatures and aridity throughout the 21st century, leading to less productive agriculture and more damaging livestock grazing practices. Approximately 80% of the population depends on subsistence farming and livestock for their livelihoods, and 42% live below the national poverty line [1]. The country is experiencing a significant food security crisis, with 3.4 million people acutely food insecure due to the worst lean season ever recorded, marking a staggering 240% increase since 2020. High food prices, below-average market supplies, and the impact of climate shocks have contributed to worsening hunger and poverty [2].

Climate change has worsened food security and intensified inter-communal conflicts over scarce natural resources. Volatile rainfall and severe floods in recent years have disrupted agricultural production, pushing food insecurity from 2.1 million people in 2022 to an unprecedented 3.8 million in 2024[3]. Given these challenges, optimizing irrigation systems like the Danouna Irrigation Scheme is essential to enhance water efficiency, boost agricultural productivity, and strengthen resilience against climate-induced food insecurity.

1.4. Research Questions and Working Hypothesis

1.4.1. Questions

- What are the main inefficiencies and challenges of the existing irrigation system at the Danouna Irrigation Scheme?
- How does the current system impact water conservation and agricultural productivity in Danouna region?
- Which optimization solutions can be implemented within the existing framework to enhance water efficiency and increase crop yields?
- What socio-economic and environmental benefits can be expected from optimizing the current irrigation system at the Danouna Irrigation Scheme?

1.4.2. Hypothesis

- H1: The existing irrigation system at the Danouna Irrigation Scheme exhibits significant inefficiencies, leading to considerable water losses and suboptimal agricultural yields.
- H2: Implementing targeted optimization solutions within the current system will effectively reduce water losses and improve crop productivity.
- H3: The optimization of the existing irrigation system will yield notable socio-economic and environmental benefits, thereby enhancing food security and promoting sustainable water resource management in the face of climate variability.

Conclusion

In Chad, farmers often face financial and technological challenges that hamper the efficient management of water resources. This research focuses on evaluating and improving irrigation methods used in the Danouna irrigation scheme to minimize water losses and increase agricultural productivity. The study aims to identify existing weaknesses and recommend customized strategies for better water management. The adoption of these optimized practices is expected to improve water use efficiency, increase crop yields, and contribute to the sustainable livelihoods of local farmers in the region.

CHAPTER TWO

2. LITTERATURE REVIEW

2.1 Introduction

A thorough analysis of the literature that establishes the theoretical and empirical framework for assessing and improving irrigation methods is provided in this chapter. It goes over important ideas, the value of irrigation in arid climates, and the standards for evaluating the sustainability and effectiveness of water management techniques. In addition, it critically analyzes contemporary and conventional irrigation techniques, stressing their advantages and disadvantages in relation to agricultural output and water conservation. The chapter als examines a number of methods and tools for assessing irrigation performance, including efficiency and sustainability indicators and modeling approaches. It also discusses the variety of elements that affect irrigation efficiency, from soil and climate to hydrological and socioeconomic limitations. This synthesis not only identifies existing research gaps but also provides the necessary background for developing targeted optimization strategies for the Danouna Irrigation Scheme in Chad.

2.2 Fundamentals of Irrigation

2.2.1 Definitions and key concepts

Irrigation is the process of supplying water to crops through artificial means, primarily to address water scarcity in semi-arid and sub-humid regions and to promote optimal plant growth in arid areas(Area et al., 2021). Unlike irrigation, traditional rainfed agriculture is highly unpredictable due to uneven rainfall distribution and the limited water-holding capacity of certain soils, even in regions with seemingly adequate seasonal precipitation. By providing a more reliable water source, irrigation ensures stable food production and reduces the risks associated with dependence on rainfall(Okuku, 2016). Irrigation is the artificial application of water to soil or land to assist in the growth of crops, maintenance of landscapes, and re-vegetation of disturbed soils in dry areas and during periods of inadequate rainfall. The key concepts of irrigation are based on the optimization of the application calendar to meet the specific needs of crops, improving the effectiveness of water use and taking into account water demand variations between different crops. For example, rice needs more water than wheat - and its effectiveness is improved by good planning and the contribution of alternative water sources such as precipitation and capillary rise(R. D. U. Tchad et al., 2022). Around the world, irrigation has substantially raised the amount of arable land and food production. Coordinating water delivery with crop water needs while reducing adverse effects such soil erosion, salinization, and declining water quality is the main goal of irrigation management(Use et al., 2001). Even though irrigation system management and design must be customized for particular physical and socioeconomic circumstances, the fundamental ideas of water efficiency, application timing, and geographical distribution are universally applicable(African Climate Policy Centre, 2011). Thus, in addition to improving crop growth and productivity, an efficient irrigation plan is essential for maintaining soil health and encouraging ecologically friendly farming methods.

2.2.2 Importance of irrigation in arid areas

Food insecurity and import dependency grew as a result of Africa's population growth rate of over 3% annually, which is far greater than the global average of 1.2%, and food production that has not kept pace with this rate. The IWMI estimates that in order to sustain productivity and lower poverty, irrigated land would need to be increased by 29% by 2025. In order to ensure food security, irrigation system development is crucial and at the top of the African political agenda(Agricole, 2020). In arid and semi-arid areas, irrigation is essential to compensate for the scarcity and degradation of water quality, thus supporting agricultural production and ensuring the sustainability of production systems despite maintenance challenges and substantial investments, as demonstrated by the evolution of irrigated perimeters in Morocco(Une et al., 2005). Irrigation is crucial for sustainable agricultural production in arid regions because of the ongoing water shortage. These areas rely primarily on irrigation, which often accounts for over 90% of water withdrawals, to sustain crop productivity and economic stability despite having few renewable water resources and only a small share of global precipitation. Since efficient irrigation methods not only help bridge the gap between agricultural demands and the limited natural water supplies, but they also goodly boost crop yields and land productivity, they are crucial for preserving food security and promoting growth in water-stressed areas(State et al., 2001). In arid areas, irrigation is essential because it provides a steady supply of water for farming, improves food security, and permits sustainable crop production in spite of irregular and infrequent rainfall. The ultimate objective is to attain a high-quality harvest and high productivity, regardless of the irrigation method employed. Prudent irrigation techniques and well-designed and implemented networks are essential to achieving this. It's common to overlook maintenance tasks that keep the network's structures and infrastructure in good operating order. This has consistently resulted in decreased water distribution efficiency and decreased irrigation technique profits.

2.2.3 Concepts of efficiency and sustainability

Irrigation efficiency is a vital indicator of how effectively water is applied across agricultural areas from individual fields to entire watersheds. This measure is fundamental to understanding the benefits of irrigated agriculture, particularly its role in ensuring a reliable, high-quality food supply to meet the demands of a growing global population(Verma et al., 2023). In irrigation science, efficiency is an engineering concept that evaluates water use, system performance, and encourages more effective resource management in agriculture and landscaping. It is typically assessed by examining three interrelated aspects: the performance of the irrigation system, the uniformity of water application, and the crop's response to the water provided(Howell, 2015). Low irrigation efficiency negatively affects farmers by reducing the water available for crop growth, yet it is often viewed favorably by water and environmental managers especially in closed catchment areas—

since it preserves water within natural systems. This divergence creates a conflict of interest: efforts to increase irrigation efficiency, if not accompanied by proper regulation of water harvesting and consumption, may inadvertently limit the water that recharges aquifers, rivers, and lakes, thereby exacerbating environmental degradation(Eghbali et al., n.d.).

Irrigation sustainability refers to the prudent use of water resources to sustain agricultural output without endangering the environment. It highlights the necessity of updating and maintaining irrigation systems in a way that not only satisfies current agricultural and human demands but also protects the ecosystem for coming generations(Abernethy & Concept, 1994). Sustainable irrigation is the prudent use of water in a variety of applications, such as landscaping, agricultural, and ornamental techniques, while making sure that these applications do not harm the environment. This strategy aims to balance the need to promote economic growth and human development with the preservation of natural resources, such as biodiversity, within the larger framework of sustainable development.

2.3 Irrigation Techniques

2.3.1 Traditional techniques

Traditional irrigation techniques in Tchad have been developed over centuries and adjusted to the country's arid and semi-arid climate. These traditional methods, which rely on the use of basic structures and hand tools like the chadouf, enable the capture and distribution of water in a simple yet efficient manner to support local agriculture (*Lin D. A., & Durand,2020)*. Despite their limitations in terms of effectiveness and water conservation, they serve as evidence of a generation-to-generation transfer of knowledge that has enabled local communities to effectively address the region's hydrological challenges. This tradition serves as the historical and cultural foundation for the Tchad's adoption of more modern irrigation systems(*Profil de Pays – Tchad*, 2005). A widely used practice in the Saharans and Sahelians regions, traditional irrigation based on total water management is one of the main ways to secure agricultural production. This method primarily relies on the use of shallow water table, from which water is extracted using simple devices like chadoufs or tiny motor pumps. However, the surface covered by this irrigation method varies significantly from year to year depending on rainfall fluctuation. Although its precise size is difficult to determine, some studies estimate that this method is used to irrigate about 8,000 hectares annually, including in the prefectures of Ouaddaï, Biltine, Kanem, and Lac(Unies, 2005).

Traditional irrigation with partial water control, commonly known as flood recession farming, relies on a single supply of water from the seasonal flooding of rivers and low-lying areas(Bruckmann & Beltrando, 2014). This irrigation system is widely practiced throughout Chad, covering an annual area estimated at between 70,000 and 100,000 hectares in years of good rainfall(No, 2019a). However, this area fluctuates according to rainfall. Flood recession farming is particularly widespread in the prefectures of Mayo-Kebbi, Chari-Baguirmi, Ouaddaï, Salamat and Lac, where it is practised in spreading areas located on the banks of rivers such as the Logone and Barh Azoum, as well as in certain natural depressions capable of retaining water(Et et al., 2024). This method of irrigation, although uncertain, plays a crucial role in agricultural production and food security for rural populations.

A better flood recession Cropping is a type of agriculture that is primarily used in the Ouaddaï region. It is based on the use of dam basins constructed by non-governmental organizations like SWISSAID and AFRICARE(Outremer, 2014). Depending on the yield of rain-fed crops, this technique permits a second crop cycle following the rainy season. These troughs are rarely used during prosperous harvest seasons, but they are crucial to ensuring food security during lean production times. About 600 hectares are currently being exploited, but 18 new dams in the Guéra, Ouaddaï, and Biltine regions are expected to expand this area(Faso, 2022). Polders are a method of farming lake inlets, where land is cultivated as the water recedes through evaporation and infiltration. Traditional polders are used without prior development, while some farmers build sand dams to isolate cultivable areas. However, in times of water shortage, these dams sometimes have to be dismantled. Improved polders incorporate devices for better water management: some use PVC pipes to convey water from the lake, covering some 4,000 hectares, while others are equipped with regulation valves, enabling better control of irrigation over an area of 1,000 hectares(Olowoyeye & Kanwar, 2023).

2.1.1 Modern techniques

Modern irrigation only developed after the colonial era and really took off in the 1970s, in response to the great drought of 1973, even though traditional irrigation in Chad, which is based on the manual extraction of water using wells and chadouf, has been used for centuries in the Saharan and Sahelian zones(Agropolis & Mobutu, 2010). As a result, more structured approaches that were tailored to the expanding demands of the agriculture industry were introduced. The Chari-Logone valley, the area surrounding Lake Chad, the Kanem and Ouaddaï wadis, the Batha, Lake Fitri, and the BET palm groves are currently the primary modern irrigation zones. Except for 3,754 hectares of sprinkler-irrigated sugarcane and 18% of farms using groundwater, supervised schemes which make up 79% of schemes larger than 100 hectares primarily use surface irrigation. These developments highlight how strategically important contemporary irrigation is to raising agricultural output and ensuring Chad's water resources are managed sustainably(L. Tchad & Tchad, 2003). On the shores of the lake, a variety of agricultural systems coexist, among which the northern polders stand out. These polders, located in interdunal lowlands at the confluence of the Kanem region Erg and the lake region, use water control systems modulated according to flood and ebb cycles to support flood-recession activities, which dominate in terms of surface area and production(Relance et al., 2000). In this area, the Société de Développement du Lac (SODELAC) has identified around 3,000 hectares of “modern polders”, characterized by complete control of pump irrigation, although only just over half of this land is currently under cultivation due to problems of salinization and soil degradation in some unrehabilitated areas(Saturnin et al., 2019). In addition, some 8,600 hectares are classified as partially developed perimeters or “semi-modern polders”, part of which has recently been built or rehabilitated (2006-2008) using cement dykes equipped with sluice gates, thus regulating the filling and draining of the basin during flood periods(De et al., 2009).

Modern irrigation schemes are characterized by the integration of advanced technologies designed to optimize water use and increase agricultural productivity. The Bongor basins A and B and the Satégui Déréssia basin, covering some 6,600 hectares, use techniques adapted to rice growing. Village irrigation schemes, ranging in size from 10 to 50 hectares and totaling some 1,200 hectares, use technical solutions adapted to local contexts to irrigate rice and market garden crops(Adoum & Ascher, 1988). In addition, the expanding private schemes around N'Djamena, covering between 2,000 and 3,000 hectares, illustrate the gradual modernization of irrigation systems to ensure even water distribution and reduce water losses(Spéciaux & Alimentaire, 2009).

In August 2023, ACF, in collaboration with an international consultant, carried out a feasibility study in the Kanem, Bahr El Ghazal and Hadjer Lamis regions, revealing that the Californian irrigation system could only make efficient use of 40-60% of the water. In response, drip irrigation, which applies water directly to the roots and considerably reduces losses through evaporation and percolation, was identified as a promising solution(Oriental, 2023). This system is currently being implemented in several locations in Chad, offering the potential to optimize water resources for more sustainable agriculture.

2.1.1 Critical comparaison

Traditional irrigation techniques, such as the use of chadouf, the most widely used in Chad for the smallest perimeters, and surface irrigation in various forms such as basin irrigation, border irrigation and flood irrigation, or gully irrigation, are based on ancestral know-how adapted to local conditions. Although they have enabled farmers to cultivate in arid environments, they are characterized by notable inefficiency due to significant water losses through evaporation and infiltration, as well as uneven distribution of the resource. These methods, often manual and poorly mechanized, limit the ability to optimize water use, resulting in relatively low agricultural yields and increased vulnerability to climatic fluctuations.

By contrast, modern irrigation techniques incorporating pumping, drainage and drip irrigation systems offer more precise and efficient water management. For example, the Bol polders, the Bongor basins and the Satégui Déréssia basin, as well as the village and private irrigated perimeters around N'Djamena, including the Danouna irrigated perimeter which is the subject of our study, illustrate a progressive modernization that has significantly reduced water losses and improved water distribution on cultivated land. Despite higher initial costs and technical training requirements, these modern approaches are a strategic response to the challenges of water scarcity, and help to boost sustainability and agricultural productivity in Chad.

2.2 Model description

CROPWAT is a decision-support tool developed by the Land and Water Development Division of the Food and Agriculture Organization (FAO) to assist professionals involved in agricultural water management. It enables agronomists, irrigation specialists, and meteorologists to perform standardized computations related to crop evapotranspiration and water requirements across various climatic and agronomic conditions(Debauche et al., 2012). Beyond its analytical capabilities, CROPWAT is widely applied in the planning, optimization, and management of irrigation systems, allowing users to simulate irrigation schedules under diverse water availability scenarios, assess crop water needs, and evaluate potential yield outcomes under both rainfed and deficit irrigation conditions(Diro & Tilahun, 2009).

2.2.1 CROPWAT Input

To estimate both crop water requirements (CWR) and irrigation needs, the CROPWAT model requires a set of input parameters related to climate, soil, and crop characteristics. The computation of the reference evapotranspiration (ETo) is based on the Penman-Monteith equation, which incorporates climatic variables such as maximum and minimum air temperature, relative humidity, wind speed, sunshine duration, and rainfall(Sciences, 2019). In addition to climatic data, a detailed cropping calendar is provided, including planting and harvesting dates, as well as specific crop parameters such as crop coefficients (Kc), growth stage durations, rooting depth, and allowable depletion fraction. These agronomic parameters allow the model to simulate the actual water needs of the crop over its development cycle. Furthermore, accurate irrigation scheduling requires soil-related inputs, including soil type, total available water (TAW), maximum rooting depth, and the level of initial soil moisture depletion, which collectively influence the calculation of irrigation frequency and depth(Clarke, 1998).

2.1.1 CROPWAT Output

Once all necessary input parameters are provided, CROPWAT processes the data and generates results automatically. These outputs are displayed in both tabular and graphical formats and can be disaggregated by day, decade, or month, depending on the desired resolution of analysis(Report, n.d.). For each crop simulated, the software delivers a comprehensive set of indicators, including reference evapotranspiration, average crop coefficient per growth stage, actual evapotranspiration, effective rainfall, readily available and total available soil moisture, as well as detailed crop water and irrigation requirements(I. Manual, 2002). Additionally, CROPWAT estimates the daily soil moisture deficit, applied irrigation depth, recommended irrigation intervals, and potential irrigation losses(Clarke, 1998). It also provides performance indicators such as the ratio of actual to potential evapotranspiration and the projected yield reduction due to water stress when actual evapotranspiration falls below optimum levels.

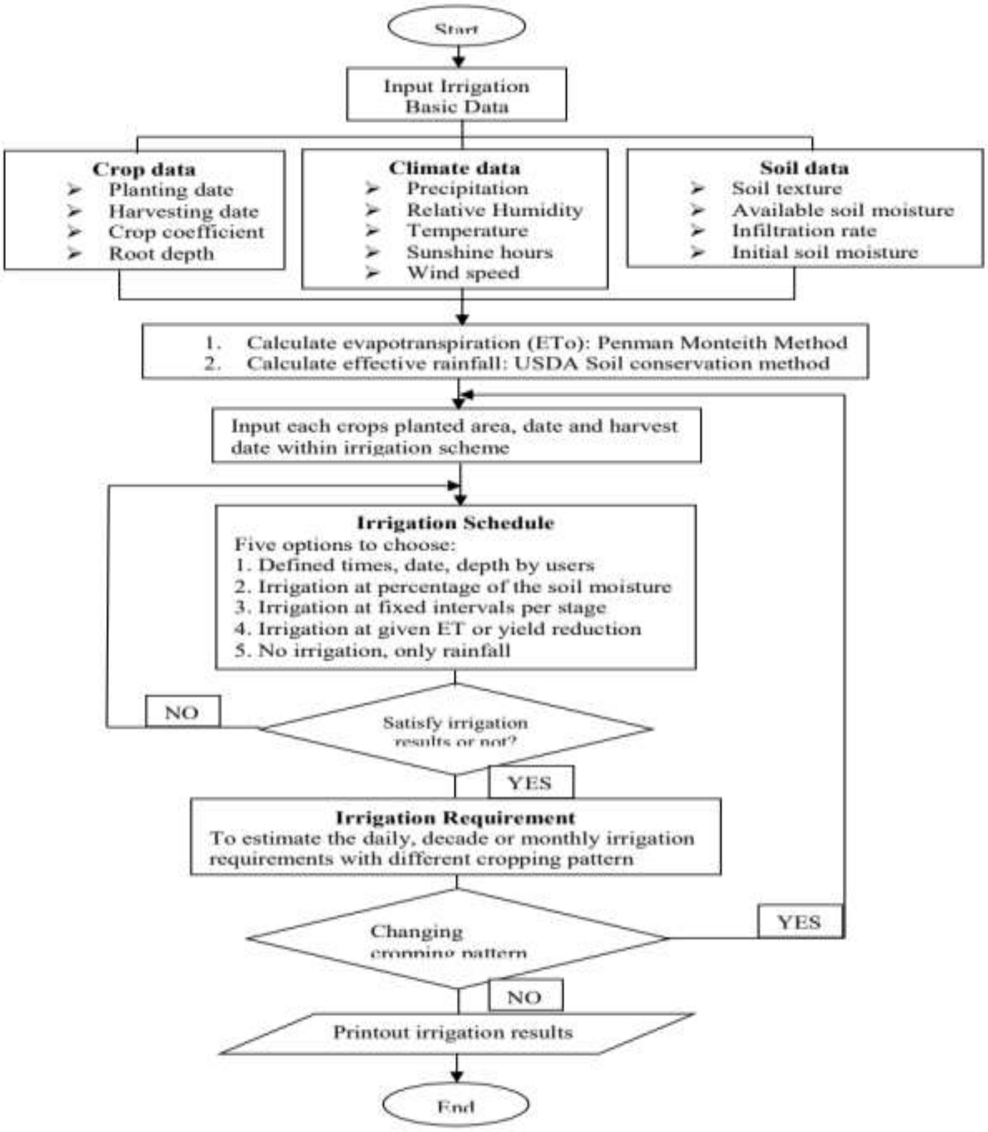


Figure 2.1: Schematic diagram of CROPWAT (Okuku, 2016)

2.2 Optimization Strategies

2.2.1 Identification of sources of losses

The main causes of irrigation losses, which are impacted by system operation and design, are evaporation, runoff, and deep percolation and infiltration. Lack of runoff control in surface irrigation causes large losses, but solutions like wave irrigation or collection pits can increase effectiveness. But excessive infiltration is still a problem. Evaporation, especially from the ground prior to vegetation cover, lowers sprinkler irrigation efficiency(Tagwi, 2018). To reduce these losses and enhance water use, optimization calls for improved system architecture and suitable procedures. Because of imprecise simplifications in the design and operation of the systems, it is difficult to identify operational losses in irrigation channels. These losses, which vary depending on the type of irrigation system and water availability, can be evaluated through an analysis based on hydraulic simulation and water demand modeling, frequently reaching levels above official recommendations(Abdirashid, 2018).

2.2.2 Modernization of infrastructures

In water-scarce areas, modernizing irrigation infrastructure has emerged as a key tactic for increasing agricultural water use efficiency and guaranteeing sustainable crop production. The needs of modern agriculture and the stresses of growing climate variability are no longer met by traditional irrigation systems, which are frequently characterized by antiquated or badly maintained canals, uncontrolled water distribution, and substantial losses from seepage and evaporation(Gore, 2015). In order to improve water governance, maintenance, and participatory management, modernization entails both institutional reforms and technological advancements, such as installing drip or sprinkler systems, installing flow regulation devices, lining canals, and remotely controlling gates. Plusquellec (2009) asserts that in order to maximize delivery and minimize water losses, infrastructure modernization should incorporate data monitoring, automation, and real-time decision-making capabilities in addition to physical enhancements. The irrigation and flood control infrastructure in Lao PDR predominantly includes dams, weirs, reservoirs, canal networks, pumping stations, small-scale pumps, minor levee systems, sluices, and temporary barriers. The advancement of irrigation infrastructure plays a vital role in enhancing agricultural productivity and mitigating climate change impacts(*GUIDANCE FOR IMPROVING IRRIGATION SYSTEMS TO ADDRESS CLIMATE CHANGE*, 2022). In Morocco, an ambitious project of modernizing irrigation infrastructure, involves implementing advanced technical practices, and strengthening stakeholder capacities through GIS systems, irrigation monitoring, participatory groundwater management, and targeted agricultural advisory services, enhancing overall water and energy efficiency(Irrigation et al., 2016). Within the framework of subobjective A focused on irrigation systems modernization, the rehabilitation of water storage tanks and the widespread adoption of micro-irrigation techniques particularly drip irrigation has significantly contributed to improved water availability. This enhanced access to water has led to increased agricultural yields across several key crops, including rice (paddy), lentils, maize, and various horticultural products in India, in the state of Tamil Nadu(No, 2019b).

2.2.3 Integrated water management

Integrated Water Management (IWM) is a holistic approach that promotes the coordinated development and management of water, land, and related resources to maximize economic and social welfare without compromising the sustainability of vital ecosystems(R. Manual, 2005). Even if individual farmer actions like rainwater collection, soil conservation, and on-farm water storage are crucial for managing water resources, they are not enough to meet the increasing extremes of water plenty and scarcity. Collective action, intersectoral cooperation, and a robust governmental framework that explicitly acknowledges agricultural water use particularly for food production and cattle welfare as a fundamental and prioritized water demand are necessary for the effective and sustainable management of water resources(Fraiture et al., 2013). Urbanization and population growth have increased the demand for food, energy, and water, underscoring the pressing need for sustainable and integrated agricultural water management strategies that take cross-sectoral interdependencies and environmental constraints into account(Seminar, 2010). In order to guide sustainable agricultural water planning under future scenarios, the Okanagan Basin Water Supply and Demand Project in Canada combined basin-level water use analysis, stakeholder consultation, and climate change modeling. This project is a noteworthy example of integrated water management in agriculture(Streicher-porte et al., 2011).

2.3 Factors influencing irrigation

2.3.1 Soil factors

The effectiveness and efficiency of irrigation techniques are largely determined by the properties of the soil. Water retention and movement within the root zone are directly influenced by important soil characteristics such texture, structure, infiltration rate, water-holding capacity, and depth(Nemera, 2013). For example, clayey or loamy soils hold water for longer periods of time but may have slower penetration rates, while sandy soils need more frequent irrigation with smaller amounts because of their high permeability and limited water-holding capacity. The presence of compacted layers or poor drainage can also lead to waterlogging, adversely affecting root development and crop productivity(Masya, 2016). Understanding and adapting irrigation methods to specific soil conditions is essential for achieving optimal water use and enhancing crop performance(North et al., 2022).

2.3.2 Climatic factors

A key factor in crop development and irrigation planning is climate. For optimum growth and productivity, each crop species has unique climatic needs. Reduced yields may result from plant development being hindered when environmental conditions drastically diverge from these thresholds, especially with regard to temperature, humidity, and light intensity(Döll, 2002). Important environmental factors that affect plant physiology as well as the design and selection of suitable irrigation systems include maximum and minimum temperatures, solar radiation, relative humidity, crop evapotranspiration, and day length(Hargreaves et al., 2013). For irrigation schemes to be planned, implemented, and managed effectively, a comprehensive understanding of the local climate is necessary.

2.3.3 hydrological Factors

When it comes to irrigation system planning, design, and management, hydrological considerations are fundamental. These elements include the accessibility, dispersion, and dependability of water resources such lakes, rivers, aquifers, and precipitation. The viability and sustainability of irrigation projects are determined by the seasonal fluctuation of precipitation, surface runoff, groundwater recharge rates, and water body flow regimes(Momenpour et al., 2021). Important factors also include the quality of the water sources (such as salinity levels and pollution hazards) and their proximity to cropland. Assessing water balance, calculating irrigation potential, and making sure that water withdrawal stays within socially and environmentally acceptable bounds all depend on an understanding of these factors(Li et al., 2016). Therefore, thorough hydrological analysis is essential to effective irrigation development in order to guarantee resource sustainability and system resilience.

2.3.4 Socio-economic factors

Irrigation system adoption, operation, and sustainability are strongly influenced by socioeconomic conditions. These include the ability of farmers to make ends meet, the availability of labor, the security of land tenure, the availability of financing and subsidies, and the degree of technical expertise and education in farming communities(Kipngetich et al., 2021). Modern irrigation techniques can be difficult to apply in many developing locations due to a lack of institutional support and resources, which forces people to rely on less effective, older methods. Market access, crop profitability, and input costs also determine farmers' willingness to invest in irrigation infrastructure(Muthui, 2015). Social dynamics such as community organization, gender roles, and cultural practices affect water management practices and collective decision-making in irrigation schemes. Integrating socio-economic considerations is vital for designing irrigation systems that are both effective and equitable.

2.3.5 Environmental factors

When designing and developing an irrigation system, a number of environmental conditions need to be taken into account. These include methane emissions from agricultural lands, drainage discharge, siltation, sedimentation, waterlogging, downstream water supply reduction or elimination, disturbance of natural ecosystems, and biodiversity consequences. Reducing the amount and quality of water accessible to downstream users can result from altering a river's natural flow to facilitate agriculture(Stockle, 1996).

2.3.6 Institutional factors

Planning, implementing, and maintaining irrigation systems all depend heavily on institutional factors. These include land tenure systems, legal frameworks, farmer organizations like Water User Associations (WUAs), and the existence and efficacy of water management authority. Proper water distribution, infrastructure upkeep, dispute settlement, and irrigation schedule enforcement are all made possible by strong institutional backing(Stewardship et al., 2019). On the other hand, poor institutional frameworks may result in poor administration, uneven water distribution, and deteriorating infrastructure. In fact, in the majority of developing nations, the institutions would have an important part in determining whether irrigation performance could be improved further and whether it could continue to contribute to the advancement and accomplishment of societal objectives(Anderies, 2024). Despite sharing many similarities with other emerging nations, Pakistan's irrigation industry appears to have certain unique institutional features.

2.4 Impact on agricultural productivity

2.4.1 Relationship between irrigation and yield

Understanding the connection between crop production and irrigation is essential to comprehending agricultural productivity, especially in areas where rainfall is insufficient to supply crop water needs. Particularly in dry and semi-arid regions, the most significant constraint on plant development and productivity is frequently the availability of water(Golla, 2021). Optimizing the use of water in agriculture has become a top priority due to the growing demand for food worldwide, competition for scarce water supplies, and the impending effects of climate change.

Numerous studies have shown that the amount of water applied through irrigation and when it is applied are directly related to crop output. In addition to increasing productivity, properly managed irrigation also enhances crop quality. On the other hand, overwatering or unplanned irrigation can cause the soil to become saturated, cause vital nutrients to drain out, and reduce production. Conversely, inadequate irrigation can result in water stress, which inhibits plant development and reduces total agricultural productivity(Lakhiar et al., 2024).

In its Irrigation and Drainage Paper No. 33 (Doorenbos and Kassam, 1979), the Food and Agriculture Organization (FAO) presented a straightforward yet extensively used technique for calculating the impact of water scarcity on yield(Agric, 2016). A crop-specific yield response factor (Ky), which measures the proportionate yield loss in response to a proportionate decrease in evapotranspiration (ET), is used in this method. This relationship is a useful tool for irrigation planning and management since it makes it possible to estimate yield under various irrigation situations(Reddy & Nayak, 2018).

The Aquacrop model, created more recently by FAO, offers a more accurate and dynamic simulation of how crop yields react to water availability. Aquacrop incorporates crop physiological reactions to water stress while accounting for soil, climate, and management variables(*The AquaCrop Model : Enhancing Crop Water Productivity The AquaCrop Model : Enhancing Crop Water Productivity*, 2019). It is particularly well-suited for assessing water production and developing effective irrigation plans in the face of climatic variability and water scarcity.

2.4.2 Comparative case studies

Comparative case studies across different regions consistently demonstrate a strong relationship between irrigation practices and crop yield performance. Morocco, for instance, has greatly increased the efficiency of water use through the modernization of irrigation infrastructure under national agricultural strategy. Crop yields and water savings were raised by implementing localized irrigation techniques like drip irrigation and strengthening institutional capacity within water user associations(Assouli et al., 2018). By encouraging higher-value crops and lowering energy and water usage, these initiatives produced two benefits.

The International Food Policy Research Institute (IFPRI) found that the use of sophisticated irrigation methods, such as treadle pumps and small reservoirs, greatly increased agricultural output. When compared to traditional rainfed farming, farmers who included these technologies into their irrigation operations saw yield increases of up to 80% for maize and rice(Wiggins & Lankford, 2019). This improvement emphasizes how important effective irrigation water management is to maximizing agricultural yield and guaranteeing food security, especially in areas where rainfall is unpredictable and water is scarce.

Especially in arid and semi-arid areas, effective irrigation scheduling is essential for increasing crop yields and water usage efficiency. under Western Liaoning, China, a study on peanut production under water-scarce conditions showed that moderate irrigation regimes, as opposed to excessive watering, produced the best yields. According to the results, providing a moderate amount of water guarantees enough soil hydration without causing needless losses or unfavorable soil conditions. The study did, however, also draw attention to the ongoing difficulty of striking the ideal balance between yield maximization and water application(Zhao et al., 2025). Crop performance was still heavily reliant on particular irrigation management techniques even though there was an increase in output.

2.5 Formulas and calculation models

2.5.1 Calculation of Reference evapotranspiration (ETo)

The amount of water required by a hypothetical crop surface with constant green cover, like grass or alfalfa, is known as reference evapotranspiration. Alfalfa's aerodynamic qualities, which are similar to those of many other crops, make it a popular choice for the standard reference crop(Allen et al., 1998). Applying a crop coefficient that accounts for the particular crop type and growth stage yields actual crop water use, which is typically less than the reference number. A commonly used method for estimating crop water requirements is reference evapotranspiration estimation, which is essential for creating efficient irrigation schedules.

The FAO Penman-Monteith method, widely recognized for its accuracy, calculates reference evapotranspiration based on key climatic variables such as solar radiation, temperature, vapor pressure, and wind speed, making it the standard approach for assessing water needs of a grass reference crop(Zotarelli et al., 2013).

The combination equation, which is displayed below, is the source of the Penman-Monteith equation:

$$\mathbf{ET_0} = \frac{0.408\Delta(Rn-G)+\gamma\frac{900}{T+273}u2\ (es-ea)}{\Delta+\gamma(1+0.34u2)} \qquad \mathbf{(2.1)}$$

Where;

$\mathbf{ET_o}$ reference evapotranspiration [mm day^{-1}],

$\mathbf{R_n}$ net radiation at the crop surface [MJ m^{-2} day^{-1}],

G soil heat flux density [MJ m^{-2} day^{-1}],

T mean daily air temperature at 2 m height [°C],

$\mathbf{u_2}$ wind speed at 2 m height [m s^{-1}],

$\mathbf{e_s}$ saturation vapour pressure [kPa],

$\mathbf{e_a}$ actual vapour pressure [kPa],

(e_s - e_a) saturation vapour pressure deficit [kPa],
Δ slope vapour pressure curve [kPa $°C^{-1}$],
γ psychrometric constant [kPa $°C^{-1}$].

The Penman Monteith equation is combined with various equations where each equation has an expression of some factors that are used to determine reference evapotranspiration.

2.5.2 Calculation of actual evapotranspiration

As can be seen below, reference evapotranspiration is first computed using geographic and meteorological data, and then the actual evapotranspiration, etc., for various crops is computed by multiplying reference evapotranspiration by crop coefficient Kc(Asce et al., 2002).

$$ETc = Eto \times Kc \qquad (2.2)$$

Where;

ETc – Actual evapotranspiration [mm]

ETo – reference evapotranspiration [mm]

Kc – crop coefficient (Varies with different growth stage)

2.5.3 Determination of the crop coefficient (Kc)

The crop coefficient (Kc) is a factor used to adjust the reference evapotranspiration (ETo) to reflect the actual water needs of a specific crop based on its type and growth stage. The growing season is divided into four stages: initial, development, mid-season, and late season each with a corresponding Kc value that varies according to climate, crop characteristics, and planting date(Abebe et al., 2021). This allows accurate estimation of actual evapotranspiration (ETc) throughout the crop cycle.

The FAO (1998) provides the crop coefficient values for the climates that are suitable for a certain location. In a sub-humid climate with an average daytime minimum relative humidity of 45% and calm to moderate wind speeds of an average of 2 m/s, the estimated average Kc value is determined by the local climate. The Kc needs to be adjusted when the normal climate has a relative humidity of at least 45% or a wind speed of at least 2 m/s(Allen et al., 1998).

The crop coefficient curve, which is divided into four major stages initial, development, mid-season, and late season is a tool used to determine the Kc values during the course of the growing season. Crop traits and climatic conditions determine the duration of each of these stages as well as the associated Kc values. Specifically, a soil surface wetting factor (fw), which takes into consideration the percentage of the surface that is wetted by irrigation or rainfall, is applied to modify the Kc for the first stage(*I Nternational J Ournal* *of Agriculture and Biosciences*, 2020). Over time, this method guarantees a more accurate estimation of crop water requirements. In the case of basin irrigation, the fraction of soil surface wetted (fw) is typically taken as 1.0, reflecting the fact that this method uniformly saturates the entire soil surface, as supported by standard values provided by Allen et al. (1998).

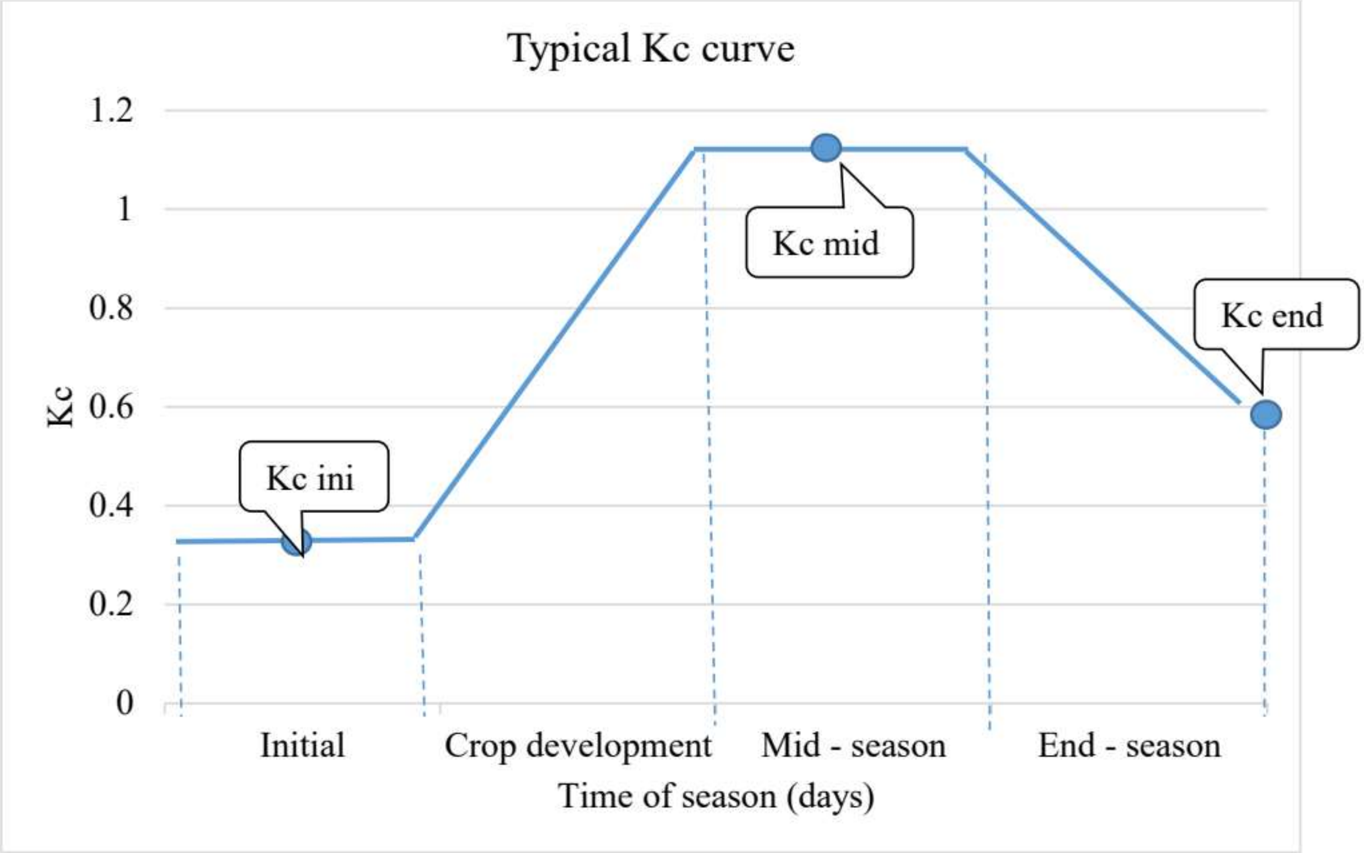


Figure 2.2: An example of Kc curve showing Kc ini, Kc mid and Kc end (Allen et al., 1998)

2.5.4 Crop water requirement

FAO (1996) states that some crop factors, such as the crop coefficient (Kc), root zone depth, permissible depletion fraction, and the length of each development stage, are used to estimate crop water requirements. The crop species has a substantial impact on these requirements. A number of factors, including the crop's growth stage, biological makeup, and meteorological circumstances, affect how much water a plant uses. Water demand is often low during the early growing stage. However, it steadily rises and peaks around the time of flowering before falling once more as the crop achieves maturity.

The crop water requirement can be calculated from the equations (2.3) shown below:

$$CWR = IR + Peff \qquad (2.1)$$

Where;

CWR – crop water requirement mm

IR – irrigation requirement, mm

Peff – effective precipitation, mm

2.6 Critical Synthesis and Gaps of the Literature Review

Irrigation systems are complex systems that include technical, agronomic, environmental, and socioeconomic aspects, as the literature reviewed in this chapter has demonstrated. Although both contemporary and traditional methods have been extensively studied, the necessity of context-specific strategies that take local water availability, soil types, and climate variability into account is frequently emphasized. Additionally, it is well known that integrating modeling tools such as CROPWAT and Aquacrop is useful for estimating water requirements and planning irrigation schedules. However, their use frequently makes assumptions about ideal input conditions that may not accurately reflect field realities, particularly in Sub-Saharan Africa.

There are still a number of unanswered questions regarding crop-water relationships and irrigation efficiency. Notably, in semi-arid areas like Chad, there is a dearth of field-based assessments of water losses in small-scale irrigation systems. Accurate estimates of the water balance are frequently hampered by the lack of trustworthy, up-to-date data on soil moisture, infiltration, and actual evapotranspiration. Moreover, it is uncommon to quantify the relationship between irrigation performance and yield outcomes in a way that enables useful suggestions. These discrepancies highlight the necessity of doing local research, like the current study on the Danouna irrigation scheme, in order to close the gap between theory and practice and to promote evidence-based decision-making for sustainable agriculture and water management.

2.7 Conclusion

The fundamental theoretical and practical understanding of irrigation systems, including both conventional and contemporary methods as well as performance assessment instruments like CROPWAT, has been compiled in this chapter. In addition to examining worldwide optimization techniques including infrastructure modernization and integrated water resource management, it highlighted the impact of environmental, technological, and socioeconomic aspects on irrigation efficiency and agricultural production. Despite the fact that the literature provides insightful information, there are still significant gaps, especially with regard to the accuracy of localized data and the practicality of simulation models

CHAPTER 3:

3. MATERIALS AND METHODS

3.1 Study Area

3.1.1 Location

The Danouna irrigation scheme is located in the Hadjer Lamis region of Chad, approximately 60 km north of N'Djamena. It is located precisely at coordinates 12°32'45.1" N and 14°51'21.6" E, corresponding to a latitude of approximately 12.53° and a longitude of 14.85°. The area is located at an altitude of 290 meters above sea level, in a region characterized by a semi-arid climate.

This strategic location, in a region where water scarcity requires rigorous management of water resources, gives the Danouna irrigation scheme particular importance for local agricultural development. Fed by the Chari-Logone River, this system plays a key role in the water supply for rice growing and constitutes a model for the optimization of irrigation techniques, aimed at reducing water losses and improving productivity in a context of increased climate variability.

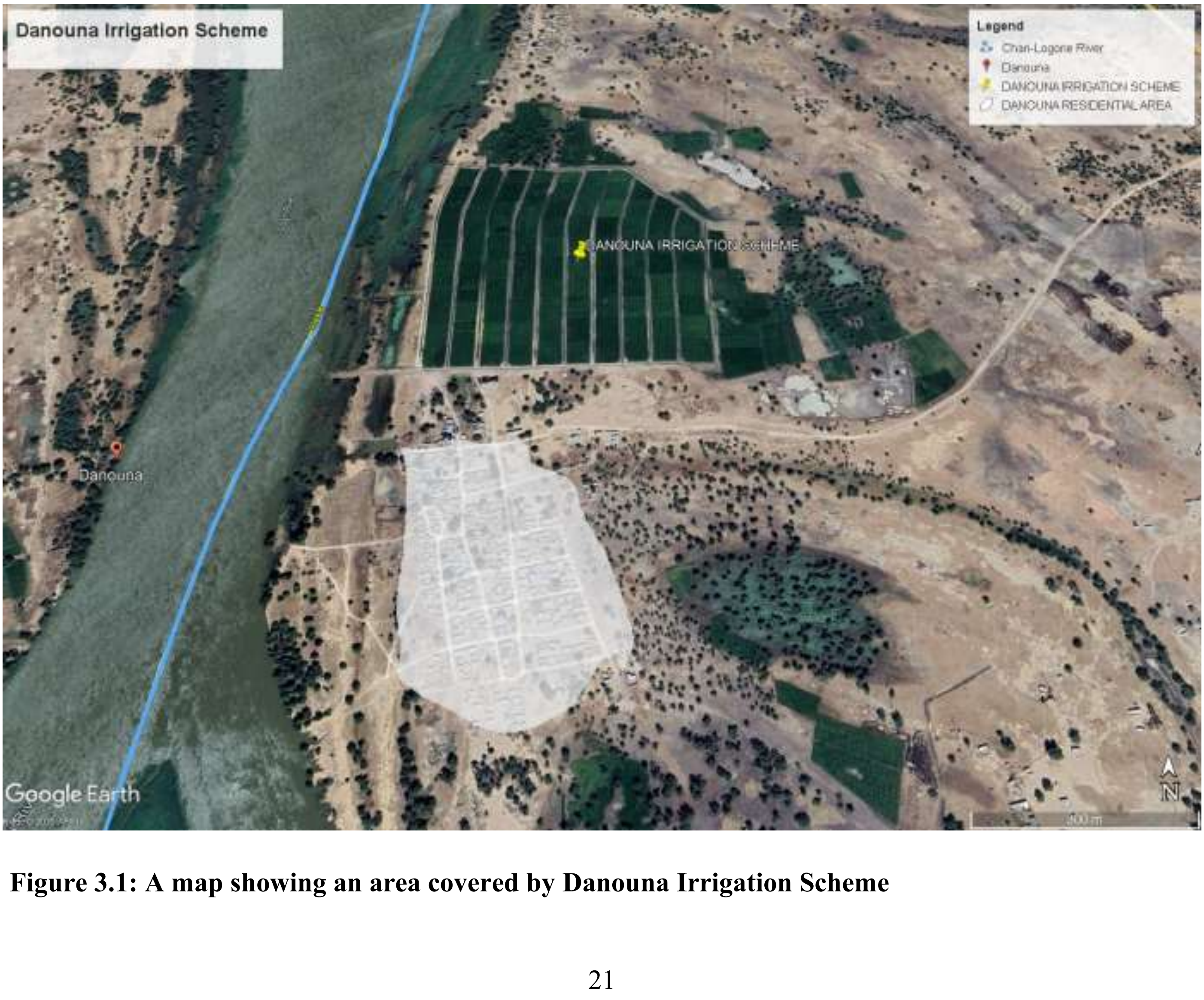


Figure 3.1: A map showing an area covered by Danouna Irrigation Scheme

3.1.2 History of establishment

The Danouna irrigation scheme is part of the PDRI-CL2 project, initiated by the Chadian government and funded by BADEA, to address water scarcity and food insecurity. It aims to modernize irrigation infrastructure across seven sites in Hadjer Lamis and Mayo Kebbi-Est. The Danouna site itself spans 20 hectares and is one of seven schemes covering a total of 350 hectares, designed to ensure sustainable irrigated rice production using water from the Chari-Logone River.

Perimeter	**Region**	**Department**	**Area (ha)**	**Coordinates GPS**	
				N	E
Roukoune (1)	HadjerLamis	Haraze Al-Biar	40	12°33’36,7”	014°51’23,5”
Danouna (1)	**HadjerLamis**		**20**	**12°32'45,1"**	**14°51'21,6"**
Amlayali (1)	HadjerLamis		50	12°29’57,2”	014°51’34,2”
Zafaya (1)	HadjerLamis		30		
N’Djaména Farah (1)	HadjerLamis		130	12°23’23,2”	014°54’44,7”
Douguia (1)	HadjerLamis		30		
Golé (1)	Mayo Kebbi Est (Guelendeng)	Mayo Lemie	50	10°45'10,5"	15°55'51,8"

Table 3.1: Geographic Location and Area of the Irrigated Perimeters under the PDRI-CL2 Project

The Danouna perimeter is an alternative that was developed by the village union (Roukoun-Danouna) where the two communities jointly exploited the Roukoun perimeter which only offered one winter company per year. The off-season was therefore done on the Danouna perimeter which has a meander, which brings the water to a reasonable distance allowing farmers to have a cold and hot off-season in this perimeter (R. D. U. Tchad et al., 2022).The establishment of the Danouna Irrigation Perimeter addresses critical challenges posed by traditional irrigation practices that have historically limited agricultural productivity. By integrating a comprehensive network of irrigation and drainage systems, along with pumping stations, storage facilities, and enhanced drying areas including dedicated spaces for rice threshing the project exemplifies a modern approach to water management. This initiative aligns with national agricultural strategies such as the Plan Directeur Agricole (PDA) and the « Programme National de Sécurité Alimentaire (PNSA) », aimed at doubling or tripling production cycles to boost crop yields and reduce rural poverty. Ultimately, the Danouna perimeter stands as a model for transforming an underutilized hydro-agricultural potential into a sustainable, resilient, and productive system, crucial for meeting the growing food demands and addressing the impacts of climate variability in Chad.

3.1.3 Beneficiaries

The beneficiaries of the Danouna irrigation system can be classified into two main categories: direct beneficiaries and indirect beneficiaries. The direct beneficiaries are around 300 farming households, representing an estimated population of around 10,000 people who are actively engaged in rice cultivation in the 20-hectare irrigated perimeter. These households benefit directly from improved access to irrigation water, higher crop yields, increased incomes and a general strengthening of food security in the region.

Indirect beneficiaries are the surrounding communities of the Hadjer Lamis region, notably the villages of Roukoun, Mani, Douguia, Karal, etc. These communities' benefit from the economic spin-offs of the project. These communities' benefit from the economic spin-offs generated by the increased availability and marketing of agricultural produce from Danouna. The development of the irrigation system has stimulated local markets and contributed to rural employment through activities such as transport, trade and post-harvest processing. In this way, the project not only supports local livelihoods, but also strengthens regional food systems and contributes to poverty reduction through the expansion of irrigated agriculture.

3.1.4 Climate

The climate of Danouna, located in the Hadjer Lamis region, is characterized by a semi-arid Sahelian regime with a short rainy season and a long dry season. The rainy season, which generally extends from April to August, is characterized by monthly accumulations varying between approximately 50 and 170 mm with peaks in July and August and annual precipitation varying between 600 and 1200 mm, although recent trends show a decrease and an irregular distribution of rainfall(Notice et al., 2024). This concentrated distribution of precipitation, resulting from the interaction between the Harmattan and the tropical monsoon, leads to high water variability that directly impacts irrigation and agricultural production.

Temperatures in Danouna show a significant thermal amplitude: averages vary from 25 to 30 °C during the rainy season, while heat peaks exceeding 40 °C occur at the beginning of the dry season, and minimum temperatures drop to between 10 and 20 °C at the end of the dry period. Wind patterns, particularly sand-blowing winds observed from January to April and in December, increase evaporation and promote the formation of dunes, which reduces the arable land(Daboua & Et, 2024). These climatic characteristics impose major challenges for water management and highlight the need to optimize irrigation systems to ensure efficient use of water resources and ensure the sustainability of agriculture in the region.

3.1.5 Topography, Soil, and Vegetation

In the Hadjer Lamis region, the Danouna irrigation scheme displays a topography characteristic of the alluvial plains of the Chadian basin. With an average elevation of around 290 meters, the terrain is predominantly flat to gently undulating, which facilitates the even distribution of water throughout the fields. The area benefits from a well-organized water network, largely sustained by the tributaries of the Chari-Logone River, which, despite their fluctuating flow, supply most of the region's water(Cnar, 2013). Additionally, natural depressions and mild slopes support the formation of water retention basins, which are vital for effective irrigation control and flood management.

Pedological studies indicate that the region is predominantly characterized by alluvial soils, with textures ranging from silty to clayey, formed from Quaternary deposits. Although these soils effectively retain water, their low permeability and poor drainage necessitate technical interventions to prevent erosion and compaction(R. D. U. Tchad et al., 2022). Recent phenological assessments have allowed for the differentiation of two primary soil types, including flood basin soils that are particularly rich in black clay and exhibit persistent hydromorphic conditions. These soil properties affect irrigation efficiency, requiring specific management practices to optimize water distribution, mitigate salinization, and support both agricultural and pastoral activities in the region(Alimentaire et al., 2025).

The study area of the Danouna irrigation scheme features vegetation typical of Sahelian regions, dominated by shrub savannahs and herbaceous formations adapted to semi-arid climatic conditions. Predominant plant species include trees such as Acacia seyal and Balanites aegyptiaca, as well as herbaceous plants such as Cenchrus biflorus(Abdoulaye et al., n.d.). These plant formations play a crucial role in preventing soil erosion and maintaining local biodiversity(Oriental, 2023).

3.1.6 Water ressources

The Danouna irrigation scheme, one of the seven sites of the PDRICL2 project, is fed by the Chari-Logone River, whose water intake is minimal compared to its total capacity. For a total area of 350 hectares, the maximum requirement is estimated at 1.05 m^3/s, corresponding to a standard of 3 l/s/ha(R. D. U. Tchad et al., 2022). However, the water supply is subject to significant seasonal fluctuations: during the rainy season, water levels rise considerably, reaching up to 1 m in the major bed, while during low-water periods, depths can drop below 1.50 m in the minor bed(Krekeler & Seeber, 2013). These variations, combined with the exceptional floods recorded in wet years, illustrate the unstable nature of the Chari-Logone flow, which nevertheless remains the sole source of perennial supply for the perimeter.

The floodwaters of the Chari-Logone originate from heavily-watered regions of the Central African Republic, Sudan and other neighboring countries, guaranteeing the availability of large quantities of water throughout the year, despite notable fluctuations. The Danouna area is located in a Sahelo-Sudanese region where rainfall is abundant, although the quantities of water delivered are highly variable(Kertemar & Mesmin, 2014). These hydrological characteristics call for the implementation of specific technical devices to optimize water distribution and ensure efficient irrigation, notably by compensating for the long setbacks observed on certain perimeters.

3.1.7 Economic activities

Agriculture, fishing, and livestock farming are the primary sources of income in the Danouna village, which is located in the Hadjer Lamis region. These three industries account for around 57%, 25%, and 15% of household income, respectively, while trade only contributes a limited 3%(H. L. Tchad, 2025). All of the localities in the region engage with almost twenty markets, allowing for extensive trade, even though only three of the six locations of the PDRICL2 project have weekly markets. Food crops like rice, maize, and sorghum are the main focus of producers in Danouna. Market gardening and, occasionally, groundnuts and sesame are also grown, though their yields vary greatly. Due to these activities, households spend approximately 64% of their income on food, which highlights the critical role that irrigation plays in ensuring food security(Magrin et al., 2014).

3.1.8 Population

According to data from the 2009 general population and housing census, the Hadjer Lamis region had a population of 559,339, with an almost balanced gender distribution (50.1% female). In the department of Haraze Al-Biar, which includes the village of Danouna and its irrigated perimeter, the population stood at 155,038, and 49.3% of whom were women(*Chad_Resultats Globaux.Pdf*, n.d.). These figures reflect a moderate population density in a region where economic activities are mainly based on agriculture, fishing, livestock breeding and trade.

With over 20 communities, including Kotokos and Arabs, who represent the indigenous and majority groups, as well as other populations from the southern, central, eastern, western, and northern parts of the nation, the study area is also distinguished by its exceptional ethnic diversity(Nodjimadji, 1993). According to estimates, the average household size is six people, and the means of transportation differ depending on the level of resources. For the most impoverished households, walking is the primary mode of transportation, while for those with more resources, bicycles and motorcycles are the primary modes. The region's demographic stability is maintained by a dense socioeconomic calendar that directs activity toward traditional sectors and keeps local migration dynamics low(H. L. Tchad, 2025).

3.2 Evaluation of the existing irrigation system

We were first able to enumerate the different irrigation methods, pinpoint the primary causes of water loss, and examine the optimization practices used in similar situations by conducting a literature review. An important theoretical foundation for comprehending the problems with irrigation system efficiency is provided by this review of the literature, especially in arid regions where water management is vital. In the particular instance of the Danouna irrigation scheme, rice cultivation a crop that requires a lot of water input is the only use of a single total water control technique. By including these Danouna’s specific details in our analysis, we are better able to determine the system's optimization requirements in order to decrease water loss and boost agricultural output.

3.2.1 Primary data collection

- Primary data collection commenced with a field survey focused on the Danouna irrigated perimeter, including site observations and interactions with key stakeholders.
- Data collection was conducted through semi-structured interviews with local farmers to gather insights on the application of the total water control technique and challenges encountered in rice cultivation.
- The collected data included irrigation scheduling, cultivated crops, field size, challenges faced by farmers, farm management practices, local food security, water application, and water management techniques adopted by farmers.
- Volumetric measurements with a calibrated 10-liter bucket were regularly conducted to estimate water volumes delivered to individual plots and the whole system water use.

3.2.2 Secondary data collection

- Secondary data collection involved retrieving technical documents and design reports related to the Danouna irrigation scheme from national irrigation offices and the PDRICL2 Project.
- Relevant climatic and hydrological data, including temperature, rainfall, and humidity, solar radiation, etc., were obtained from national meteorological agency (ANAM).
- Additional data, such as rice yield statistics and documented farming practices in the region, were analyzed to provide a comprehensive understanding of irrigation efficiency and agricultural productivity.

3.3 Climatic, hydrological and agricultural data

The climatic, hydrological and agricultural data used in this study were collected over a **15-year** period (from 2005 to 2020) to ensure a representative analysis of local conditions and inter-annual variations. These data mainly include minimum and maximum temperatures, relative humidity, wind speed, solar radiation and precipitation. They were obtained from the local meteorological station in N'Djamena and from institutional databases, then processed and classified into monthly averages to facilitate their integration into the **CROPWAT software**. All the information was organized to ensure consistency in the analysis of irrigation water requirements and the efficiency of the water management system for the irrigated perimeter studied. The following tables show the processed and classified data, ready to be used in the water simulations.

Month	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Years**
Temp min moy (°C)	15.2	19.7	22.7	26.3	27.1	25.6	21.9	21.1	21.5	21.4	17.9	14.5	21.24

Temp max moy (°C)	33.1	34.6	40.4	42.1	41.1	37.4	35.8	34.9	35	34.6	33.7	32.8	36.3

Table 3.2: Average monthly temperatures from 2005 to 2020 (Source: ANAM)

Month	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Years**
Precip (mm)	0	0	0	1.4	17	50	162.6	202.1	94.3	18.9	16.5	0	562.8

Table 3.3: Average monthly rainfall from 2005 to 2020 (Source: ANAM)

Month	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
RH max (%)	40.9	33.5	28.7	39	56.9	75	81.1	86.9	93.2	79.2	43.8	43
RH min (%)	25.1	20	16.9	23.7	43	50.9	55.7	68.5	70	50.5	25.6	27.6
RH (%)	33	26.75	22.8	31.35	49.95	62.95	68.4	77.7	81.6	64.85	34.7	35.3

Table 3.4: Average monthly relative humidity from 2005 to 2020 (Source: ANAM)

Month	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
Sun (hr/day)	9.7	9.5	8.7	8.3	8.3	7.8	7	6.1	7.5	7.3	10.2	10.1

Table 3.5: Average daily sunshine values from 2005-2020 (Source: ANAM)

Month	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
Wind speed (km/day)	206	242	242	191	210	223	175	157	156	159	183	182

Table 3.6: Average wind speed values from 2005-2020 (Source: ANAM)

3.4 Volumetric Measurement of Water Input to DIS Plots

To accurately determine the volumes of water distributed to each plot within the Danouna irrigated perimeter, a direct volumetric approach was implemented. Given that the irrigation method used by farmers consists in siphoning water from the secondary canals to their respective plots, it was necessary to adopt an appropriate technique to measure these inputs accurately. We therefore used a calibrated container, in this case a 10-litre graduated bucket, and timed the time taken to fill it completely. To guarantee the reliability of the measurements, this operation was repeated several times on five different plots, representative of the entire irrigated perimeter. The average of the results obtained was then used to rigorously estimate the actual water flow allocated to each plot. This simple, straightforward and reliable methodology enables a realistic assessment of irrigation practices and provides a solid basis for subsequent system optimization to reduce water losses and improve agricultural productivity.

Figure 3.2: 20-litre graduated bucket

Figure 3.3: stopwatch

The flow rate (Q) in liters per second (L/s) is calculated by:

$$Q = \frac{\textit{Volume of water measured } (l)}{\textit{filling time measurement } (s)} \qquad (3.1)$$

the total volume (V) supplied to the plot during the entire irrigation period can be estimated by:

$$V(m^3) = Q \times \text{Total irrigation time (s)} \qquad (3.2)$$

3.5 Evaluation of rice Yield and water productivity at DIS

Assessing the performance of the Danouna irrigated perimeter relies, among two things, on measuring agricultural productivity (rice yield) and analyzing water use efficiency. These two components are intrinsically linked and make it possible to assess the technical relevance of the irrigation system used.

Primary and secondary sources were used to estimate the average agricultural yield, which is measured in tons per hectare (t/ha). Growers' information was gathered via focus groups, semi-structured interviews, and field surveys. Technical reports and monitoring and evaluation documents from the Projet de Développement des Périmètres Irrigués Chari-Logone Phase 2 (PDRI-CL2), which is in charge of overseeing the perimeter under study, were used to confirm and finish this information.

The amount of water actually applied was determined on the basis of observation and volumetric measurements of in situ irrigation practices. The total volume of water applied per hectare for a complete cycle was then determined.

To relate production performance to water inputs, the Water Productivity (WP) coefficient is used to evaluate the quantity of rice produced per unit volume of water consumed. It is expressed in kilograms per cubic meter (kg/m³) and calculated according to the following formula:

$$WP_{(\mathbf{kg/m^3})} = \frac{Y}{V} \qquad (3.3)$$

Where:

- Y is the average rice yield (kg/ha)

- V is the total volume of water applied for this yield (m³/ha)

According to the FAO 56 paper and several reference studies on irrigated rice growing, the indicative target value for WP is between 0.6 and 1.2 kg/m³, depending on agro-ecological conditions and the level of irrigation control. This method enables us to compare the water productivity level of the DIS with these standards, with a view to identifying possible optimization margins.

3.6 Development/calibration of the CROPWAT for irrigation water needs

The data collected in part 3.2 above was used in the development of the irrigation water needs as follows;

3.6.1 Determination of the reference evapotranspiration

The reference evapotranspiration Eto was calculated by the FAO Penman-Monteith method, using CROPWAT 8.0 developed by the FAO. We used meteorological data from the nearby N'Djamena weather station to estimate Eto. The Penman-Monteith equation integrated into the CROPWAT program is expressed as follows:

$$\mathbf{ET_0} = \frac{\mathbf{0.408\Delta(Rn-G)+\gamma\frac{900}{\mathit{T}+273}u2\ (es-ea)}}{\mathbf{\Delta+\gamma(1+0.34u2)}} \qquad \mathbf{(3.3)}$$

Where;

ET_0 reference evapotranspiration [mm day^{-1}],
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m^{-2} day^{-1}],
T mean daily air temperature at 2 m height [°C],
u_2 wind speed at 2 m height [m s^{-1}],
e_s saturation vapour pressure [kPa],
e_a actual vapour pressure [kPa],

(e_s - e_a) saturation vapour pressure deficit [kPa],
Δ slope vapour pressure curve [kPa °C^{-1}],
γ psychrometric constant [kPa °C^{-1}].

The reference evapotranspiration (ETo) is the only value that we determined using the meteorological data. Meteorological data used in the determination of Eto was latitude, longitude and altitude of the station, maximum and minimum relative humidity, wind speed, sunshine hours and maximum and minimum temperature. Eto was calculated for every decade then expressed in a month.

3.6.2 The effective rainfall

The effective rainfall was calculated by CROPWAT using the United States Department of Agriculture (USDA) soil conservation service method as shown.

$$PE=124.8P_{tot} \qquad (3.4)$$

$$\text{For } P_{tot} < 250 \text{ mm}$$

$$PE=125+0.1P_{tot} \qquad (3.5)$$

Where;

PE – effective rainfall, mm

$Ptot$ – total rainfall, mm

3.6.3 Crop data

As part of our study on the evaluation and optimization of irrigation techniques to reduce water losses and improve agricultural productivity in the Danouna irrigated perimeter in Chad, we collected data specific to rice cultivation. These data include crop coefficients (Kc) at different growth stages, as well as planting and harvesting dates. This information was obtained from the local management authorities of the Danouna irrigated perimeter, i.e., the PDRICL2 project and the Rural Engineering Directorate of the Ministry of Agriculture.

We focus exclusively on rice cultivation, given its predominance in this region and the fact that it is the only crop grown in our study area. The values of crop coefficients for the initial, intermediate, and final growth stages were adapted to local climatic conditions, based on available published data, notably the FAO report on crop water requirements. FAO 56 was used to determine the duration of each rice growth stage. This document provides indications of the duration of the different stages and the total growth period for specific climates and locations, as well as for a wide variety of crops.

Stage	Replanting and recovery	Trim	Montaison	Foraison-épiaison	Maturation
Durée	**30**	**20**	**30**	**40**	**30**
Kc	**1.20**	**1.05**	**1.1**	**1.20**	**1.05**

Table 3.7: Crop coefficients for rice (Source : FAO 56)

3.6.4 Soil parameters

Soil characteristics required for the determination of crop water requirement include; available water content, total available water, depth of the plant root zone, depletion volume and readily available water which was using the formulas below:

$$AWC = FC - WP \qquad (3.6)$$

$$TAW = AWC \times Rd \qquad (3.7)$$

$$RAW = p \times TAW \qquad (3.8)$$

Where:

TAW – total available water capacity within the plant root zone (mm)

AWC – available water capacity of the soil, (mm /m)

Rd – depth of the plant root zone, (m)

p – an average fraction of TAW that can be depleted from the root zone before water stress sets in.

The depth of the zone from which water uptake can occur, Rd, is calculated by assuming that maximum rooting depth coincides with the development of full canopy (Adeboye et al., 2009).

3.6.5 Crop evapotranspiration (ETc)

Eto obtained was multiplied by an empirical crop coefficient (Kc) to produce an estimate of crop evapotranspiration (ETc) as follows;

$$ETc = Kc \times Eto \qquad (3.9)$$

Where :

Etc - Crop evapotranspiration

Kc - Crop coefficient

Eto - Reference crop evapotranspiration.

3.7 Simulation of the irrigation water application using CROPWAT

Following the collection and organization of all necessary input data, the CROPWAT model was configured to reflect the specific conditions of the Danouna irrigation scheme. This calibration involved integrating climate parameters, crop characteristics, soils characteristics and local agronomic practices relevant to the study area. Once the model was fully parameterized, simulations were carried out to determine the crop water requirements (CWR). These requirements were derived by the model based on the combined influence of climatic factors, crop development stages, and field management conditions.

CLIMATE	SOIL	CROP	IRRIGATION
Rainfall	Kc	Type of soil	System type
Maximum Temperature	Rooting depth		
Minimum Temperature	Planting date	Field capacity	Efficiency
Wind speed	Harvesting date	Permanent wilting point	
Humidity	Length of each stage	Saturation capacity	
Sunshine hours	Critical depletion factor	Root depth	
	Infiltration rate		

Table 3.8: Summary of the CROPWAT Input Data

OUTPUT	
Reference crop evapotranspiration (mm/period)	Actual crop evapotranspiration (mm)
Average crop coefficient for each stage	Effective rainfall (mm/period)
Irrigation requirements (mm/period)	Readily available moisture (mm)
Daily soil moisture deficit (mm)	Total available moisture (mm)
ETc/ETm ratio (%)	Crop water requirements (mm/period)
Estimated yield reduction due to water stress	Irrigation depth applied (mm)
Irrigation interval (days)	Irrigation Losses (mm)

Table 3.9: summary of the CROPWAT output data

CHAPTER FOUR:

4. RESULTS AND ANALYSIS

4.1 Assessment of existing irrigation practice

The Danouna irrigation system, covering 20 hectares, uses basin irrigation with total water control for rice cultivation. Although this method guarantees efficient soil saturation, it can lead to considerable water losses if not properly managed. To assess its performance, water flow in a few selected representative plots was measured using a volumetric approach based on siphoning practices. These measurements provided essential information on the volumes of water actually applied, forming the basis for assessing irrigation efficiency and identifying opportunities for improvement or optimization. The results are presented in the table below:

Farmer	Inflows (l/sec)
Bachir Ahmat	3.2
Ali Adam	2.9
Younous Brahim	3.0
Mahamat Saleh	3.3
Average	3.1

Table 4.1: Inflows of water in the field

On average, each ¼ hectare plot (2500 m^2) receives a flow rate of 3.1 liters per second. Farmers typically irrigate their plots for 10 hours a day every 3 days. The total volume of water applied per plot is therefore calculated as follows:

V=3.1 L/s×10 hours×3600 s/hour=111,600 liters=111.6 m^3

V= 111.6m^3

Depth of water applied per irrigation per plot

$Deph = \frac{111.6m^3}{2500m^2}$= =0.04464 m

Depth =44.64 mm

Number of irrigations during the rice growth cycle

- Rice growth period : 150 days
- Irrigation every 3 days :

$Number\ of\ irrigations \frac{150\ days}{3}$= 50 irrigations

Total water volume applied per plot over the season:

$111.6\ m^3 \times 50 = 5\ 580\ m^3$

Water volume applied for the whole scheme:

The whole scheme is a total of 80 plots of 2500 m2 each

$V_{total} = 5\ 580\ m^3 \times 80 = 446{,}400\ m^3$

$\mathbf{V_{total} = 446{,}400\ m^3}$

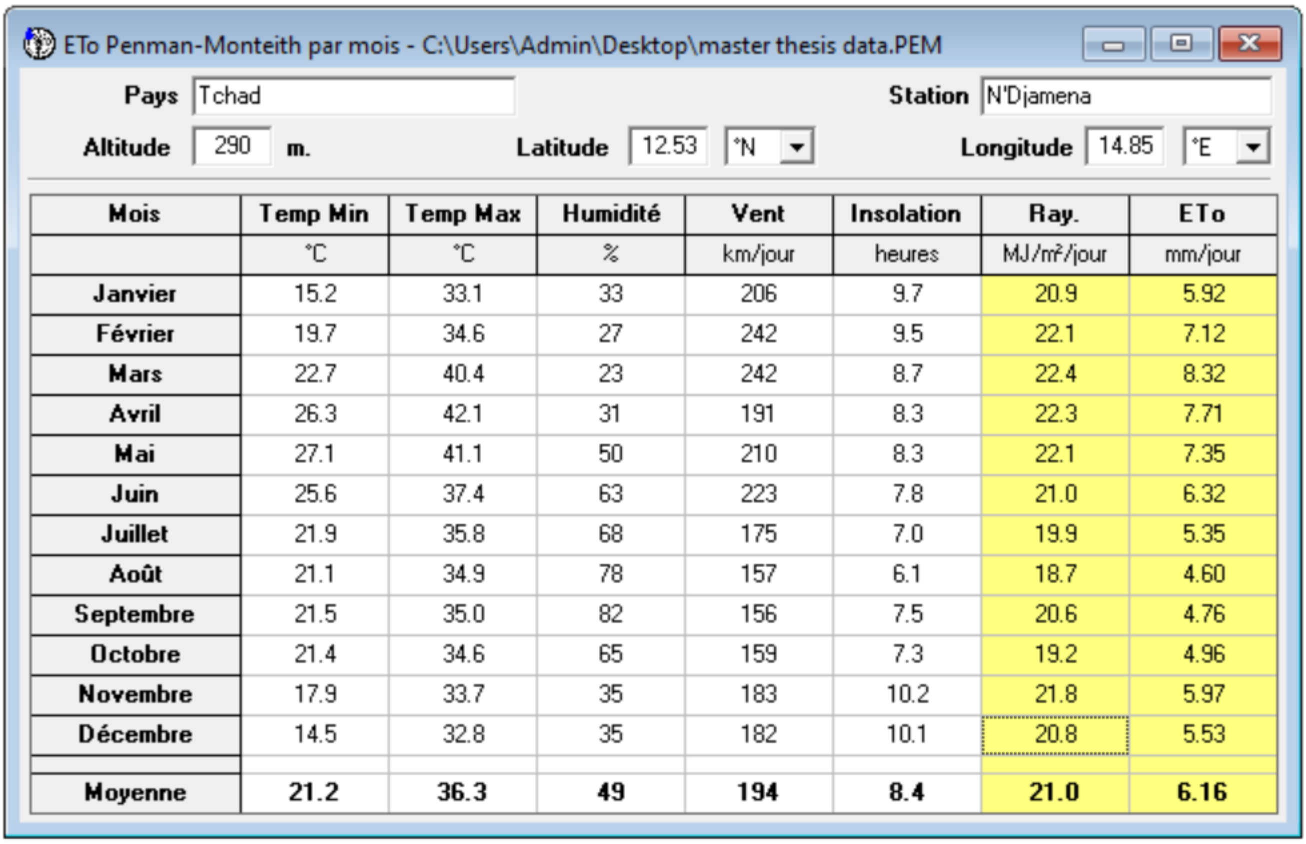
Total water depth applied for the whole scheme:

$$Detph\ = \frac{446{,}400m^3}{200{,}000m^2} = 2.232\ m$$

$\mathbf{Depth_{\ total} = 2{,}232\ mm}$

4.1.1 Reference Crop evapotranspiration, ET0

ETo was calculated in CROPWAT using the Penman-Monteith method. The FAO recommends this approach because it consistently produces better results than other approaches. Climate information for the DIS Project site is shown in the figure below.



ETo Penman-Monteith par mois - C:\Users\Admin\Desktop\master thesis data.PEM

Pays: Tchad
Station: N'Djamena
Altitude: 290 m.
Latitude: 12.53 °N
Longitude: 14.85 °E

Mois	Temp Min	Temp Max	Humidité	Vent	Insolation	Ray.	ETo
	°C	°C	%	km/jour	heures	MJ/m²/jour	mm/jour
Janvier	15.2	33.1	33	206	9.7	20.9	5.92
Février	19.7	34.6	27	242	9.5	22.1	7.12
Mars	22.7	40.4	23	242	8.7	22.4	8.32
Avril	26.3	42.1	31	191	8.3	22.3	7.71
Mai	27.1	41.1	50	210	8.3	22.1	7.35
Juin	25.6	37.4	63	223	7.8	21.0	6.32
Juillet	21.9	35.8	68	175	7.0	19.9	5.35
Août	21.1	34.9	78	157	6.1	18.7	4.60
Septembre	21.5	35.0	82	156	7.5	20.6	4.76
Octobre	21.4	34.6	65	159	7.3	19.2	4.96
Novembre	17.9	33.7	35	183	10.2	21.8	5.97
Décembre	14.5	32.8	35	182	10.1	20.8	5.53
Moyenne	**21.2**	**36.3**	**49**	**194**	**8.4**	**21.0**	**6.16**

Figure 4.1: Monthly weather variables and ETO for PIS

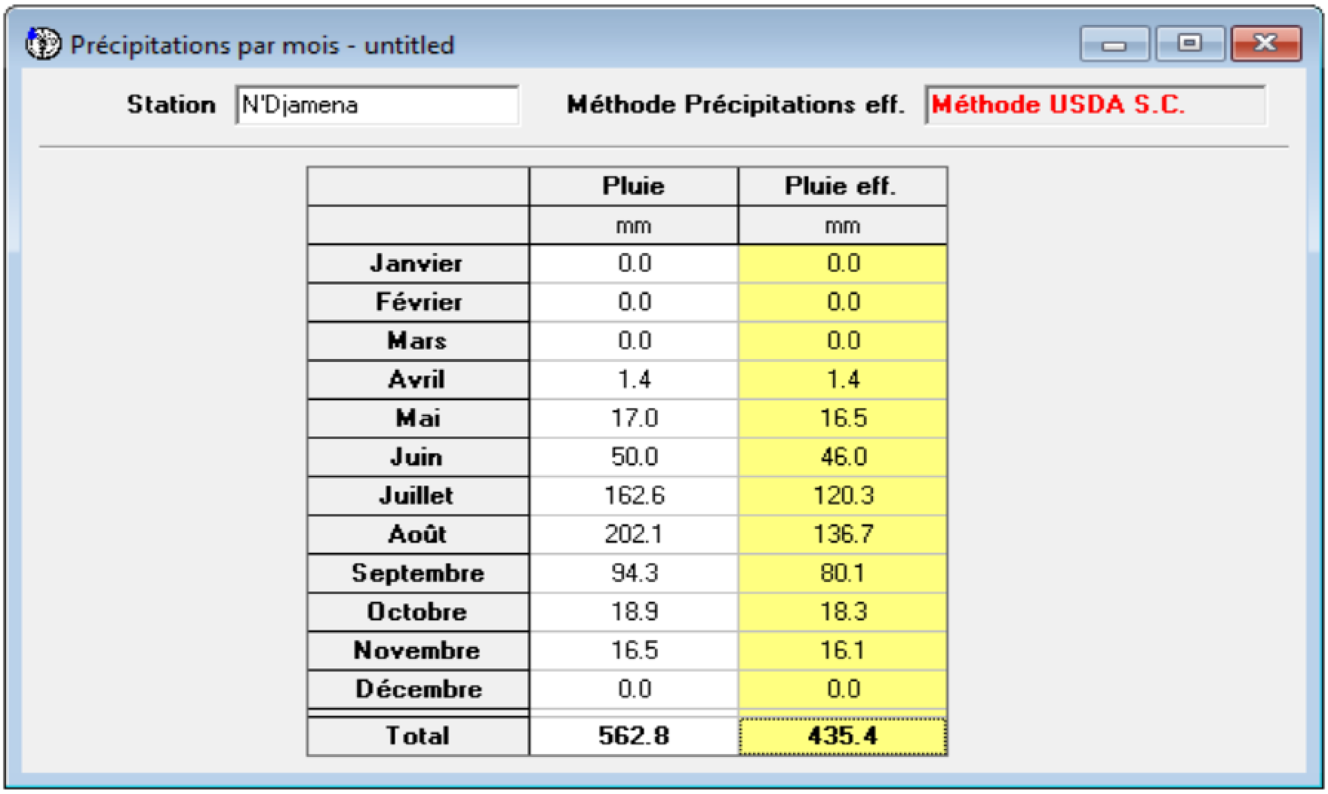
The mean daily reference evapotranspiration (ETo) for the Danouna irrigation perimeter is **6.16 mm/day**, indicating a relatively high-water demand for crops, particularly rice, which is the main cultivated crop in the area. The highest ETo values are observed between February and May, a period characterized by high temperatures, low humidity, and strong winds, all of which contribute to increased evaporative demand. Conversely, the lowest ETo values occur between July and September, coinciding with the rainy season, where higher humidity and lower temperatures reduce atmospheric demand for water.

Danouna experiences moderate to high wind speeds, with the highest values recorded from February to May, further intensifying evapotranspiration during these months. The mean monthly temperature is 21.2°C (minimum) and 36.3°C (maximum), reinforcing the region's classification as semi-arid. Given these climatic conditions, efficient irrigation scheduling is crucial to minimize water losses and ensure optimal crop growth. This highlights the need for improved irrigation techniques to enhance water use efficiency and reduce percolation losses, particularly during the dry season when water availability is more critical.

4.1.2 Rainfall

The graphic below illustrates how monthly rainfall averages are used to determine the percentage of rainfall that helps build soil moisture content, or effective rainfall. August has the highest monthly total rainfall equal to 202.1 mm, followed by July with 162.6 mm and September with 94.3 mm. January through March have the lowest total rainfall numbers, with no notable rainfall.
The effective rainfall, or the amount of precipitation accessible for crop use, is calculated using the USDA S.C. Method. The rainy season peaks in August with 136.7 mm of effective rainfall, followed by July with 120.3 mm and September with 80.1 mm. However, especially during months with heavy rainfall, a sizable amount of water is lost to runoff or deep percolation.

Of the **562.8 mm** of total annual rainfall**, 435.4 mm** are regarded as effective rainfall, which means that only roughly **77.3%** of the precipitation helps replenish soil moisture; the remainder is lost. These findings demonstrate how important it is to schedule irrigations effectively during the dry months of November through May, when there is not enough rainfall to support rice farming within the Danouna irrigation perimeter.



Station N'Djamena

Méthode Précipitations eff. Méthode USDA S.C.

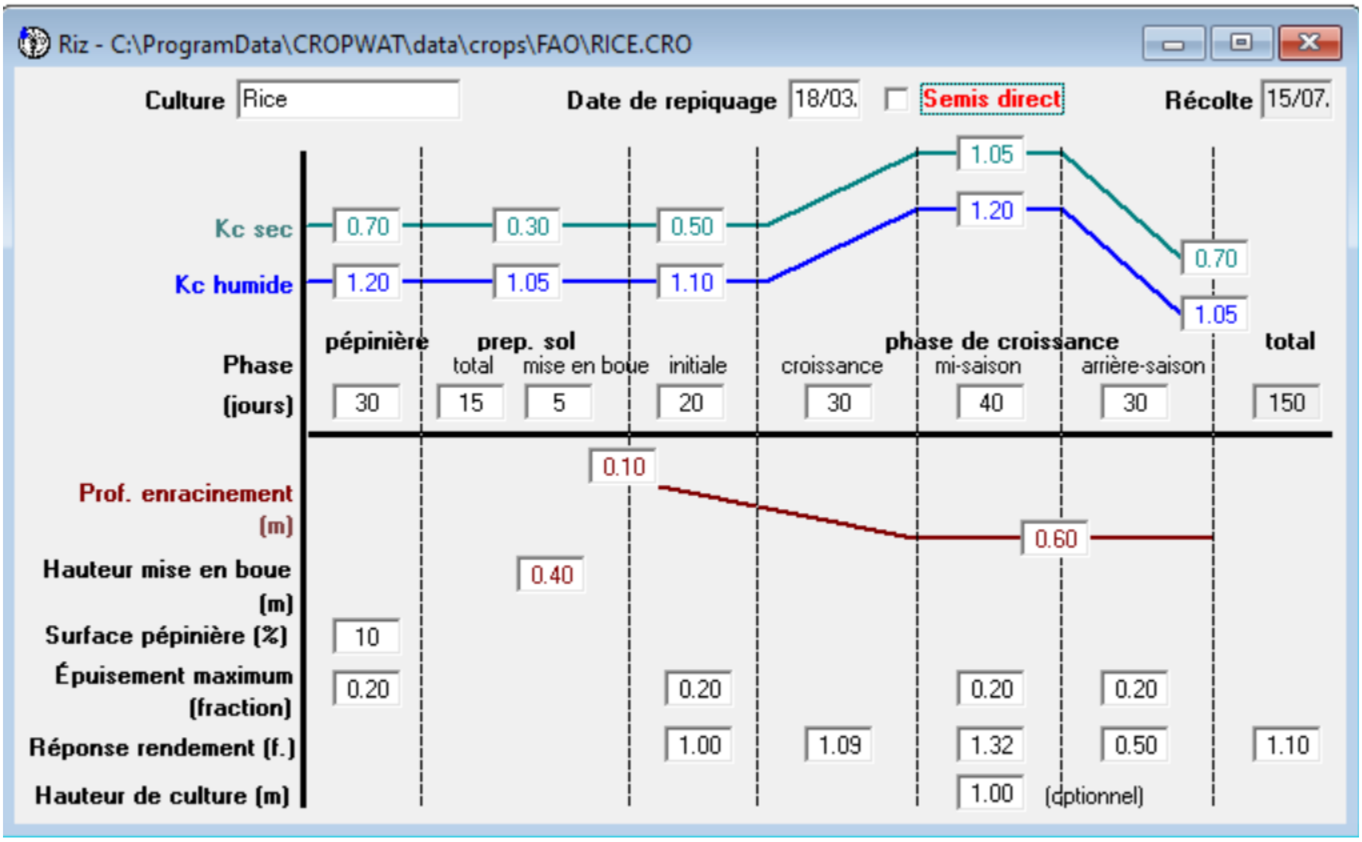
	Pluie	Pluie eff.
	mm	mm
Janvier	0.0	0.0
Février	0.0	0.0
Mars	0.0	0.0
Avril	1.4	1.4
Mai	17.0	16.5
Juin	50.0	46.0
Juillet	162.6	120.3
Août	202.1	136.7
Septembre	94.3	80.1
Octobre	18.9	18.3
Novembre	16.5	16.1
Décembre	0.0	0.0
Total	562.8	435.4

Figure 4.2: Monthly rainfall and effective rainfall

Based on FAO Irrigation and Drainage Paper No. 56, and the rainfall data for DIS, it is clear that in the first quarter of the year from January to March, rainfall is nearly absent, indicating extreme dry conditions. From April to May, rainfall remains low, representing only light showers insufficient to sustain crop growth. June to September sees moderate to heavy rainfall, with August recording the highest monthly precipitation equal to **202.1 mm**. However, despite this peak, effective rainfall is lower due to runoff and percolation. October and November receive minimal rainfall, classifying them as light showers, while December records no rainfall. Overall, rainfall is insufficient for rice cultivation, making irrigation necessary throughout the growing season to meet the crop's water requirements.

4.1.3 Crop data

Rice cultivation data for the Danouna irrigated perimeter have been integrated into CROPWAT to assess water requirements and optimize irrigation. These data include the crop coefficient (Kc) taken from the FAO 56 manual, rooting depth, duration of growth stages, as well as planting and harvesting dates adapted to local conditions. The permissible soil moisture depletion limit was also taken into account to avoid water stress. These parameters make it possible to establish a precise irrigation schedule to improve water efficiency and ensure optimum rice productivity in the study area.



Riz - C:\ProgramData\CROPWAT\data\crops\FAO\RICE.CRO

Culture: Rice

Date de repiquage: 18/03.

☐ Semis direct

Récolte: 15/07.

	pépinière	prep. sol				phase de croissance		total
Phase		total	mise en boue	initiale	croissance	mi-saison	arrière-saison	
Kc sec	0.70	0.30		0.50		1.05	0.70	
Kc humide	1.20	1.05		1.10		1.20	1.05	
(jours)	30	15	5	20	30	40	30	150
Prof. enracinement (m)				0.10		0.60		
Hauteur mise en boue (m)			0.40					
Surface pépinière (%)	10							
Épuisement maximum (fraction)	0.20			0.20		0.20	0.20	
Réponse rendement (f.)				1.00	1.09	1.32	0.50	1.10
Hauteur de culture (m)						1.00	(optionnel)	

Figure 4.3: Crop data for Rice

4.1.4 Soil Type

The predominant soil type in the Danouna irrigation perimeter is clay which is well suited for rice cultivation due to its high-water retention capacity. This information was obtained from the records of the PDRI-CL2 project, which oversees the seven irrigated perimeters dedicated to rice production. The soil characteristics were confirmed through field observations and soil analysis.

At the beginning of the crop growth cycle, it is assumed that the soil moisture content is at field capacity to ensure proper water availability for the initial irrigation before transplanting the rice seedlings.

Soil Water Holding Capacity Calculations

The available water content (AWC) of the clay loam soil is calculated as follows:

$$\text{AWC} = \text{FC} - \text{WP}$$

From FAO 56 standard values:

- Field Capacity (FC) : 35%
- Wilting Point (WP) : 20%

$$\text{AWC} = (35 - 20) \times 10 = 150 \text{ mm/m}$$

The total available water (TAW) within the rooting depth of rice is calculated using:

$$TAW=AWC\times Rd$$

From FAO 56, the rooting depth (RD) of rice is 0.60 m, and the AWC for clay loam is 150 mm/m.

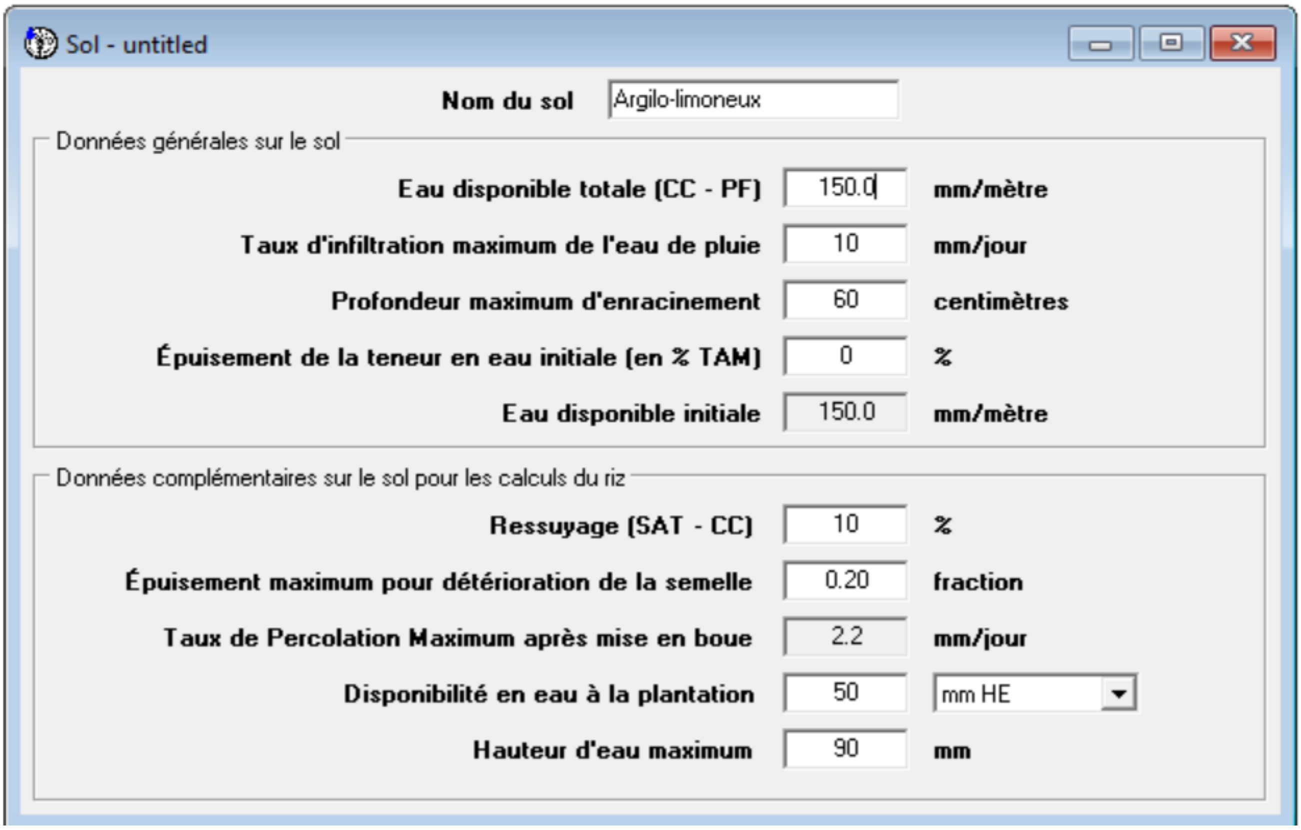
$$TAW=150\times 0.60=90 \text{ mm}$$

Since rice is highly sensitive to water stress, the fraction of allowable depletion (p) is set at 20% according to FAO 56(Allen, 2006). The readily available water (RAW) is then:

$$RAW=p\times TAW$$

$$RAW=0.20\times 90=18 \text{ mm}$$

The values calculated above was then fed into CROPWAT 8.0



Sol - untitled

Nom du sol: Argilo-limoneux

Données générales sur le sol

Eau disponible totale (CC - PF): 150.0 mm/mètre
Taux d'infiltration maximum de l'eau de pluie: 10 mm/jour
Profondeur maximum d'enracinement: 60 centimètres
Épuisement de la teneur en eau initiale (en % TAM): 0 %
Eau disponible initiale: 150.0 mm/mètre

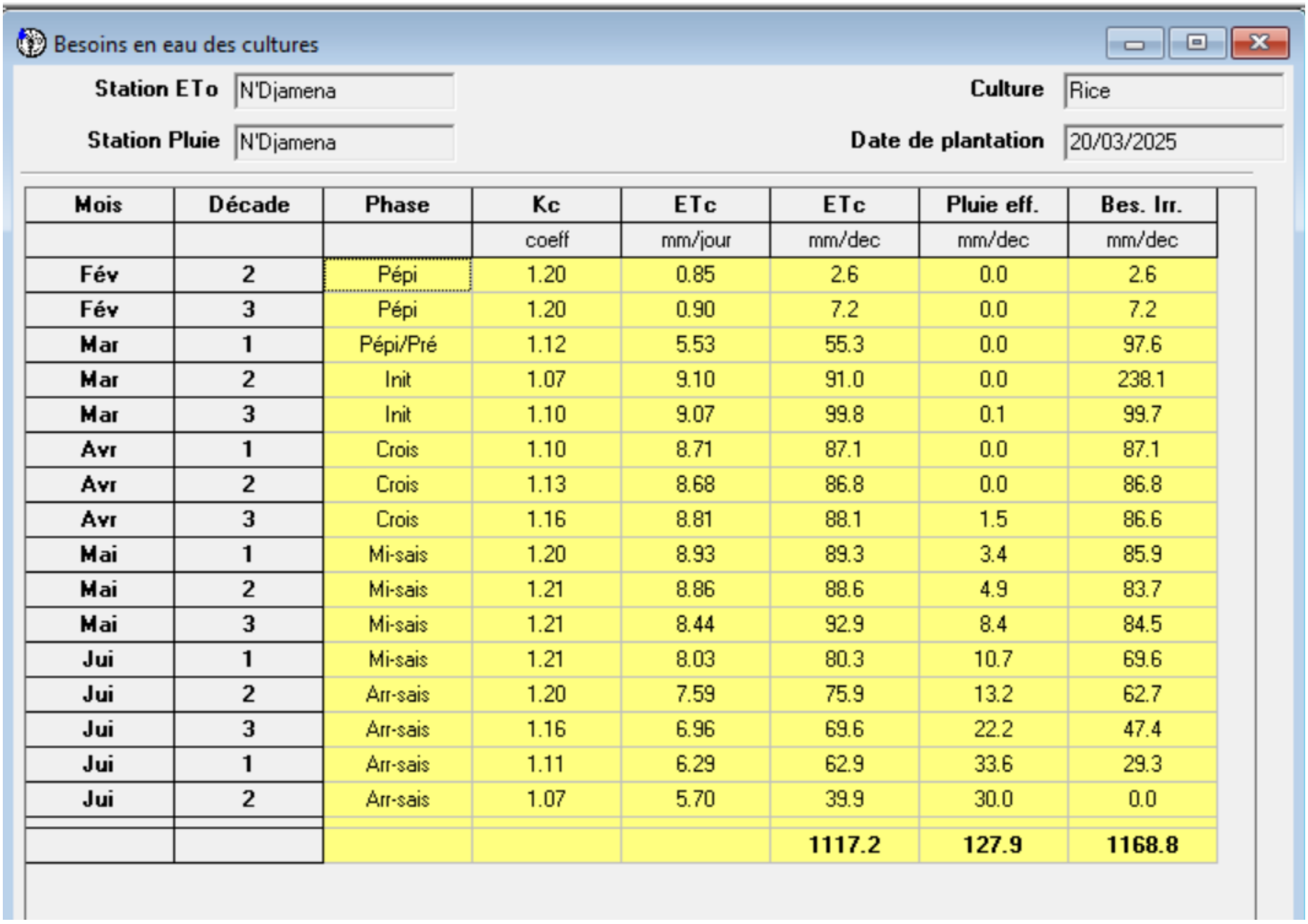
Données complémentaires sur le sol pour les calculs du riz

Ressuyage (SAT - CC): 10 %
Épuisement maximum pour détérioration de la semelle: 0.20 fraction
Taux de Percolation Maximum après mise en boue: 2.2 mm/jour
Disponibilité en eau à la plantation: 50 mm HE
Hauteur d'eau maximum: 90 mm

Figure 4.4: Soil data

4.1.5 Actual crop evapotranspiration, ETc

Results indicate that the total crop water requirement (ETc) for rice in the Danouna irrigation scheme is 1117.2 mm, with a net irrigation requirement of 1168.8 mm, highlighting a high dependence on irrigation due to limited effective rainfall of 127.9 mm. The highest water demand occurs during the early and mid-season growth stages, when evapotranspiration is at its highest, confirming the need for optimal irrigation scheduling to avoid water stress. The data underline the importance of effective water management strategies according to specific growth stages to optimize water use efficiency in the Danouna irrigation scheme and to minimize losses and improve irrigation efficiency for sustainable rice production in the region.



Station ETo N'Djamena

Station Pluie N'Djamena

Culture Rice

Date de plantation 20/03/2025

Mois	Décade	Phase	Kc	ETc	ETc	Pluie eff.	Bes. Irr.
			coeff	mm/jour	mm/dec	mm/dec	mm/dec
Fév	2	Pépi	1.20	0.85	2.6	0.0	2.6
Fév	3	Pépi	1.20	0.90	7.2	0.0	7.2
Mar	1	Pépi/Pré	1.12	5.53	55.3	0.0	97.6
Mar	2	Init	1.07	9.10	91.0	0.0	238.1
Mar	3	Init	1.10	9.07	99.8	0.1	99.7
Avr	1	Crois	1.10	8.71	87.1	0.0	87.1
Avr	2	Crois	1.13	8.68	86.8	0.0	86.8
Avr	3	Crois	1.16	8.81	88.1	1.5	86.6
Mai	1	Mi-sais	1.20	8.93	89.3	3.4	85.9
Mai	2	Mi-sais	1.21	8.86	88.6	4.9	83.7
Mai	3	Mi-sais	1.21	8.44	92.9	8.4	84.5
Jui	1	Mi-sais	1.21	8.03	80.3	10.7	69.6
Jui	2	Arr-sais	1.20	7.59	75.9	13.2	62.7
Jui	3	Arr-sais	1.16	6.96	69.6	22.2	47.4
Jui	1	Arr-sais	1.11	6.29	62.9	33.6	29.3
Jui	2	Arr-sais	1.07	5.70	39.9	30.0	0.0
					1117.2	**127.9**	**1168.8**

Figure 4.5: Monthly actual crop evapotranspiration and irrigation requirement

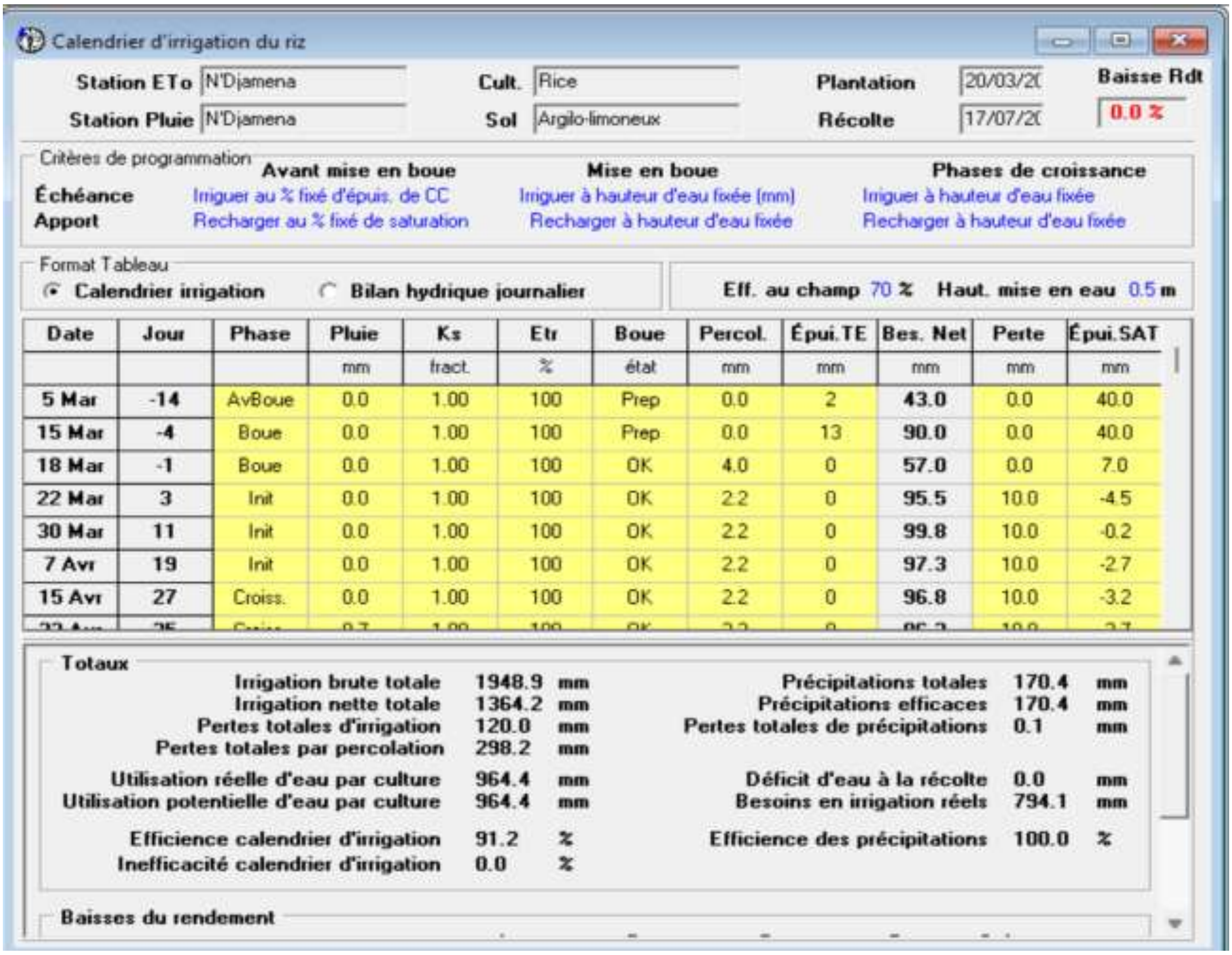
The analysis of current irrigation practices in the DIS reveals a considerable discrepancy between the volumes of water actually applied by farmers and the actual water requirements of the rice crop. Field measurements of the volume of water applied on the basis of a 150-day crop cycle show that each 0.25-hectare plot receives an average total volume of 5,580 m³, representing a cumulative water head of around 2,232 mm. However, according to CROPWAT software estimates, irrigation requirement for rice in this area do not exceed 1,200 mm (figure4.3) over the same period.

With nearly three times the amount of water needed to guarantee ideal crop development, this shows a definite pattern of over-irrigation. The high frequency of irrigations, which are performed every three (03) days for ten (10) hours regardless of the actual state of soil moisture, helps to explain this overconsumption.

Although this kind of water management is comforting to farmers, it also reduces irrigation system efficiency and causes a large loss of resources due to deep percolation, infiltration, or runoff. It may worsen waterlogging or salinization conditions, encourage nutrient leaching, and negatively impact soil structure. These findings highlight the necessity of putting optimization techniques into practice that are founded on a deeper comprehension of the actual water needs of crops and the modification of irrigation schedules.

4.2 Irrigation scheduling for rice cultivation

Irrigation is applied when the soil reaches wilting point, in order to restore soil moisture to field capacity. The rice irrigation schedule is based on an initial soil water depletion of 0%. This approach aims to avoid any reduction in yield, thus guaranteeing optimum water availability for the crop. The figure below illustrates the irrigation scheduling strategy adopted.



Station ETo: N'Djamena
Station Pluie: N'Djamena
Cult.: Rice
Sol: Argilo-limoneux
Plantation: 20/03/2(
Récolte: 17/07/2(
Baisse Rdt: 0.0 %

Critères de programmation

	Avant mise en boue	Mise en boue	Phases de croissance
Échéance	Irriguer au % fixé d'épuis. de CC	Irriguer à hauteur d'eau fixée (mm)	Irriguer à hauteur d'eau fixée
Apport	Recharger au % fixé de saturation	Recharger à hauteur d'eau fixée	Recharger à hauteur d'eau fixée

Format Tableau
● Calendrier irrigation ○ Bilan hydrique journalier
Eff. au champ 70 % Haut. mise en eau 0.5 m

Date	Jour	Phase	Pluie	Ks	Etr	Boue	Percol.	Épui.TE	Bes. Net	Perte	Épui.SAT
			mm	fract.	%	état	mm	mm	mm	mm	mm
5 Mar	-14	AvBoue	0.0	1.00	100	Prep	0.0	2	43.0	0.0	40.0
15 Mar	-4	Boue	0.0	1.00	100	Prep	0.0	13	90.0	0.0	40.0
18 Mar	-1	Boue	0.0	1.00	100	OK	4.0	0	57.0	0.0	7.0
22 Mar	3	Init	0.0	1.00	100	OK	2.2	0	95.5	10.0	-4.5
30 Mar	11	Init	0.0	1.00	100	OK	2.2	0	99.8	10.0	-0.2
7 Avr	19	Init	0.0	1.00	100	OK	2.2	0	97.3	10.0	-2.7
15 Avr	27	Croiss.	0.0	1.00	100	OK	2.2	0	96.8	10.0	-3.2

Totaux

Irrigation brute totale	1948.9 mm	Précipitations totales	170.4 mm
Irrigation nette totale	1364.2 mm	Précipitations efficaces	170.4 mm
Pertes totales d'irrigation	120.0 mm	Pertes totales de précipitations	0.1 mm
Pertes totales par percolation	298.2 mm		
Utilisation réelle d'eau par culture	964.4 mm	Déficit d'eau à la récolte	0.0 mm
Utilisation potentielle d'eau par culture	964.4 mm	Besoins en irrigation réels	794.1 mm
Efficience calendrier d'irrigation	91.2 %	Efficience des précipitations	100.0 %
Inefficacité calendrier d'irrigation	0.0 %		

Baisses du rendement

Figure 4.6: Irrigation Scheduling for the maize crop in PIS

The irrigation schedule drawn up using CROPWAT software indicates an actual total water requirement of 794.1 mm during the rice growing season at DIS, compared with a gross applied irrigation of 1948.9 mm. This clearly reveals a significant excess in water application, resulting in high total losses equal to 584.6 mm, or around 30% of the total volume applied. Among these losses, deep percolation is particularly significant, reaching 298.2 mm, while the remaining 286.4 mm corresponds to other losses such as evaporation, infiltration and surface runoff, reflecting sub-optimal irrigation water management and the need for better regulation to reduce this phenomenon. Despite a high overall efficiency estimated at 91.2%, these losses represent a substantial margin for improvement.

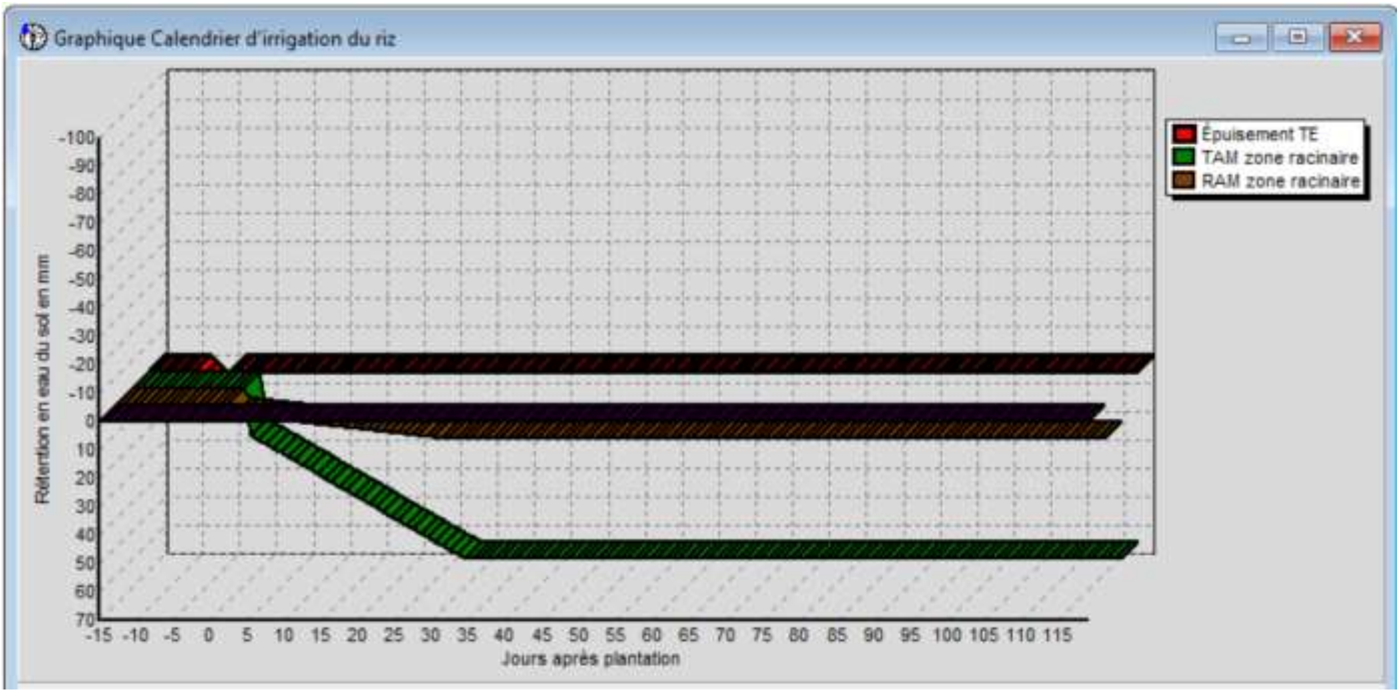


Figure 4.7: Graphical representation of the Irrigation Requirement for rice in DIS

The soil water content (red line) in the root zone continuously stays above the readily available moisture (RAM, brown line) and noticeably above the total available moisture (TAM, green line). This suggests potential over-irrigation and related water waste because it shows that the Danouna scheme's existing irrigation methods maintain soil moisture levels above the minimum level needed for rice growing. In order to minimize water losses and improve water-use efficiency while preserving high crop yields, optimizing the irrigation strategy would entail modifying water applications closer to the RAM level.

4.3 Water productivity for rice cultivation at DIS

Analysis of the data collected in the Danouna irrigated perimeter has enabled us to estimate an average rice yield of 6t/ha, which is relatively satisfactory compared with regional averages in sub-Saharan Africa between 2 to 5 t/ha. This yield is deemed to be in line with the performance expected in a fully water-controlled system, although it remains below the optimum yields observed in intensified or better-equipped systems (up to 10 t/ha). It is noteworthy that during the 2022 off-season, a farmer achieved an exceptional 8 t/ha, highlighting the high potential productivity of the perimeter under proper water management and cultural practices.

The total volume of water applied during the entire crop year, determined from direct volumetric measurements on representative plots, taking into account the frequency and duration of irrigation and the growth period of the rice, is equivalent to an average of 446,400 m³ for the entire perimeter. Relating this volume to the total area of 20 ha gives an average volume applied of:

$$V = \frac{446\ 400\text{m3}}{20ha} = 22\ 320\ \text{m}^3/\text{ha}$$

Based on this volume of water applied and the average yield of 6 t/ha, water productivity (WP) is calculated as follows:

$$\text{WP}=\frac{6000\ Kg/ha}{22\ 320\ \text{m3/ha}}=0.27\ \text{kg/m}^3$$

4.4 Water distribution system

DIS is fitted with a structured water distribution network that consists of secondary earthen canals and a main canal. The main canal, which is 450 meters long and made of reinforced concrete, has a trapezoidal cross-section with an average depth of 50 cm, an upper width of 60 cm, and a lower width of 40 cm. It serves as the primary water distribution channel from the source to the secondary distribution system. The secondary canals, which are made of unlined compacted earth, are about 2,508 meters long and have a trapezoidal cross-section with an average depth of 30 cm, a lower width of 20 cm, and an upper width of 40 cm as well.

Water is channeled from the secondary canals to individual plots by means of siphoning systems operated manually by the farmers. Each farmer connects to the secondary canal at a suitable point that allows gravity flow to his plot. No tertiary canal is built permanently. This semi-manual distribution approach requires careful coordination between users to ensure equitable access to water on all plots.

4.5 Method of water application

Surface basin irrigation, which is especially well-suited for cultivating rice in flat fields, is how water is applied in the Danouna irrigation system. Using the siphoning method, farmers manually direct water from the secondary canals to their plots, controlling the flow with tiny pipes or hoses. After entering the field, the water is dispersed uniformly in basins shaped like troughs that are intended to hold a steady, shallow layer of water.

This gravity-fed system is easy to use, low-cost, and compatible with the infrastructure of the project. However, the quality of the land preparation and the management techniques used by farmers have an important impact on its performance.

4.6 Commercialization of the products

Rice is produced in the Danouna Irrigation Scheme for both commercial and subsistence uses, with a recent emphasis on commercialization. The majority of farmers grow rice mainly for market sale during the dry season rather than for domestic usage. The majority of producers depend on rice sales revenue to pay for their agricultural inputs and provide for their families, according to field interviews and conversations. Farmers frequently sell their crop to local dealers or in regional marketplaces like N'Djamena, despite the lack of a structured contract farming system. Market opportunities have been improved by the area's closeness to major cities and the rising demand for rice grown nearby.

4.7 Downstream-right

In the Danouna Irrigation Scheme, downstream water management is approached with careful consideration of environmental and social responsibilities. The water source for the scheme is the Chari-Logone River, which holds a substantial and reliable flow volume, particularly during the dry season. The abstraction rate for irrigation estimated at 1.05 m^3/s is minimal compared to the river's total discharge, making it a negligible fraction of the available water. This low withdrawal rate ensures that the needs of downstream users, including pastoralists, domestic users, and natural ecosystems, remain largely unaffected. Furthermore, local water management practices, supported by the PDRICL2 project and community-based irrigation committees, include rotational irrigation scheduling. These coordinated efforts help maintain a fair balance between agricultural demands and the preservation of water availability downstream, thus promoting sustainable and equitable water use in the region.

4.8 Land ownership

Among 100 farmers interviewed, less than 2% of them said they rent the land for farming or sharecropping in order to split the harvest profit, while over 98% of the farmers said they own the land.

4.9 Tillage practices of farmers

The preparation of farmland in the Danouna irrigation perimeter relies essentially on mechanical tillage, mainly through the use of tractors, either individually owned or made available through the PDRICL2 project. The initial land preparation phase involves tractor ploughing, a necessary step to break up the compact clay-loam soil that characterizes the region. Given the density and structure of this type of soil, traditional animal-drawn implements are rarely used, as they prove ineffective in loosening the soil adequately.

Once the primary ploughing operation is complete, secondary ploughing is carried out using hand tools. Farmers use manual equipment for tasks such as harrowing, levelling and weed control. This sequential tillage method improves seedbed preparation and promotes uniform water distribution in rice fields.

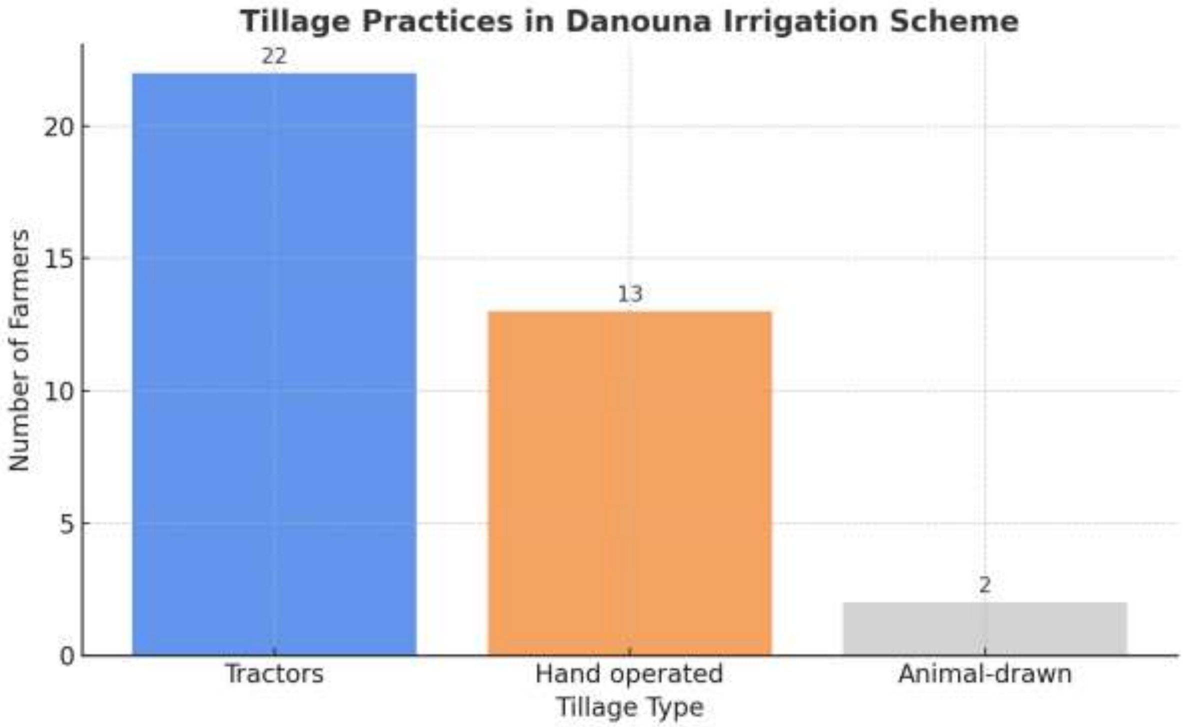


Figure 4.8: Tillage practices of farmers in PIS

CHAPTER FIVE:

5. DISCUSSION

This chapter discusses the key findings of the study regarding the irrigation practices in the Danouna perimeter. The analysis focuses on the effectiveness of water use, crop water requirements, and the overall performance of the current irrigation system based on data generated through CROPWAT simulations and field observations. The findings are examined in relation to both technical efficiency and agricultural productivity. Particular attention is given to water losses, irrigation scheduling, and the adequacy of water supply in meeting the rice crop's actual needs. This discussion sets the foundation for recommendations aimed at improving irrigation management and ensuring more sustainable use of water resources in the area.

5.1 Current performance of the Danouna irrigation scheme

5.1.1 Irrigation balance sheet

The assessment of the water balance in DIS enables the real water needs of the rice crop to be addressed with amounts that are effectively used during the agricultural campaign. Based on simulations using the CROPWAT software, the water requirements of rice in this agroclimatic environment are estimated to be around 1,200 mm for a 150-day cultural cycle. At the same time, field data reveal that, on average, each 0.25-hectare plot receives a flow rate of around 3.1 liters per second, applied for 10 hours every three days. This irrigation rhythm, repeated over the entire cycle, enables us to calculate a total applied volume of 446,400 m^3 for the 20ha perimeter, representing a total water head of 2,232mm. When comparing the amount of water applied to cultural needs, which is 2 232 mm versus 1 200 mm, one can see that 86% of the water is overfed. This suggests an excessive distribution in relation to cultural requirements, which may result in significant losses due to deep percolation, excessive drainage, or useless evaporation. This inefficiency threatens not only the effectiveness of irrigation but also the sustainability of the water resource, particularly in a semi-arid environment like Hadjer Lamis.

5.1.2 Effectiveness of current irrigation schedule

Analysis of irrigation efficiency in the Danouna irrigation perimeter, combining field observations and CROPWAT simulations, reveals a marked gap between actual practices and optimal scheduling. Farmers irrigate every three days for ten hours, using an average flow rate of 3.1 l/s per 0.25 ha plot, resulting in the application of a significant amount of water per season, far exceeding the crop's net irrigation requirement as calculated by CROPWAT. While the simulation indicates high calendar efficiency (91.2%) under controlled scheduling, the reality in the field shows excessive water application, lack of moisture-based triggers and lack of synchronization with crop growth stages. These conditions lead to high percolation losses, inefficient use of irrigation water and the risk of leaching nutrients from the soil. Although the system guarantees yield security by avoiding water stress, its operational performance remains inefficient, underlining the need for optimized irrigation scheduling based on actual crop demand and field-level water control mechanisms(June, 2010).

5.2 Agricultural yield and water productivity

5.2.1 Average observed yield

Based on PDRICL2 project technical files and field data gathered from farmer interviews and direct observations, an analysis of rice yields in the Danouna irrigation system indicates an observed average yield of about 6 tons per hectare. When compared to average yields in sub-Saharan Africa, which typically range between 2 and 5 t/ha due to different agro-technical restrictions, this level of output indicates rather efficient management of crops under controlled irrigation(Jayne, T., Yeboah, K. F., and Carla, 2017). Notably, one farmer achieved an outstanding yield of 8 t/ha during the 2022 dry season harvest, highlighting the system's potential for increased production with the right circumstances and water management(R. D. U. Tchad et al., 2022). These results imply that rice yield in the scheme may approach or perhaps surpass the ideal reference range of 7 to10 t/ha observed in controlled irrigation systems with better irrigation techniques, input use, and extension services.

5.2.2 Water productivity (WP)

By contrasting the average observed yield with the total amount of irrigation water used during the growing season, the water productivity of the Danouna irrigation system was evaluated. The estimated water productivity is around 0.27 kilogram of rice per cubic meter of water applied. For effective irrigated rice production, the FAO recommends a range of 0.6 to 1.2 kg/m^3, which is far lower than this amount(Workshop, 2017). The lack of adaptive scheduling and excessive irrigation are the primary causes of the low WP, which indicates a notable disparity between water use and production. The scheme's existing irrigation management produces less than ideal returns in terms of yield per unit of water, even though there is enough water available. This highlights the need for better water control tactics and precision irrigation techniques to increase resource-use efficiency and sustainability.

5.2.3 Influence of over-irrigation on crop performance

An examination of DIS's irrigation methods shows that a significant amount of water was used in excess throughout the crop cycle. The performance of the rice crop is directly impacted by this over-irrigation, which exceeds 85% of the crop's requirements. Over-irrigation could impair root aeration, decrease nitrogen uptake efficiency, and encourage fertilizer leaching, even though water availability was not a limiting factor. likewise, continuously exceeding ideal water saturation levels raises the possibility of lodging and postpones crop maturity, both of which can lower grain quality and homogeneity(Eisenhauer, 2021). Even though yields stayed high (averaging 6 t/ha), they did not correspond with the amount of water utilized. This suggests that excessive irrigation did not increase yields proportionately but instead led to inefficiencies in resource management and water use.

5.2.4 Gaps between theoretical and practical requirements

The substantial difference between the theoretical water needs of the rice, estimated to be around 1200 mm across the entire cultural cycle, and the actual water volumes applied in the Danouna irrigation zone highlights a number of ineffectiveness sources, including organizational, structural, and technical ones. The distribution infrastructures play a key role in the hydrological plan: water loss in upstream, which is linked to deep infiltration and percolation in secondary unlined canals, improperly managed siphonage, and the lack of regulation devices, results in water consumption that does not, in turn, improve the actual satisfaction of plant needs(Crookston et al., 2020). In the absence of tools to measure the humidity of the soils and precisely control the quantities applied, producers are forced to use empirical methods, frequently based on frequent irrigation without taking into account the phenological stages of the rice.

Thus, the balance between supply and absorption is distorted because even though a lot of water is mobilized, a sizable amount is lost in the system before it even reaches the root zone(Pereira, 2002). To close these gaps and maximize the perimeter's overall effectiveness, better coordination between cultivation methods, plant physiological requirements, and hydraulic network efficiency is therefore essential.

5.3 Identification of Water Losses in the Danouna irrigation scheme

Significant water losses have been noted in the Danouna irrigated perimeter, even though basin irrigation was used as a total water control technique for rice cultivation. These losses affect water availability and sustainability for other users, as well as the overall effectiveness of the irrigation system. This study identified a number of possible sources of water loss, which are described below along with technical and contextual justifications.

5.3.1 Percolation Losses

Deep percolation is one of the most significant sources of loss in rice basin irrigation. Due to the continuous presence of stagnant water in the fields, especially at the beginning and middle of the rice growing season, water tends to percolate below the root zone(Monitoring et al., 2002). At Danouna, the clay-loam soil has moderate permeability, but given the prolonged saturation and lack of soil compaction in some plots, percolation rates can reach or exceed the 2.2 mm/day observed in the simulations. This was confirmed in the CROPWAT irrigation schedule, which showed total percolation losses amounting to almost 298 mm, equivalent to around 30% of the crop's actual requirements over the season.

5.3.2 Seepage from Irrigation Canals

Danouna's secondary canals, although made of compacted embankments, their unlined characteristics still allow infiltration, particularly where maintenance is inadequate. The long distances between the main canal and individual fields, combined with uneven flow distribution and damaged sections, contribute to infiltration losses(Pitt & Lantrip, 2000). These can be difficult to quantify without field infiltration tests, but literature estimates suggest that unlined clay-loam channels can lose 15-30% of the water transported, depending on soil quality and compaction(Scientist et al., 2005).

5.3.3 Inefficient Irrigation Timing

The excessive frequency and volume of water applications in comparison to the actual crop water needs is another important aspect that contributes to an irrigation scheme's inefficiency(*A TRAINING MANUAL ON WATER USE EFFICIENCY IN A Training Manual on Water Use Efficiency in Agriculture*, 2020). Irrigation events were frequently initiated when soil moisture was still much above the 20% depletion threshold that is advised for rice, according to an analysis of irrigation practices and the simulated soil water balance derived from CROPWAT. As a result, over-irrigation became routine. Although the theoretical crop water demand assessed for rice in this region was just 1,200 mm, 2,232 mm of irrigation water was administered during the course of the cropping season. This disparity highlights significant water use inefficiencies and suggests an over-application of almost 86%. Such excessive irrigation not only leads to water wastage but also raises concerns related to nutrient leaching, soil degradation, and long-term sustainability of the irrigation system(Republic, 2014).

5.3.4 Non-uniform Siphon Application

Plots receive irrigation from the subsidiary canals via siphons. Although this approach is popular and useful for surface irrigation, variations in siphon size, operator technique, and elevation can result in inconsistent flow rates between plots(Specifications & Agency, 2020). Even with comparable watering times, our volumetric measurements using calibrated 10-liter buckets revealed differences in the actual quantities applied to various plots.

5.3.5 Evaporation Losses

Surface evaporation is naturally high in open basin systems, especially under high temperatures and wind speeds(Rodney et al., 2013). With monthly average reference evapotranspiration (ETo) ranging between 5 and 8 mm/day in Danouna, uncovered and saturated fields exposed to direct sunlight contribute to water losses. This is exacerbated during the seedling and land preparation stages when water surfaces are broad and plant canopy is minimal.

5.3.6 Management and Operational Inefficiencies

Unnecessary losses are also caused by poor scheduling, a lack of farmer training, and a lack of real-time soil moisture monitoring equipment(Allen, 2006). Over use of water resources results from irrigation scheduling that is frequently determined by habit or visual evaluation rather than data.

5.4 Prospects for system optimization

5.4.1 Readjustment of irrigation schedule

Optimizing irrigation in the Danouna perimeter means first and foremost reforming the current schedule, adapting it to the real needs of the rice crop at each phase of development. An effective strategy would be to switch from a fixed schedule to a dynamic one based on daily water requirements, as defined by current evapotranspiration and agro-climatic data(Mayor, 2019). This readjustment would enable water supply to be more closely aligned with actual crop demand. The integration of scheduling tools such as CROPWAT, coupled with simple soil moisture indicators or empirical observations of crop stages, would enable better timing of inputs. The aim is to reduce irrigation frequency to periods when demand is low, and concentrate inputs at critical stages (flowering, grain filling). This approach would ensure more rational use of water, limit unnecessary losses, and promote better overall system efficiency without compromising crop yields. In addition to lowering the danger of yield loss, the implementation of an adjusted schedule would increase the amount of time that resources are available for other agricultural and environmental purposes by improving the ability to predict the critical periods of water stress(Kumble et al., 2020).

5.4.2 Improvement of Hydraulic Infrastructure

Improving the DIS's hydraulic infrastructure is essential to attaining high gains in system performance and water use efficiency. Huge volume of water losses is evident in the field, especially through deep percolation and seepage along secondary earthen and unlined canals that are deteriorated structurally and poorly maintained(Experience, 2024). These losses lead to systemic inefficiencies and decrease the amount of water available for efficient crop usage. To mitigate such losses, a progressive strategy involving the partial or complete lining of secondary canals with impermeable materials such as reinforced concrete or synthetic membranes should be adopted. This would substantially reduce infiltration and ensure more consistent water delivery across the network(Official & Only, 2018).

The absence of tertiary canals has been noted as one of the main flaws. Due to this structural gap, farmers are forced to use inefficient and imprecise artisanal diversion methods like siphoning. Directly, regulated water distribution to the plot would be made possible by the development of well-sized tertiary canals that are tailored to the local topography(The et al., 2018). This would cut down on transfer times and line losses and make it easier to adopt more sensible watering schedules.

The installation or rehabilitation of key hydraulic structures, including flow regulation gates and calibrated intake devices, would also enhance the control and distribution of water(Brentan & Lima, 2023). Integrating volumetric measurement systems at various delivery points would also support real-time monitoring, enabling the tailoring of irrigation volumes to actual crop needs.

Infrastructure modernization not only minimizes conveyance losses but also strengthens the technical foundation for scheduling optimization, equitable water allocation, and long-term sustainability of the irrigation system(Bank, 2024). These interventions would promote improved agricultural productivity while reducing pressure on the water resource, aligning with broader goals of resource efficiency and resilience in semi-arid environments.

5.4.3 Adoption of best practices

The adoption of better farming and hydraulic practices is an essential element in optimizing the Danouna irrigation system. On-demand irrigation, the use of tensiometers and rain gauges to better control water inputs to plots, and irrigation scheduling according to anticipated rainfall are examples of best practices that should be encouraged(Hensley & Deputy, 1999). In this situation, the controlled intermittence technique which involves momentarily stopping irrigation while preserving the humidity needed for rice development could also be investigated. It would improve root growth, increase soil oxygenation, and lower the system's extremely high percolation losses, which are believed to be over 30% of water input.

It is also essential that farmers receive regular training in soil preparation, water balance, input management, and the best times to plant and transplant. In this regard, the active participation of water management committees, PDRI-CL2 project personnel, and supervisory structures might ensure greater appropriation of sustainable methods and promote their broad adoption for a better management of the DIS (Fao et al., 2002). An important tactic for guaranteeing the sustainability of the Danouna irrigated perimeter while optimizing crop yields and minimizing water losses is the incorporation of sensible cropping methods, which are founded on the ideas of climate-smart agriculture and integrated water management(Daboua & Et, 2024).

5.4.4 Economic, social and environmental challenges of optimization

The economic, social, and environmental ramifications of the Danouna irrigation system optimization must be carefully considered. Economically speaking, lowering water losses, increasing water supply efficiency, and enhancing irrigation planning would lower operational costs associated with pumping, infrastructure upkeep, and input purchases while guaranteeing higher agricultural production profitability(East, 2020). Farmers might expand their revenue and operational area while improving food security by raising yields and making sure water is used wisely.

From a social standpoint, more efficient water management would encourage an equitable distribution of the resource between farmers, thus reducing tensions linked to water availability during critical periods(Seijger & Hellegers, 2023). In addition, professionalizing farming practices and increasing farmers' skills could help to structure farmers' organizations and consolidate local governance over water resources.

The advantages for the environment are equally important. Improved irrigation control lowers the chance of saturation and soil deterioration while lowering deep percolation losses that may cause salinization or contaminate groundwater(Ayars & Christen, 2001). Conservation of the Chari-Logone river's volumes also contributes to the preservation of aquatic habitats downstream and the system's ability to withstand the effects of climate change, especially in an area that's as vulnerable as Hadjer Lamis(Sethi, 2022).

5.5 Study limitations and future prospects

5.5.1 Methodological constraints encountered

There are some important methodological limitations in this study. The precision of the water balance was greatly compromised by the lack of regular and direct measurements of soil moisture prior to irrigation. In the same way, the results are questionable when empirical estimates of the quantities of water allocated to each plot are used without advanced measuring tools. Last but not least, the conclusions' applicability is restricted by the observation period's single crop cycle, which emphasizes the need for more, longer-term research.

5.5.2 Tools and available data limitations

Despite being an effective tool for calculating crop water requirements, CROPWAT has limitations, especially when it comes to its inability to account for local context-specific characteristics. Specifically, it is unable to precisely estimate water losses in unlined channels or evaluate actual soil infiltration. The analysis was also constrained by the lack of comprehensive information on past water management in the irrigated perimeter and the scarcity of reliable local climate data. It would be prudent to think about using more sophisticated technologies such as SWAT and Aquacrop and bolstering field data collecting in order to increase the dependability of the results and optimize irrigation operations at Danouna.

5.5.3 Avenues for further research

Further research could be considered in order to solve the limitations noted and consolidate the results gained. Real field infiltration testing should be used to conduct in-depth study on infiltration losses related to the DIS. A thorough analysis of the effects of various updated irrigation systems, particularly sprinkler or drip irrigation, may reveal important areas for development. Similarly, an important topic of study would be a thorough economic analysis contrasting the adoption of new water management techniques with investments in enhancing current infrastructure.

5.5.4 Future integration of simulation or remote sensing tools

Using satellite data would allow for real-time crop and soil water status monitoring, allowing for quick and accurate irrigation schedule modifications. As a supplement to CROPWAT, the use of predictive models like Aquacrop or SWAT may present intriguing opportunities to improve irrigation forecasts and more accurately predict how climate change will affect agricultural output, ultimately enhancing the sustainability of the agricultural system under study.

CHAPTER 6:

6. CONCLUSION AND RECOMMENDATION

In this chapter, the primary findings from the assessment and improvement of irrigation methods in the Danouna irrigation system are presented. Important conclusions have been drawn from the examination of agricultural results, water efficiency, and irrigation techniques. Following that, specific suggestions are made to raise overall production, reduce water losses, and improve irrigation management. At last, recommendations are given for future lines of inquiry to further develop sustainable irrigation techniques in Danouna and other agricultural settings.

6.1 Conclusion

This study identified the primary causes of water inefficiency and losses while critically assessing present practices in the irrigation system at the Danouna irrigated perimeter. Current irrigation water management poses serious challenges, mostly due to a systematic excess of applied water, according to data gathered in the field and simulations conducted using CROPWAT software. In fact, a severe over-irrigation of about 86% was noted, with an estimated total applied water height of about 2,232 mm over the course of a cropping period compared to the optimal theoretical need calculated at 1,200 mm.

The main cause of this excessive water use is an approximate irrigation plan that was implemented without considering the actual water dynamics of the soil or the unique requirements of the crop at various growth stages. This imprecision is made worse by a significant lack of hydraulic infrastructure, particularly the lack of tertiary canals, and the deteriorated and unlined state of the secondary canals that are currently in place, which allows for substantial infiltration and restricts strict control over the water that is distributed to plots.

Overall, agricultural yields are still good, averaging around 6 tons per hectare, indicating the Danouna perimeter's genuine and promising agricultural potential. Water productivity, however, is still much below the FAO-recommended levels, suggesting that there is a lot of room to improve water management and maximize agricultural production.

A comprehensive reorganization of the irrigation schedule is necessary to bring about an ongoing improvement in the current state of situations, with emphasis placed on strategies based on accurate crop requirements and the real measurement of soil moisture. In order to reduce losses from evaporation and infiltration, it is also crucial to drastically enhance infrastructure by building sufficient tertiary canals and maintaining existing structures on a regular basis.

6.2 Recommandations

Following the completion of this study, which was focused on evaluating the Danouna irrigation scheme's irrigation system, several specific recommendations have come up for enhancing crop yields, boosting the project's socioeconomic viability, and sustainably increasing the effectiveness of water management.

- Setting up an irrigation schedule according to the actual requirements of the crop at various stages of growth is advised. This calls for the methodical use of soil moisture monitoring tools, like capacitive probes or tensiometers, to apply the appropriate amounts of water without going overboard and thereby minimizing the notable water losses that are currently being noted.
- To reduce seepage losses, an extensive program of secondary canal maintenance and rehabilitation must be started, including complete lining. Tertiary canal construction is necessary to guarantee uniform, regulated water distribution to individual plots, reducing water waste and ensuring greater farmer equity.
- Technical training for farmers must be given special attention, with frequent sessions devoted to soil management, efficient water use, and good irrigation techniques. The incorporation of participatory approaches will enhance water productivity on a perimeter scale and make it easier for farmers to adopt contemporary practices.
- It is important to support the gradual adoption of innovative methods like the System of Intensive Rice Cultivation (SRI), rational ferti-irrigation or fertigation, and other water-saving irrigation strategies. In addition to greatly increasing crop yields, these methods can save water usage overall and safeguard the environment.
- It is strongly recommended to integrate modern and more efficient tools such as water, soil and crop simulation software (SWAT, Aquacrop, ARCGIS, etc.) or remote sensing tools to ensure continuous monitoring and adaptive management of water and agricultural resources. The use of these tools will facilitate real-time decision-making and enhance the operational efficiency of the irrigated perimeter.
- To precisely measure infiltration and evaporation losses and evaluate the effects of current practices on soil and groundwater resources, more thorough research is required. These studies will enable better quantification of inefficiencies and target improvements more precisely.
- An efficient monitoring-evaluation system must be put in place in order to regularly gather trustworthy data on irrigation techniques, water usage, agricultural yields, and the condition of hydraulic infrastructures. The continuous improvement of integrated water resource management and agricultural performance within the Danouna irrigated perimeter will be ensured by this mechanism, which will also facilitate the quick adjustment of adopted strategies and techniques and provide regular feedback.

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