RESADE

Improving Agricultural Resilience to Salinity Through the Development and Promotion of Pro-Poor Technologies

OPTIMAL IRRIGATION MANAGEMENT IN IRRIGATED AREAS BASED ON SOIL-WATER-PLANT MODELING.

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Improving Agricultural Resilience to Salinity Through the Development and Promotion of Pro-Poor Technologies (RESADE)

Report

Project Activity 4

Activity 4.3: Proposal of optimal irrigation and drainage allocation in irrigated areas based on soil-water-plant modeling and ground truthing: Application of water allocation and management models

The report concentrated on particular areas within the Best Practice Hub (BPH), utilizing available information including online open-source data.

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From authors

This report forms part of the project titled "Improving Agricultural Resilience to Salinity Through the Development and Promotion of Pro-Poor Technologies (RESADE)," which is jointly financed by the International Fund for Agricultural Development (IFAD) and the Arab Bank for Economic Development in Africa (BADEA). The RESADE project seeks to address the increasing challenges posed by soil salinization in seven sub-Saharan African (SSA) countries: Botswana, Namibia, Mozambique, Liberia, Sierra Leone, The Gambia, and Togo. One of the primary objectives of this project is to evaluate and identify deficiencies in water management practices, thereby enhancing agricultural resilience across nations in Sub-Saharan Africa (SSA). The improvement of irrigation and drainage methodologies is essential for ensuring sustainable agricultural production and enhancing livelihoods within the sector.

The International Center for Biosaline Agriculture (ICBA) leads the RESADE project, with implementation carried out in collaboration with national partners in the target countries. These partners include the National Agricultural Research Institute of The Gambia (NARI), the Institute of Agricultural Research (IIAM) of Mozambique, the Togolese Institute of Agronomic Research (ITRA), the Sierra Leone Agricultural Research Institute (SLARI), and the Central Agricultural Research Institute of Liberia (CARI). The unwavering support and technical expertise provided by these national partners are essential to achieving the project's objectives. We extend our sincere appreciation for their contributions to this report as well as to the RESADE project as a whole.

This report, titled "Proposal for Optimal Irrigation Management in Irrigated Areas Based on Soil-Water-Plant Modeling and Ground Truthing: Application of Water Allocation and Management Models," is grounded in a comprehensive soil-water-plant modeling study. The data utilized in this report comprises online open-source data, model simulations, and insights garnered from partner organizations, in addition to data collected from the Best Practice Hub (BPH). Soil-water-plant modeling is instrumental in optimizing irrigation schedules to ensure crops receive the requisite water supply.

The authors express profound gratitude to Dr. Tarifa Al Zaabi, Director General of ICBA, for her overarching guidance and leadership in the successful implementation of this project. We also acknowledge the invaluable support rendered by our esteemed partners and reaffirm our commitment to the successful execution of this critical initiative. Additionally, we wish to extend our appreciation to the field teams and scientists in all target countries for their active contributions to data collection and analysis.

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Executive Summary

Improving crop management is essential for achieving food security in Sub-Saharan Africa. By utilizing advanced techniques and tools, farmers can enhance yields and improve the quality of their produce, thereby reducing hunger and malnutrition. The RESADE project aims to enhance irrigation and drainage in seven Sub-Saharan African countries through soil-water-plant modeling. Efficient irrigation systems, such as drip and sprinkler irrigation, significantly improve water use efficiency and crop health. Soil-water-plant modeling is crucial in optimizing irrigation schedules, ensuring that crops receive the appropriate amount of water. Enhancing soil fertility with both organic and inorganic fertilizers boosts soil health and increases yields. Practices like conservation agriculture and the use of nonconventional resources help mitigate the impacts of climate change, while stress-tolerant crop varieties enable farmers to adapt more effectively. Additionally, digital tools and Precision Agriculture Technologies facilitate data-driven irrigation scheduling, allowing for accurate determination of water needs and resulting in significant savings in both water and energy. These insights underscore the importance of customized irrigation and drainage practices to maximize crop production across all RESADE sites.

The soil-water-plant modeling study conducted in ***Sierra Leone***'s irrigated regions reveals several significant findings and insights. RESADE's precision agriculture tools enable data-driven irrigation scheduling, which precisely identifies water requirements, resulting in considerable savings in both water and energy. This methodology not only enhances the efficiency of crop growth but also prioritizes profitability, sustainability, and environmental protection. The study identifies weed infestation and low soil fertility, stemming from insufficient fertilization, as critical factors contributing to yield loss in Sierra Leone. Weeds are estimated to diminish biomass by approximately four tonnes per hectare. The use of saline water (6 dS/m) could potentially decrease yields by up to twenty tonnes per hectare, presenting a stark contrast to a maximum potential yield of twenty-seven tonnes per hectare. Soil quality emerges as a primary determinant of yield losses, with salinity adversely impacting agricultural productivity. Therefore, improving soil fertility is imperative for augmenting crop water productivity, ultimately leading to enhanced yields and increased profitability from underutilized water resources. Supplementary irrigation during the dry season is essential for improving yield and water productivity, particularly for sorghum, which necessitates approximately 200 mm of irrigation. Timely irrigation is critical before the onset of significant rainfall in May to preserve crop health during the dry months. Despite the salinity challenges, enhancing soil fertility remains important, with potential rice production on affected lands estimated at 2.3 tonnes per hectare. The region exhibits resilience to salinity accumulation, as high rainfall effectively leaches away accumulated salts. During the rainy season, rice typically does not require additional irrigation due to adequate natural rainfall, averaging 1567.1 mm. However, supplementary irrigation can significantly bolster rice yields during critical growth stages. Irrigating with saline water does not pose substantial risks to soil health, given the region's soil types and average annual rainfall. Traditional irrigation methods, such as permanent flood irrigation, demand considerable water (6240 mm) for optimal growth. Nevertheless, reliance on saline water may elevate soil salinity, thereby threatening future yields. These findings underscore

the necessity for customized irrigation and drainage practices to optimize crop production within Sierra Leone.

The soil-water-plant modeling study conducted in the irrigated regions of ***The Gambia*** reveals several important insights and conclusions. Freshwater irrigation significantly allows good sorghum yield, whereas the use of saline water results in substantial yield declines over time due to salt accumulation, particularly in the absence of adequate drainage. During dry seasons, approximately 800 mm of irrigation water is required. Saline water reduces transpiration, making it essential to incorporate a leaching fraction to remove the accumulated salts. The model indicated zero water drainage, which points to toxic salt buildup in the root zone, underscoring the urgent need for an effective drainage system when utilizing saline water. Without proper drainage, salinity levels will continue to rise, threatening plant health and highlighting the critical importance of managing irrigation practices with saline water.

Optimal irrigation scheduling is vital for maintaining adequate soil moisture levels, which in turn promotes crop growth and maximizes yield potential. While freshwater is crucial for achieving optimal rice yields, satisfactory results can still be attained with moderately saline water (2 dS/m) when best agricultural practices are employed. During the rainy season, which receives 656 mm of precipitation, supplemental irrigation may be necessary during key growth stages due to erratic rainfall patterns. Timely irrigation helps prevent soil moisture from dropping to wilting points, a crucial factor for sustaining crop performance, while precise fertilization can enhance water productivity. Understanding water dynamics within plant rooting zones is essential, and effective management of both rainfall and irrigation is necessary to maintain a favorable water balance throughout the rice growing season. Achieving acceptable soil salinity levels is possible through the use of a leaching fraction, which supports healthier soil conditions and sustainable rice production in saline environments. These findings underscore the critical need for tailored irrigation and drainage practices to optimize crop production in The Gambia.

The soil-water-plant modeling study conducted in ***Togo***'s irrigated regions reveals several key insights and findings. Supplementary irrigation during the dry season is essential for achieving optimal sorghum productivity. Weed infestation can reduce yields by as much as 50%, and this impact is exacerbated under conditions of low soil fertility, highlighting the urgent need for effective weed management and improved soil practices. Additionally, low soil fertility adversely affects sorghum biomass accumulation, underscoring the importance of maintaining optimal soil conditions. An irrigation volume of 200 to 250 mm is critical for satisfactory sorghum growth, with notable differences observed between irrigation and non-irrigation scenarios. In the region of Atti-Apedokoe, an average of 360 mm of rainfall is supplemented with an additional 260 mm of irrigation water necessary for optimal sorghum development during crucial growth phases. There is a significant risk of soil salinity accumulation when using saline water (6 dS/m) in clay loam soils, especially without proper drainage and leaching strategies, which can adversely affect soil health and agricultural sustainability. The combination of freshwater irrigation and optimal fertilization proves to be effective in achieving high yields and improving water productivity. Continuous flooding with saline water significantly diminishes yields, further emphasizing the importance of water quality. Maintaining soil moisture at field capacity necessitates an irrigation volume of 213 mm, in addition to 352 mm from rainfall. Continuous flooding demands substantially higher water volumes, presenting greater management challenges. Monitoring the water budget is vital for tracking soil moisture dynamics, which are critical for plant uptake and transpiration. With adequate water supply, potential yields can reach between 2.5 to 3.5 tonnes per hectare. The threat of salt accumulation from using saline water, particularly in clay loam soils, jeopardizes soil quality and crop yields. Effective leaching methods and drainage systems are essential to mitigate salinity risks and ensure sustainable farming practices. These findings underscore the need for tailored irrigation and drainage practices to optimize crop production in Togo.

The soil-water-plant modeling study conducted in ***Liberia***'s irrigated regions reveals several important findings. The model serves as a valuable resource for scientific and technical teams, requiring minimal data on weather conditions, crops, and soil to derive crucial irrigation management parameters. It aids smallholder farmers by offering comprehensive outputs that facilitate the evaluation of water requirements and management strategies. Calibration of the model has produced various production scenarios, highlighting the effects of salinity on crop yields resulting from insufficient irrigation and drainage. To mitigate yield losses, the use of salinity-tolerant crops is recommended, particularly as sensitive sorghum genotypes have demonstrated significant biomass loss due to salinity. The model's irrigation schedule is effective in maintaining soil water content and preventing over-irrigation while ensuring adequate water supply, especially during the rainy season. In the absence of irrigation, soil moisture levels can fall below the wilting point during the dry season, leading to severe reductions in yields. Fortunately, certain regions in Liberia are free from the risk of salinity accumulation, as rainfall helps leach away salts. These findings underscore the necessity of tailored irrigation and drainage practices to optimize crop production.

The soil-water-plant modeling study on irrigation and drainage in ***Mozambique*** highlighted several important findings. Sorghum sown on April 29 required 194.3 mm of rainfall and an additional 343 mm of irrigation, whereas sorghum planted on November 17 received 909.7 mm of rainfall but still needed an extra 103 mm of irrigation due to uneven rainfall distribution. Ensuring an adequate water supply is crucial for optimal biomass production and yield, regardless of the planting date. Sensitive crops irrigated with saline water (6 dS/m) over two years faced substantial yield losses, underscoring the importance of selecting salt-tolerant varieties and implementing effective agricultural practices, including reliable drainage systems. The proposed irrigation schedule successfully maintained soil water content between the wilting point and field capacity, thereby enhancing crop performance. Additionally, the rainy season in mid-May further increased soil moisture levels. Without irrigation during dry periods, soil moisture at a depth of 0-30 cm can drop below the wilting point, leading to significant yield reductions if irrigation is not applied. Therefore, irrigation is essential to meet crop water requirements before the effective onset of rainfall, typically starting in May. Some locations in Mozambique may face a risk of salinity accumulation from saline water irrigation, necessitating effective management strategies, including appropriate drainage and a leaching fraction. The soil exhibits good drainage capabilities, and the use of salt-tolerant genotypes is recommended. These findings emphasize the need for tailored irrigation and drainage practices to optimize crop production in Mozambique's irrigated regions.

The soil-water-plant modeling study conducted in ***Botswana*** identified optimal irrigation and drainage practices for enhancing crop production, demonstrating the model's reliability across various scenarios. The use of freshwater significantly increases biomass production, while salt-tolerant genotypes can maintain yields even with saline water. However, postponing sowing from December 22 to April 22 results in a 30% reduction in yield, underscoring the importance of timely planting. Sensitive genotypes irrigated with saline water over multiple seasons experience substantial yield declines, highlighting the necessity for tolerant genotypes and effective drainage strategies. Salinity adversely affects sorghum biomass yield, particularly for sensitive varieties, necessitating careful management practices. To accommodate the water needs of sorghum planted on December 22, 343 mm of irrigation is required due to high evapotranspiration rates. Adopting drought-resistant sorghum genotypes can improve water productivity and crop yields, particularly in resource-limited environments. An effective irrigation schedule is essential for maintaining soil moisture between the wilting point and field capacity, allowing for supplemental irrigation during dry spells. Reliable irrigation systems, such as drip or sprinkler systems, are crucial for optimal crop growth. Furthermore, there is a potential risk of salinity accumulation at the BPH location when using saline water for irrigation, necessitating robust management strategies that include appropriate drainage solutions and carefully selecting salt-tolerant genotypes.

In the context of RESADE Component 4, the soil-water-plant modeling exercise was conducted to evaluate and analyze the optimal irrigation and drainage management in the irrigated lands. This study specifically concentrates on the selected location of the Best Practice Hub (BPH).

Introduction

Environmental stresses such as water scarcity and salinity affect crop production, causing up to 70% yield losses in food crops. Sub-Saharan Africa is particularly vulnerable to these issues, with seasonal water scarcity already impacting food production. Salinity affects one-fifth of the world's irrigated lands and causes a decrease in crop yield, leading to economic penalties of about USD 27.3 billion per year. In sub-Saharan Africa, salinity affects 19.09 million hectares of land, mainly due to inappropriate irrigation practices and seawater intrusion caused by climate change. It is crucial to introduce high-yielding, tolerant, and resilient crops and improve crop management practices to maintain a sustainable production system under marginal environments.

Agriculture is essential to provide food for the world's population. However, the changing climate and limited natural resources have made sustainable agriculture a pressing concern. The successful future of agriculture in such challenging environments depends on the following key factors:

- Identifying new genetic resources that are more resilient to changing environmental conditions and can thrive in these challenging environments.
- Developing and promoting the best farming practices, especially with regard to water use requirements, fertilizer, and disease control for the new proposed crops.
- Improving the processing and marketing of agricultural products to ensure that farmers receive fair prices for their produce and that consumers have access to quality food products.

By focusing on these factors, we can ensure that agriculture remains a sustainable and viable option for farmers in these challenging environments while also meeting the growing demand for food products worldwide.

The Improving Agricultural Resilience to Salinity Through the Development and Promotion of Pro-Poor Technologies (RESADE) project is a collaborative initiative between the International Center for Biosaline Agriculture (ICBA), the International Fund for Agricultural Development (IFAD), and the Arab Bank for Economic Development in Africa (BADEA). The project aims to address the growing concern about the salinization of agricultural land in seven sub-Saharan African countries: The Gambia, Liberia, Sierra Leone, Togo, Botswana, Mozambique, and Namibia. The primary objective of the RESADE project is to enhance food security and reduce poverty among smallholder farmers, particularly women, in these seven countries. This goal will increase agricultural productivity and income by introducing salt-tolerant crops and best agronomic management practices. In addition, the project will develop value chains for the crops introduced and strengthen the capacities of farmers and extension agents in salinity-resistant and climate-smart agriculture in collaboration with the National Agricultural Research and Extension Systems (NARES).

The RESADE project provides technical solutions for areas affected by salinity, with the ultimate aim of improving the livelihoods of smallholder farmers, particularly women. Through this initiative, the project partners seek to build resilience in the agricultural sector in the aforementioned countries, thereby contributing to the overall economic development of the region.

Optimal irrigation and drainage allocation in irrigated areas based on soil-water-plant modeling/cases of study.

Improving crop management is essential to achieving food security in Sub-Saharan Africa. With the right techniques and tools, farmers can increase their crop yields and improve the quality of their produce. This, in turn, can help ensure a steady food supply and reduce the risk of hunger and malnutrition in the area. By investing in crop management strategies and providing farmers with the support they need, we can work towards building a more sustainable and food-secure future for the region. The RESADE project seeks to enhance the allocation of irrigation and drainage in irrigated regions by employing soil-water-plant modeling techniques across seven sub-Saharan African nations: The Gambia, Liberia, Sierra Leone, Togo, Botswana, Mozambique, and Namibia (Figure 1).

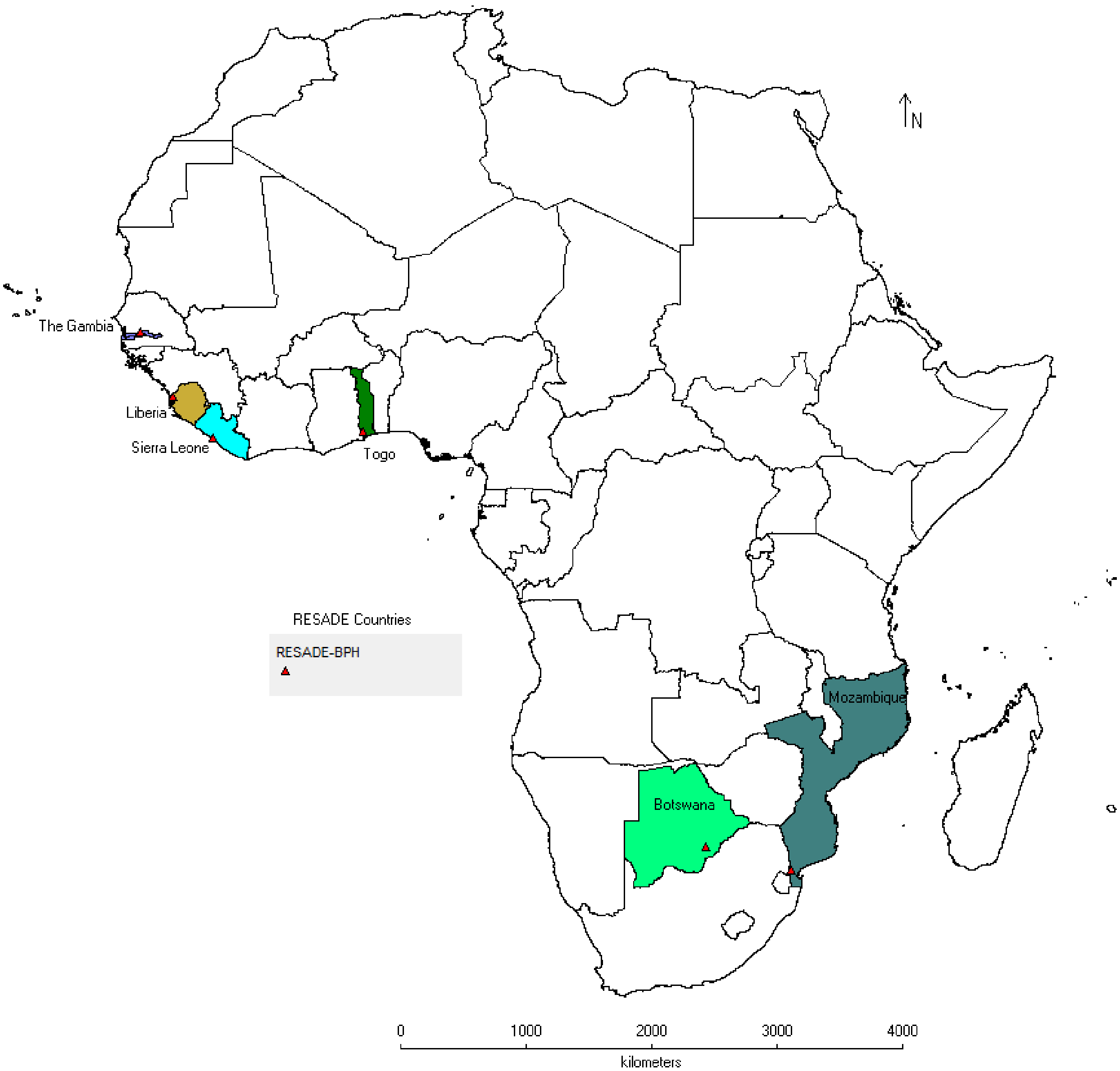


Figure 1: RESADE countries map and the localization of the Best Practice Hub (BPH).

Improving crop management is critical to pursuing food security for Sub-Saharan Africa, a region grappling with multiple agricultural challenges. One of the most effective ways to enhance agricultural productivity is by implementing efficient irrigation systems. Technologies like drip and sprinkler irrigation can drastically improve water use efficiency, ensuring that crops receive adequate moisture while minimizing water wastage. By targeting water application directly to the plant root zones, these systems not only conserve water but also promote healthier plant growth and higher yields.

In addition to advanced irrigation, soil-water-plant modeling serves as a vital tool for optimizing irrigation schedules and drainage systems. This advanced modeling allows researchers, technicians, and farmers to predict water needs based on various factors, including soil moisture levels, weather forecasts, and crop growth stages. By accurately balancing the water supply, farmers can avoid both under- and over-irrigation, leading to more sustainable farming practices. This proactive approach, enabled by advanced modeling, ensures that farmers are well-prepared for the varying water needs of their crops, thereby enhancing their farming efficiency and productivity.

Enhancing soil fertility is another key strategy in crop management. The judicious use of both organic and inorganic fertilizers can significantly boost soil health and crop yields. This emphasis on soil fertility as a foundational aspect of successful farming ensures that the audience is aware of the key strategies to improve their crop management. Organic fertilizers, such as compost and manure, enrich the soil with essential nutrients while improving its structure and water-holding capacity. In contrast, inorganic fertilizers provide immediate nutrient availability, which can be crucial during critical growth periods. Additionally, practices like crop rotation and intercropping—where different crops are grown in a planned sequence or alongside each other—can further enhance soil nutrient cycling and resilience against pests and diseases.

Adopting techniques such as conservation agriculture and agroforestry can be extremely beneficial in mitigating the impacts of climate change. Conservation agriculture involves practices that maintain soil cover and minimize soil disturbance, thus promoting biodiversity and protecting against erosion. Agroforestry integrates trees and shrubs into agricultural landscapes, offering shade, additional income, and improved biodiversity. Furthermore, employing stress-tolerant crop varieties more resilient to drought, pests, and diseases can greatly enhance farmers' capacity to adapt to changing climatic conditions.

The integration of digital tools and mobile applications represents a transformative approach to modern agriculture. These technologies provide farmers with real-time data on weather patterns, pest outbreaks, and fluctuating market prices, empowering them to make informed decisions. This access to information not only improves yield outcomes and economic viability but also instills a sense of control and confidence in their farming practices. Moreover, increasing access to affordable machinery, whether through ownership or rental services, can further promote productivity. Mechanization not only reduces labor costs but also enhances efficiency in operations such as planting, harvesting, and land preparation. Finally, adopting genetically improved seeds designed to be more resistant to common pests, diseases, and environmental stresses can lead to significant advances in agricultural output. These seeds often result in higher yields, better quality produce, and ultimately, greater food security.

By investing in a comprehensive range of strategies and providing tailored support to farmers, we can pave the way for a more sustainable, resilient, and food-secure future for Sub-Saharan Africa.

1. Objective

Crop yield modeling is an effective way to enhance agricultural production efficiency. One useful approach is yield gap analysis, which can identify and address inefficiencies in crop production. Following the Auacrop modeling training, which was meant to equip the project partners with skills to propose optimal irrigation and drainage allocation in irrigated areas based on soil-water-plant modeling, sensors were installed at the hubs in partnering countries to collect climatic data.
The proposed water-crop model aims to achieve the following objectives:

Effects of crop conditions on irrigation planning and water productivity:
This section focuses on analyzing how variations in crop conditions impact irrigation scheduling within the designated plot. To achieve this, we will rely on the specific parameters outlined in the RESADE project. The study will explore several scenarios of operational conditions, each designed to simulate different influences on irrigation practices. These scenarios will encompass a range of variables, including soil moisture levels, crop growth stages, and climatic factors, allowing us to gain a comprehensive understanding of how these changes affect the efficiency and timing of irrigation. By rigorously testing these scenarios, we aim to refine irrigation strategies to optimize water usage and enhance crop yield.
The following variables of operating conditions will be tested:

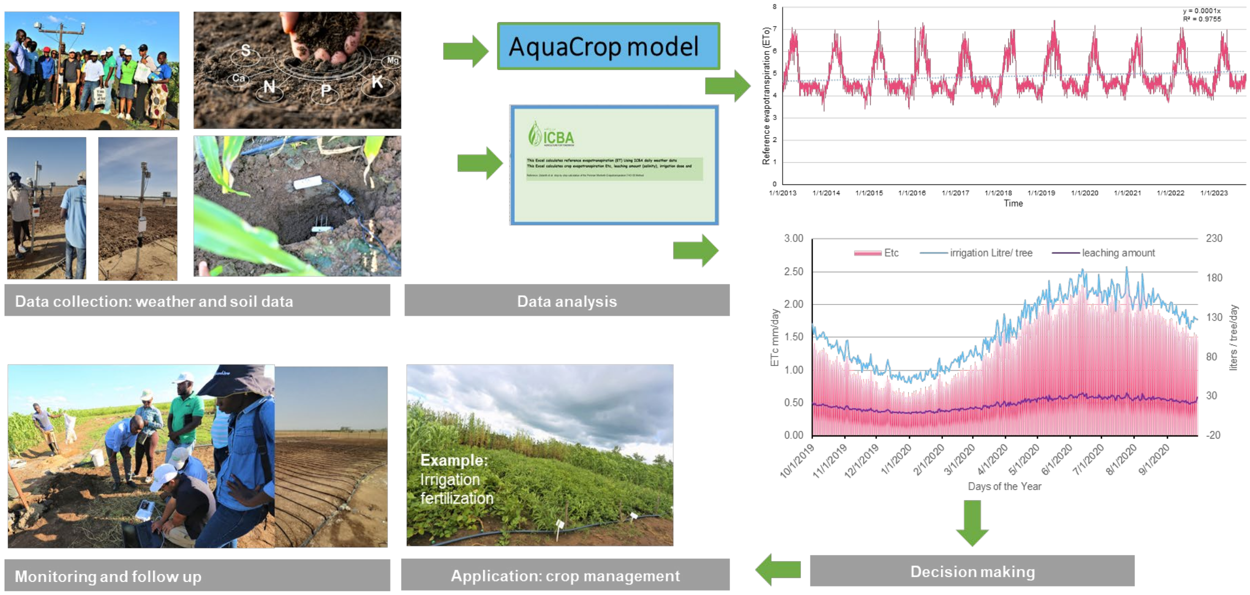
- Climatic conditions
- Irrigation mode
- Irrigation alert criteria (when and how much)
- Irrigation water quality
- Soil type
- Soil fertility
- Sensitivity of the genotype to salinity

Create different scenarios using the model:
During the report phase, we will create different scenarios based on the available data. These scenarios will address various contexts and applications, focusing on key themes and objectives related to RESADE's goals. Each scenario aims to provide useful insights and improve engagement, helping us understand irrigation strategies and water decision-making better. The scenarios will reflect diverse farming situations in RESADE countries, highlighting both challenges and opportunities for thorough analysis and strategic planning.
The following scenarios/outputs will be tested:

- Effects of field conditions on irrigation scheduling, water productivity, and crop performance
- Generation of irrigation schedules
- Salinity of water and soil effect on plant growth and performance
- Genotype effect
- Temperature effect

The objective of the model is to analyze and assess the effects of various factors on irrigation planning and water productivity. By employing this model, we can gain valuable insights into how these factors influence water usage and identify strategies to enhance efficiency and productivity in irrigation planning. Below is a general overview of how data collection and analysis are utilized to manage irrigation and crop cultivation.

The following infographic summarizes the overall strategy for optimal irrigation and drainage allocation in irrigated areas based on soil-water-plant modeling.



2. Required Data

To implement the most effective farming techniques in a specific region, it is essential to gain a thorough understanding of the acquisition and analysis of pedo-climatic data for area characterization. Various methods can be utilized to analyze and accurately characterize this data, ultimately contributing to more successful and sustainable farming practices.

Aqua Crop calculates reference evapotranspiration (ETo) using the FAO Penman-Monteith method, relying on daily weather data. This weather data encompasses maximum and minimum temperatures (in Celsius), mean relative humidity (in percentage), wind speed (in meters per second), and solar radiation (in megajoules per square meter per day). The data is organized within an Excel sheet before being converted to a text file for import into the model as input parameters. The model features an ETo calculator that employs the FAO Penman-Monteith equation to estimate reference evapotranspiration, and it can accommodate weather data presented in various units. The model requires a set of data, as mentioned in Table 1.

Table 1: Data required for the AquaCrop model.

	Category	Required information	Minimum data	Data format and notes
Climate		Daily rainfall, Daily Temperatures Daily humidity Wind Speed / Direction, solar radiation or Light and UV index measurement CO2 concentration	**Min Daily Temperature** **Max Daily Temperature** **Daily Rain**	- all data in one Excel sheet - the ET0 will be calculated using the model

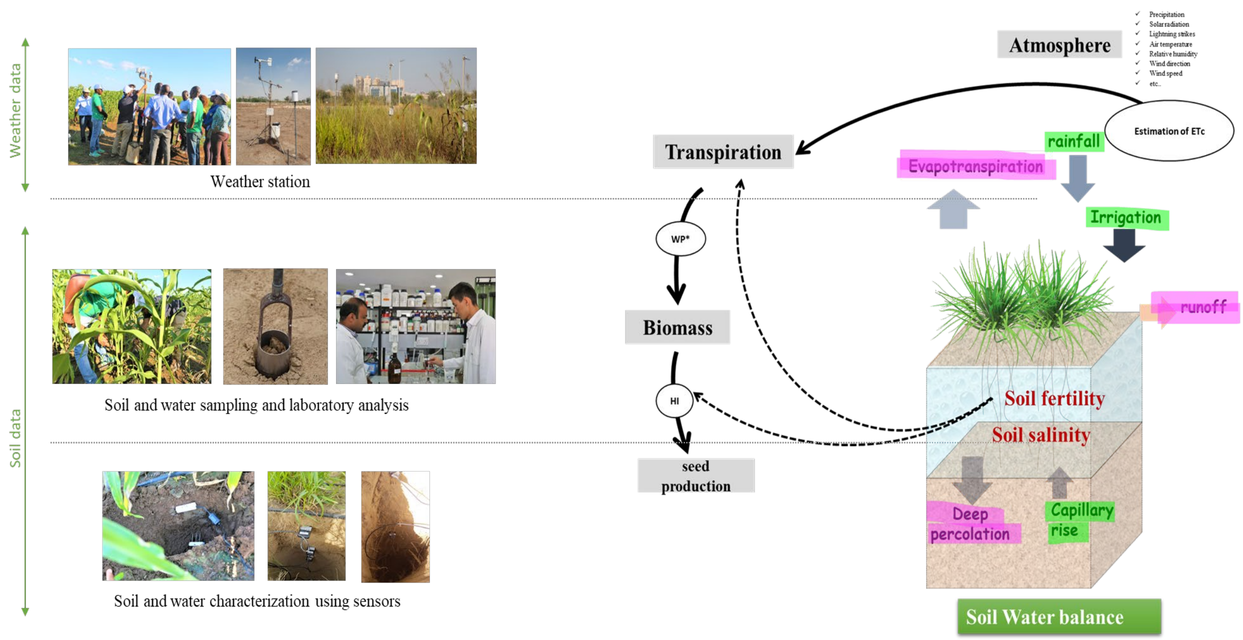
Crop	Limited set	Crop development and production parameters, which include phenology and life cycle	Crop development and plant cycle.	
	Crop parameters	- Harvest index - Root zone threshold at the end of canopy expansion - Threshold root zone depletion for early senescence - Time for maximum canopy cover - Maximum vegetation - Flowering time - Initial vegetative cover - Depletion threshold root zone for stomata closure - Extraction of water	Min required information: - **Initial vegetative cover** (in % it can be 0%) - **Sowing time** - **Plant population /m^2 or ha (sowing rate)** - **Time for maximum canopy cover** (number of days after sowing) - **Flowering time** (number of days after sowing/ date) - **root zone depth.** - Harvest index: **biomass yield and grain yield**	Information in a file The reference crops for this training will be - **Sorghum** - **Rise** **The biomass yield and grain yield of these crops from the field is required**
Soil	Field	Soil fertility, mulch Field practices (surface runoff presence, ground bond)	Basic information about the field: - **Soil fertility (levels: low medium optimal)** - **Mulches (yes, none, etc.)** - **Field surface practices (*If it affects surface runoff or prevents surface runoff, soil bund if exists, etc.)*** - **Weed management**	Information in a file
	Soil profile	Characteristics of soil horizon (no. of soil horizons, thickness, PWP, FC, SAT, K_{sat}); soil surface (runoff, evaporation); restrictive soil layer capillary rise	- **Soil texture of the BPH site (s) if available** - **Soil profile** - **Soil salinity** - **Organic matter**	Information in a file
	Soil water and groundwater	Constant depth, variable depth, water quality	- Water table depth from the surface - The salinity of that water	
Irrigation	Water used for irrigation during the dry season	- **Irrigation mode** - **irrigation schedule**	- **Irrigation mode** (surface irrigation, sprinkler irrigation, drip irrigation. Surface irrigation: basin irrigation Farrow irrigation. - **irrigation schedule** (quantity and timing) - **water salinity levels**	Information in a file
Any additional information related to the crop production system that you collect will be useful for the modeling exercise is a valuable addition.				

3. Methods of characterizing pedoclimatic data to be used in the model in case no field data are available.

To improve agricultural practices, it is crucial to have a comprehensive understanding of the soil and climate conditions in a specific area. Pedo-climatic data provides valuable information that can help devise better farming techniques and achieve higher crop yields. The RESADE project uses both traditional and modern methods.

The RESADE project offers comprehensive hands-on training on methods for characterizing pedoclimatic data that can be utilized in models when no field data is accessible.

Tools and approaches adopted and implemented by RESADE for collecting pedoclimatic data are as follows:



3.1. Sensors installed by RESADE in each BPH

To effectively utilize the AquaCrop model for irrigation management, comprehensive data on various key variables must be gathered. This data can be categorized into two main groups: atmospheric and belowground.

- Atmospheric Data: This data is essential for estimating atmospheric evaporative demand, influencing how much water crops require. Key atmospheric variables include air temperature, humidity, wind speed, and solar radiation, as well as water input through precipitation. To collect this data, the RESADE project has established a fully equipped weather station (Table 2). This station is outfitted with a range of advanced weather sensors capable of measuring essential parameters such as precipitation, barometric pressure, maximum wind gusts, solar radiation, vapor pressure, air temperature, relative humidity, wind direction, and wind speed. The data from these sensors can be accessed in real-time through a dedicated platform (Figure 2), ensuring timely and accurate weather observations.
- Belowground Data: Understanding water availability in the soil is crucial for meeting the water needs of crops. For this purpose, we will monitor several soil-related factors, including soil water content and potential, soil salinity, soil temperature, and water

movement within and beneath the root zone. To achieve this, RESADE installed TEROS-12 sensors from the METER Group, USA (Table 2). These sensors provided measurements, allowing us to assess the soil's moisture conditions and make informed irrigation decisions.

By integrating both atmospheric and belowground data, we aim to create a robust framework for effective irrigation management using the AquaCrop model.

Table 2: Sensor system installed in the BPH.

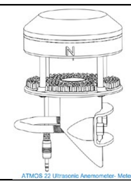
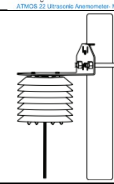
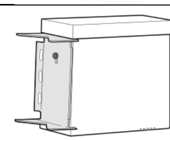
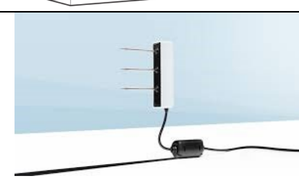
Sensor system installed in the BPH.	Photo
ATMOS 22 Ultrasonic Anemometer • Horizontal wind speed • Wind direction • Wind gust	
ATMOS 14 • Temperature sensor • Relative humidity (RH) sensor	
PYRANOMETER Radiation	
ECRN-50 Rain gauge	
TEROS 12 The TEROS-12 sensors are precise tools for measuring • Volumetric water content (VWC), the temperature in the soil, and soil-less substrates • Electrical conductivity. It has a maximum EC threshold of 20 dS/m. • Soil temperature	
ZL6 DATA LOGGER For data storage and download	

Figure 2: Visualization and data collection remotely using the Zentra Cloud platform, installed by RESADE.

3.2.Climate based on satellite data: Downloading climate data

In areas where climate data is not readily available, it can be challenging to acquire accurate climate parameters. However, a feasible solution to this problem is to obtain these parameters through satellite models that have a proven track record of producing reliable results. In such cases, we recommend using the website developed by the Worldwide Energy Resource (POWER) Project, funded by the National Aeronautics and Space Administration (NASA) Applied Sciences Program. The POWER website is a reliable source of climate data that can be accessed easily through https://power.larc.nasa.gov/data-access-viewer/

3.3.The determination of reference evapotranspiration (ETo)

Determining reference evapotranspiration (ETo) is a critical parameter in fields such as agro-meteorology, hydrology, and irrigation management. Various methods are available for calculating ETo, but the FAO Penman-Monteith method is widely accepted as the standard method for computing ETo (Allen et al., 1998). This technique provides consistent ETo values across different regions and climates and has been verified using a lysimeter under different climatic conditions. In this report, we use climate data from different RESADE countries BPH sites to calculate ETo using the AQUACROP model.

3.4.Soil data

❖ Soil texture testing

Soil texture testing is a simple process that can be done without sending samples to a laboratory. It can provide valuable information about the type of soil used in irrigation. There are two easy methods for testing soil texture. The first and most common method is the jar method, which is typically used for gardening. Although it requires some basic arithmetic skills, it is not complicated. The second method is called the "feel or ribbon" method, which is considered more suitable for experts due to the lack of knowledge about its details. However, this method is easier and faster than the jar method. (https://www.the-compost-gardener.com/soil-texture-testing.html)

❖ FAO Soil Portal for Soil Data Collection

To gain a thorough understanding of the soil, the most accurate approach is to collect and analyze soil samples in a laboratory. However, if this is not a feasible option, other alternatives can still be helpful. One such option is soil data collection through the FAO soil portal. This online platform provides a wealth of soil-related information, such as maps, reports, and databases, which can help you to understand better the soil properties and characteristics of your land (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/.). Although this method may not be as comprehensive as laboratory analysis, it can still provide valuable insights into your soil and inform your agricultural practices.

❖ Soil water properties from the Soil Water Characteristics software

In the absence of data on the soil's water content characteristics (namely, θsat, θcc, and θpfp), it is possible to estimate these values from the results of the soil particle size analysis based on pedo transfer functions. This is one of the most-used functions developed by Saxton et al. (1986 and 2005). The USDA's SPAW software is based on these pedo transfer functions.
https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/drainage/?cid=stelprdb1045331.

3.5.field conditions and crop management practices.

To successfully operate a crop model, a comprehensive understanding of field conditions and crop management practices is essential. Crop management encompasses a range of agricultural activities executed throughout the growing season, beginning with seedbed preparation, followed by seed sowing or transplantation, and culminating in crop maintenance and harvest. The effectiveness of a crop model depends on various parameters, as the timing and sequence of these activities are influenced by several factors, including the type of crop being grown, the season (whether dry or wet), and the end product, such as grain or biomass. Key elements that affect the timing and sequence of agricultural practices include sowing methods, soil type, climate, weather conditions, and the age of the plants. By taking these factors into account, we can optimize crop management practices using dynamic crop models, thereby helping farmers achieve optimal crop yields.

4. Soil-water-plant modeling

Crop simulation models represent a significant asset in agriculture, enabling the prediction of crop yields and the optimization of production under diverse climatic conditions. These models are grounded in mathematical algorithms that articulate the interactions between crops and soil. They may be conceptualized in two frameworks: as a system of equations delineating the dynamics of the crop-soil system or as a series of equations generating relevant outputs based on various explanatory variables. These models primarily estimate crop responses to applied technical packages, plant characteristics, and environmental influences. Technical packages encompass factors such as water management, mineral uptake, and water quality. Plant characteristics include species, varieties, and sensitivity of growth to stress. Environmental influences consist of climate, air pollution, soil texture, and the implications of climate change.

Crop models are extensively employed to simulate the impact of salinity on crop development and final yield, as well as to assess crop water requirements. The SWAP model serves as a prime example, employed to simulate wheat growth under various irrigation strategies utilizing both fresh and saline water. Verma et al. (2012) calibrated and validated the SWAP model from 2000 to 2003, recording simulated relative yield values ranging from 4.2% to 9.7%. Following validation, the model was utilized to demonstrate the long-term effects of saltwater usage on crop growth, revealing that the application of saltwater up to 8 dS/m could preserve over 80% of yield potential and mitigate salt accumulation issues.

AquaCrop has been identified as a reliable and precise model for estimating crop yield under saline stress, specifically regarding soil salinity. This model excels in simulating crop yield responses to water, particularly in regions where water scarcity constitutes a primary constraint to agricultural production. It is founded on the principles of crop yield response to water articulated by Doorenbos and Kassam (1979) and employs input variables that allow for straightforward calculation methodologies (Steduto et al., 2009).

Furthermore, AquaCrop elucidates the core processes underlying crop productivity and responses to water deficits from both physiological and agronomic viewpoints. Daily simulations of crop growth and development utilize either thermal time (i.e., growth degree days) or calendar days. The model has undergone extensive testing by researchers across the globe on various crops in diverse environments, consistently yielding positive outcomes.

This document offers valuable perspectives on simulating crop production growth, estimating crop water requirements, and determining irrigation needs across varied agroecosystems, as illustrated in the figure.

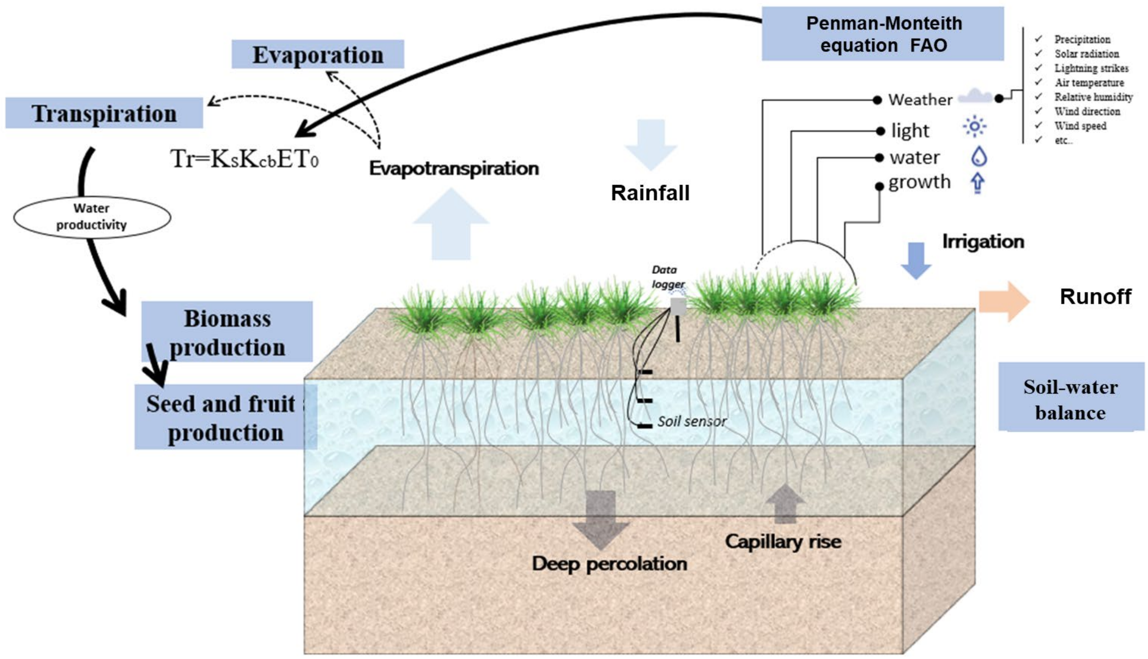


Figure 3: The soil-plant-atmosphere model considered in the RESADE modeling exercise.

4.1.Brief about the model

Aqua Crop is a crop water productivity model that comprises four sub-model components: the soil (water balance), the crop (development, growth, and yield), the atmosphere (temperature, rainfall, evapotranspiration (ET), and carbon dioxide (CO2) concentration), and the management (major agronomy practices such as planting dates, fertilizer application, and irrigation if any). AquaCrop requires five weather input variables to operate, including daily maximum and minimum air temperatures (T), daily rainfall, daily reference evapotranspiration (ETo), and the mean annual CO2 concentration in the bulk atmosphere.

Aqua Crop has several advantages, the foremost being its requirement for only a minimum of input data, which is readily available or can be easily collected. Its simplicity and ease of use make it particularly appealing to farmers, researchers, and policymakers. By providing insights into crop water productivity, AquaCrop can help improve irrigation management, enhance food security, and support sustainable agriculture.

4.2.Description of the AquaCrop model

With AquaCrop, soil, crop, and atmosphere are considered as a continuum and processes that involve the water balance and plant growth, development, and yield processes, along with the atmosphere together with its thermal regime, precipitation, evaporation demand, and carbon dioxide (CO_2) concentration. Aspects of crop management, such as irrigation and soil fertilization, are also considered. The AquaCrop model is based on the relationships between relative yield and relative evapotranspiration (Doorenbos and Kassam, 1979), as follows:

$$\frac{Y_x - Y_a}{Y_x} = K_y\left(\frac{ET_x - ET_a}{ET_x}\right)$$

In this formula, Y_x is the maximum yield and Y_a is the actual yield, ET_x is the maximum evapotranspiration, ET_a is the actual evapotranspiration, and K_y is the yield response factor between the relative decrease in yield and the relative decrease in evapotranspiration.

The AquaCrop model simulates the water content of the soil in the rhizosphere based on the inlet and outlet of water. It is a tool for irrigation management and efficient water use (Raes et al., 2009). Steduto et al. (2009) described the concept, aspects, and basis of the model, and Raes et al. (2006) explained its use.

The AquaCrop model avoids confusion of the effect of unproductive water use on yield by separating evapotranspiration (ET) into crop transpiration (T) and soil evaporation I (Figure 4):

$$ET = E + Tr$$

where ET is actual evapotranspiration, E is soil evaporation, and Tr represents the actual transpiration of the crop.

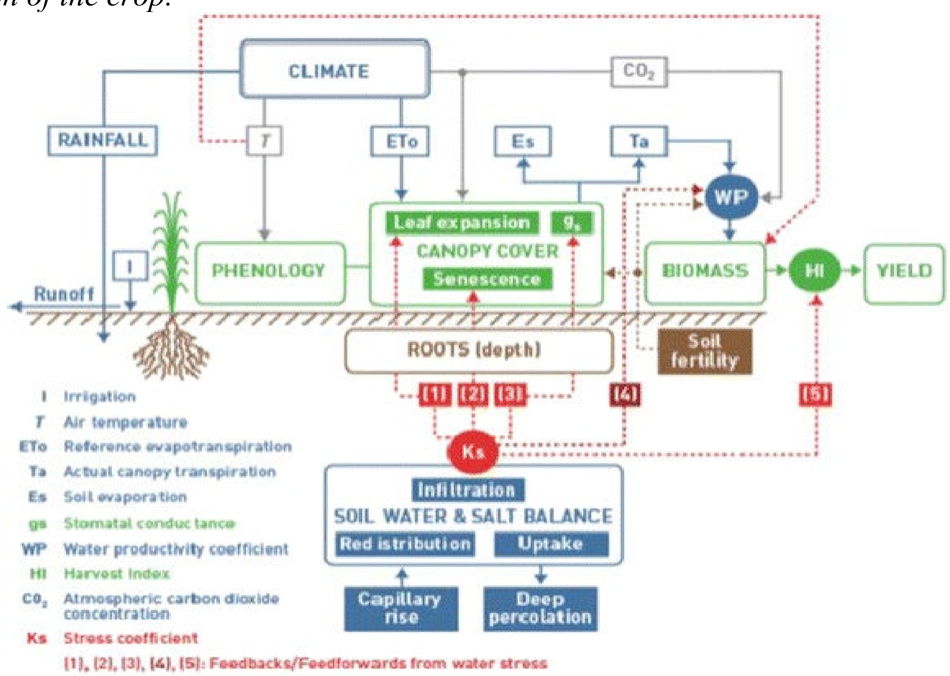


Figure 4: AquaCrop diagram showing the main components of the soil-plant-atmosphere continuum and the parameters characterizing phenology, canopy coverage, transpiration, biomass production, and final yield (AquaCrop reference manual – Steduto et al., 2008).

Abbreviations: I = irrigation; Tn = minimum air temperature; Tx = maximum air temperature; ETo = reference evapotranspiration; E = soil evaporation; Tr = transpiration of the canopy; gs = stomatal conductance; WP = water productivity; HI = harvest index; CO_2 = atmospheric concentration of carbon dioxide; (1), (2), (3), (4), water stress response functions on leaf expansion, senescence, stomatal conductance, and harvest index. Continuous lines indicate direct links between variables and processes. Broken lines indicate feedback.

Using daily time steps, the model successively simulates the following processes: (i) groundwater balance, (ii) development of green canopy (CC), (iii) crop transpiration, (iv) biomass (B), and (v) conversion of biomass to crop yield (Y). So, through the daily potential evapotranspiration (ET_0) and water productivity (WP*), daily transpiration (Tr) is converted into vegetal biomass as follows:

$$B_i = WP^* \left(\frac{T_{ri}}{ETo_i}\right)$$

WP is standardized water productivity (Hanks, 1983; Tanner and Sinclair, 1983). The amount of water stored in the root zone is simulated throughout the plant's growing season by balancing water inputs through irrigation and precipitation and losses by runoff, deep infiltration, efficient evapotranspiration (transpiration), and inefficient evapotranspiration (evaporation) within the root development zone. In this model, canopy cover (CC) is used instead of leaf area index (LAI). Also, the model uses standardized water productivity values for evaporative demands and CO_2 concentrations that give it a high extrapolation capacity for various locations, seasons, and climates (Steduto et al., 2009).*

The estimation and prediction of yield are based on the final biomass and harvest index (HI). This allows a clear distinction between the impact of stress on B and HI in response to the environmental conditions:

$$Y = HI * (B)$$

where Y = final yield, B = biomass, and HI = harvest index.

During the calibration and testing of the model, we calculated water productivity:

$$WP = \left[\frac{Y}{\sum Tr}\right]$$

where Y is the yield expressed in kg/ha and Tr is the daily transpiration simulated by the model.

4.3.Summary of calculation structure

Figure 5 shows a calculation diagram for AquaCrop. With a daily time step, the model successively simulates the following processes:

- ***Step** 1:* Water balance of the soil
- ***Step*** 2: Development of the green canopy (CC)
- ***Step*** 3: Sweating of the crop
- ***Step*** 4: The aboveground biomass (B)
- ***Step*** 5: The conversion of aboveground biomass (B) into yield (Y)

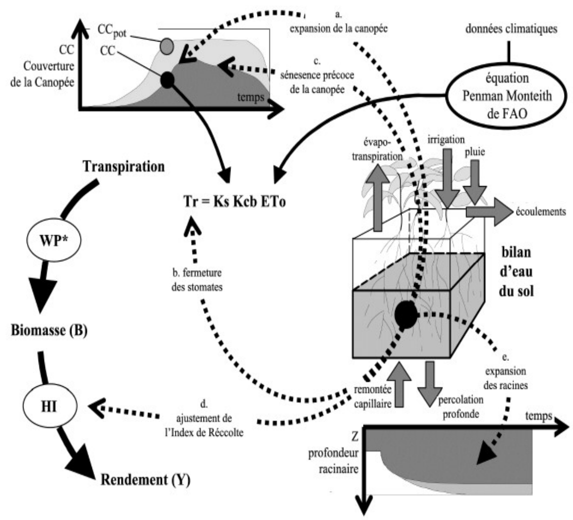


Figure 5: AquaCrop calculation diagram showing (in dotted lines) the processes affected by stress (AquaCrop reference manual – Rael et al. 2017).
Abbreviations: CC = simulated canopy cover, CCp = potential canopy cover, Ks = water stress coefficient, Kcb = crop coefficient, ETo = reference evapotranspiration, WP = water productivity for a standardized crop, and HI = harvest index.*

4.4.Crop response to soil salinity stress

The electrical conductivity of saturated soil paste extracts from the root zone (ECe) is commonly used as an indicator of the soil salinity stress used to determine the total reduction in biomass production, which determines the value for soil salinity stress coefficient ($K_{s,\ salt}$).
The coefficient of soil salinity stress ($K_{s,\ salt}$) varied between 0 (full effect of soil salinity stress) and 1 (no effect). The following equation determined the reduction in biomass:

$B_{rel} = 100 - 1 - K_{s,\ salt})$

B_{rel} represents the expected biomass production under given salinity stress relative to the biomass produced in the absence of salt stress. The coefficient is adjusted daily to the average ECe in the root zone.

It is well established that the reduction in biomass production due to salinity results from the closure of the stomata and poor development of the vegetation cover, which involve slow expansion of the canopy, low canopy cover, and a decline in canopy during the crop cycle.
In AquaCrop, this total reduction in biomass is determined by a stress coefficient of the salinity of the soil ($K_{s,\ salt}$), whose value depends on the average electrical conductivity of the extracts of the saturated paste of the soil (ECe) of the root zone. The stress coefficient of soil salinity ($K_{s,\ salt}$) varies between 0 tbsp of the full effect of soil salinity stress and 1 tbsp (i.e., no effect of salinity; Figure 5).

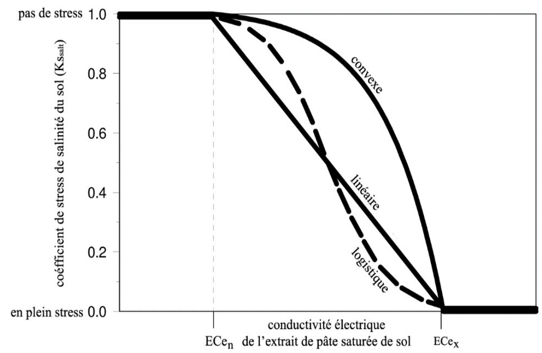


Figure 6: The different shapes of the K_s curve (AquaCrop reference manual – Rael et al*.,* 2017).

Soil salinity similarly influences the development of the green canopy (CC) and the productivity of biomass water (WP*). It also directly influences crop transpiration by closing the stomata (Figure 6).
In AquaCrop, the effect of soil salinity stress on the crop can be specified by choosing a crop sensitivity class or by specifying the crop's threshold values for soil salinity in its root zone. The electrical conductivities of the saturated soil paste extracts (CEe) are given for thresholds and expressed in deciSiemens per meter (dS/m): the lower threshold (ECin) at which soil salinity stress begins to affect biomass production and the upper threshold (ECex) at which soil salinity stress has reached its maximum effect and stress becomes so severe that biomass production stops.

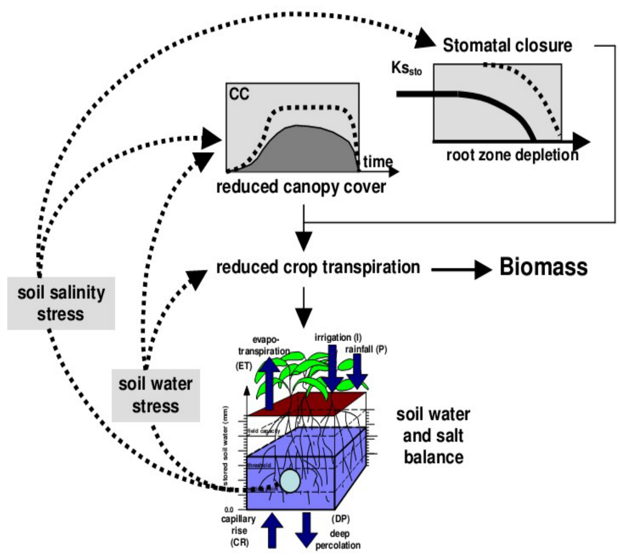


Figure 7: The effect of soil salinity and water stress on biomass production (AquaCrop reference manual – Rael et al., 2017).

4.5.Soil salinity estimation

AquaCrop adopts the calculation procedure presented in BUDGET to simulate the movement and retention of salt in the soil profile. After irrigation using saline water, salts enter the soil profile through capillary action, rising from a shallow groundwater table (vertical downward and upward salt movement). The average ECe in the compartments of the effective rooting depth determines the effects of soil salinity on biomass production.

To explain the movement and retention of soil water and salts in the soil profile, AquaCrop divides the soil profile into 2 to 11 soil compartments called "cells," depending on the type of soil in each horizon (clay, sandy) and its saturated hydraulic conductivity (K_{sat} in mm/day). The salt diffusion between two adjacent cells (cell j and cell j + 1) is determined by the differences in salt concentration and is expressed by the EC of the soil water.
AquaCrop determines the vertical salt movement in response to soil evaporation, considering the amount of water extracted from the soil profile by evaporation and the wetness of the upper soil layer. The relative soil water content of the topsoil layer determines the fraction of the dissolved salts that moves with the evaporating water.
AquaCrop determines the vertical salt movement because of capillary rise. Finally, the salt content of a cell is determined by:

$$Salt_{cell} = 0.64\, W_{cell} EC_{cell}$$

where $Salt_{cell}$ is the salt content expressed in grams of salts per m^2 soil surface, W_{cell} its volume expressed in liters per m^2 (1 mm = 1 L/m^2), and 0.64 a global conversion factor used in AquaCrop to convert dS/m to g/L.

The electrical conductivity of the soil water (EC_{sw}) and of the saturated soil paste extract (ECe) at a particular soil depth (soil compartment) is calculated as

$$EC_{sw} = \frac{\sum_{j=1}^{n} Salt_{cell.j}}{0.64\,(1000\,\theta\Delta_z)\left\{1 - \frac{Vol\%_{gravel}}{100}\right\}}$$

$$EC_e = \frac{\sum_{j=1}^{n} Salt_{cell.j}}{0.64\,(1000\,\theta_{sat}\Delta_z)\left\{1 - \frac{Vol\%_{gravel}}{100}\right\}}$$

where n is the number of cells in each soil compartment, θ is the soil water content (m^3/m^3), θ_{sat} is the soil water content (m^3/m^3) at saturation, Δz (m) is the thickness of the soil compartment, and Vol% gravel is the volume percentage of the gravel in the soil horizon of each compartment.

Sierra Leone

1. General information

Sierra Leone, a country located in West Africa, is known for its high rainfall levels throughout the year, with an annual average ranging from 2,000 to 4,000 mm, according to the Sierra Leone Agricultural Research Institute. This country has been blessed with seven main rivers that flow through it, providing enormous potential for irrigation. In 1981, the Food and Agriculture Organization (FAO) estimated that Sierra Leone's irrigation potential was 807,000 hectares. Surprisingly, despite the abundant water resources available, only an estimated 0.3 km^3/year is utilized primarily for agricultural activities, as reported by the Ministry of Agriculture, Forestry, and Food Security - Ministry of Fisheries and Marine Resources (MAFFS-MFMR) in 2004. This is mainly due to the absence of a national strategy to use surplus annual rainfall to extend the agricultural growing season. It is important to note that the total river catchment area in Sierra Leone ranges from 720 to 14,140 km^2 (Figure 8).

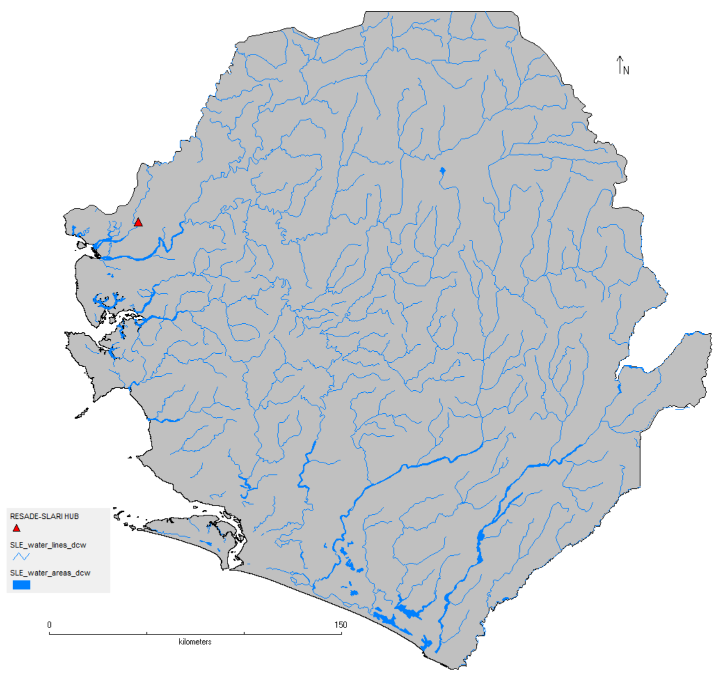
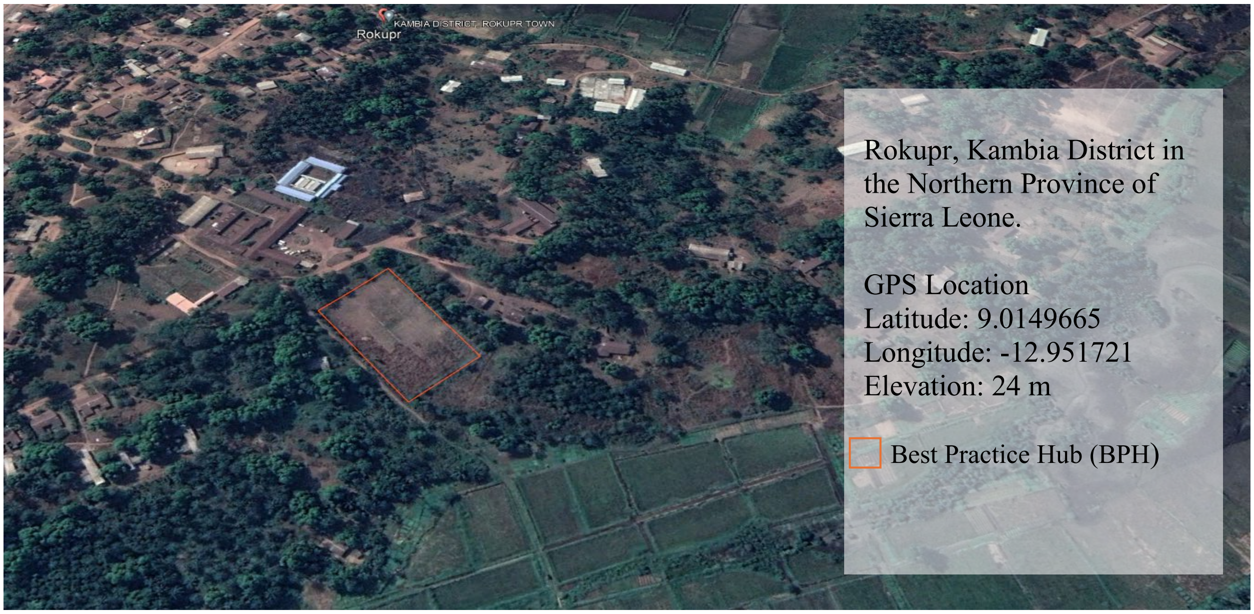


Figure 8: Sierra Leone map with the geographical distribution of water and rivers as well as the Best Practice Hub location.
DIVA-GIS software (version 7.5) was used to create the maps.

2. Study site characterization

2.1. Site name

Site name: RESADE-SLARI HUB, Location: Rokupr
Rokupr is a small town in Kambia District in the Northern Province of Sierra Leone.



Best Practice Hub (BPH), Rokupr, Kambia District in the Northern Province of Sierra Leone.

2.2.Soil characteristics

The soil information includes both the physical and chemical properties of the soil (Table 4) and its water status (Table 5) for the Hub situated in the Rokupr region of the Kambia District, Northern Province of Sierra Leone. This data has been gathered from the FAO portal and analyzed using Soil Water Characteristics software to assess the proposed Soil Water Properties.

Table 4: Physical and Chemical Properties of the Soil of the Hub in the region of Rokupr, Kambia District in the northern province of Sierra Leone.

Parameters	**Topsoil (0-30 cm)**	**Subsoil (30-60)**
Sand Fraction (%)	52	48
Silt Fraction (%)	25	24
Clay Fraction (%)	23	28
USDA Texture Classification	sandy clay loam	sandy clay loam
Reference Bulk Density (kg/dm3)	1.41	1.37
Bulk Density (kg/dm3)	1.31	1.3
Gravel Content (%)	1	5
Organic Carbon (% weight)	0.95	0.35
pH (H2O)	4.7	4.9
CEC (clay) (cmol/kg)	16	12
CEC (soil) (cmol/kg)	6	5
Base Saturation (%)	39	57
TEB (cmol/kg)	2.6	3.7
Calcium Carbonate (% weight)	0	0
Gypsum (% weight)	0	0
Sodicity (ESP) (%)	2	2
Salinity (ECe) (dS/m)	0.1	0.1

Table 5: Soil-Water Status of the Hub in the region of Rokupr, Kambia District in the Northern Province of Sierra Leone.

Parameters	Unit	Topsoil (0-30 cm)	Subsoil (30-60)
Wilting point	% vol	11.40	18.20
Field capacity	% vol	27.10	30.20
Saturation	% vol	44.50	44.80
Available water	in/ft	1.39	1.43
Salt hydraulic conductivity	in/ha	0.52	0.30
Matric bulk density	Ib/ft3	91.81	91.30

1 in/ft=83.33 millimeter/meter

2.3.Weather condition

Climate data for daily precipitation and maximum and minimum temperature in the Rokupr region of Kambia District, located in the Northern Province of Sierra Leone, was collected between January 1st, 2013, and December 31st, 2023 (Figure 9). This data was obtained from the Worldwide Energy Resource (POWER) Project, which is funded by the National Aeronautics and Space Administration (NASA) Applied Sciences Program. The POWER website is a dependable source of climate data and can be easily accessed through https://power.larc.nasa.gov/data-access-viewer/.

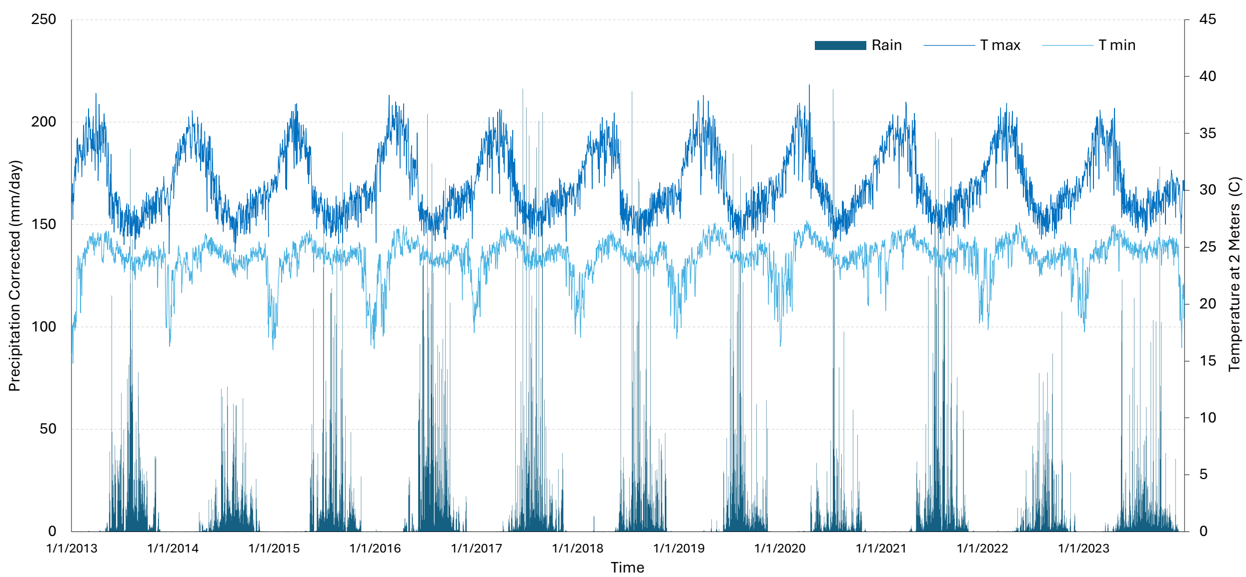


Figure 9: Daily precipitation, maximum and minimum temperature in the region of Rokupr, Kambia District in the Northern Province of Sierra Leone, from January 1st, 2013, to December 31st, 2023.

To assess the water requirements for irrigation, daily reference evapotranspiration (ETo) was determined using the FAO Penman-Monteith method. This calculation was based on weather data collected daily over a ten-year period, from January 1, 2013, to December 31, 2023. The AquaCrop model facilitated this process, enabling precise evaluation of ETo by taking into account various climatic factors during this span (Figure 10).

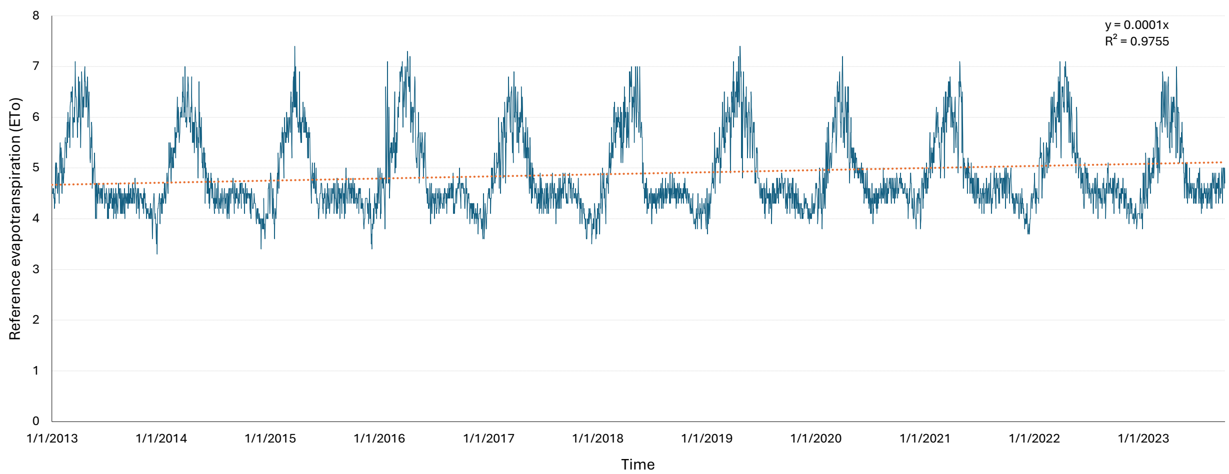


Figure 10: Daily Reference evapotranspiration (ETo) in the region of Rokupr, Kambia District in the Northern Province of Sierra Leone, from January 1st, 2013, to December 31st, 2023.

The sensing system installed in the BPH was utilized to gather crucial data concerning the field's weather conditions. This real-time data, illustrated in Figure 11, was used to fine-tune and calibrate the online generated data from satellites, ensuring greater accuracy and precision.

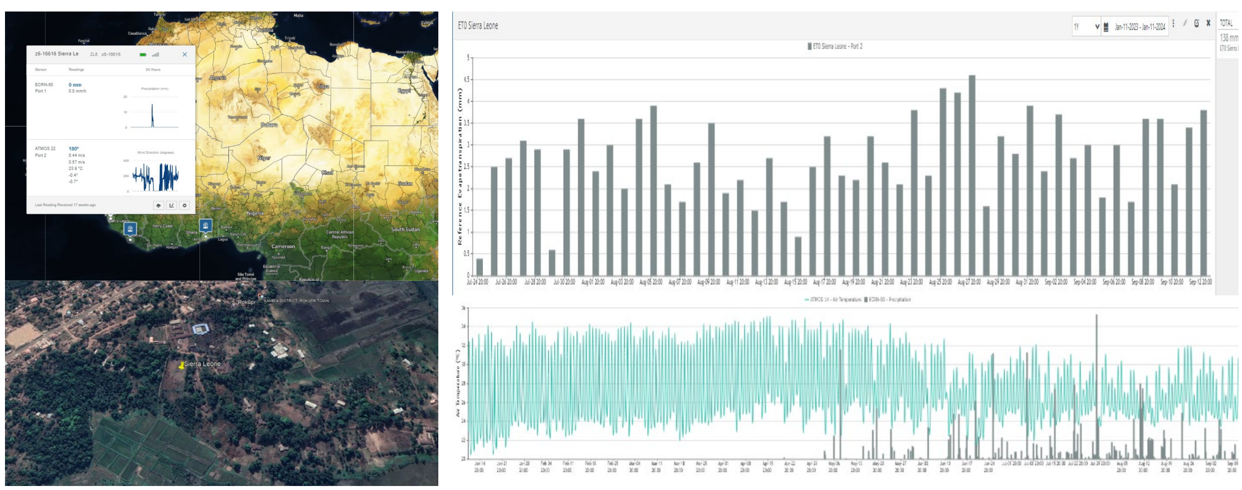


Figure 11: Climatic data collected and analyzed in real-time using the sensor installed in the BPH.

2.4.Soil sensors data

Precision agriculture is a farming management technique that aims to increase the accuracy and efficiency of crop growth. The primary goal of this technique is to achieve efficiency, profitability, and sustainability while also protecting the environment.

This component aids in data-driven irrigation scheduling and helps determine the actual water requirements of selected crops, allowing significant potential for on-farm water and energy savings. The objective of sensory system platforms is to estimate atmospheric evaporative demand, below-ground data, and plant data. This helps measure the plant's response to atmospheric water demand and soil water supply. The final aim is to fine-tune crop coefficients required for irrigation and other management practices. This, in turn, increases crop productivity while preserving natural resources, mainly water and soil.

The system improved irrigation and fertilization practices generated quantitative data for water-saving initiatives and capacity-building efforts, and supported water security. Figure 12 displays the estimated soil water content data and the percentage of plant-available water for Hub-Rokupr, Sierra Leone, during 2022-2023, using TEROS 12 Moisture/Temp/EC sensors. Additionally, Figure 13 shows the percentage of plant-available water in the BPH-Rokupr area, indicating a management allowable depletion (%VWC) of around 50%. The result confirmed the need for supplementary irrigation during the dry season.

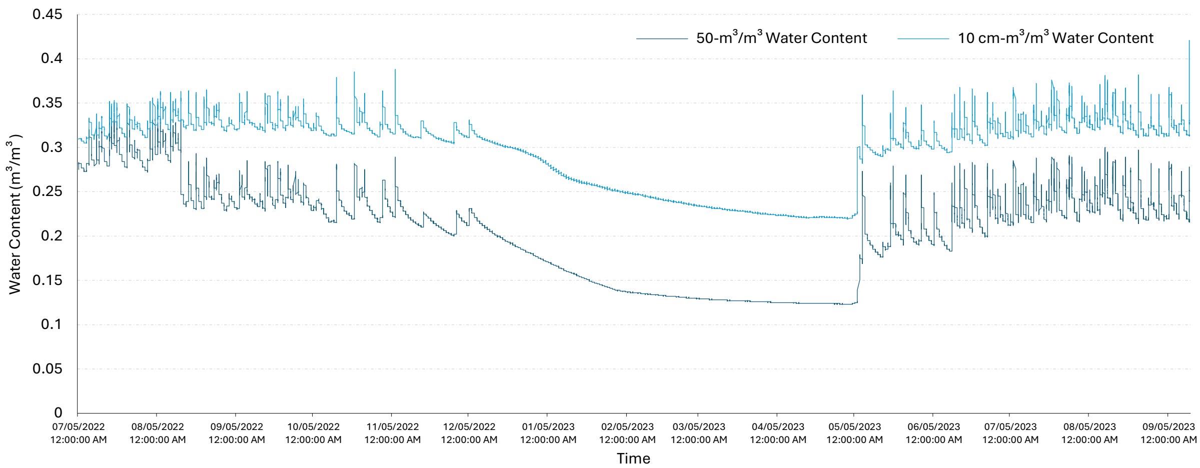


Figure 12: Soil Water Content during 2022-2023 in the Hub- Rokupr, Sierra Leone, estimated using TEROS 12 Moisture/Temp/EC sensors.

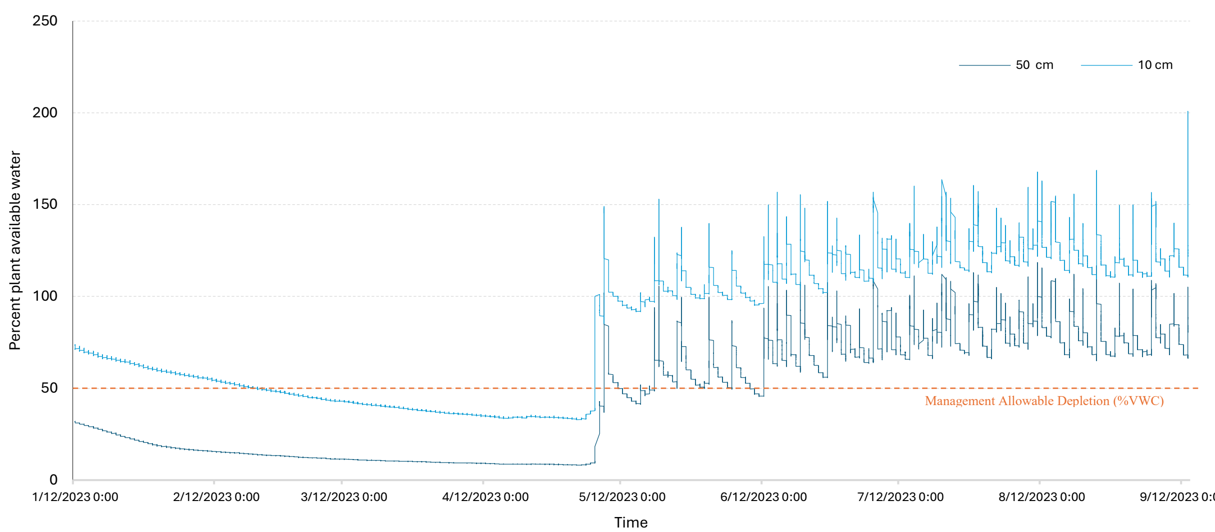


Figure 13: Percent plant available water in the BPH- Rokupr, Sierra Leone with a management allowable depletion (%VWC) around 50%.

3. Simulation modeling results

AquaCrop is a tool that can be used easily in the RESADE target countries. It operates on a few essential parameters and predominantly utilizes straightforward input variables, which can be gathered through simple methods. The required inputs encompass various aspects, including weather data, detailed crop characteristics, and specific soil attributes. Additionally, it incorporates a comprehensive overview of field and irrigation management practices that outline the growing environment for the crops. Soil characteristics are categorized into two key areas: the soil profile, which includes various layers and their properties, and soil water characteristics, providing a complete picture of the soil's hydrological conditions. This holistic approach ensures that crop models effectively support agricultural planning and decision-making processes.

3.1.Calculation of the reference evapotranspiration (ETo)

AquaCrop was used in this report to calculate the reference evapotranspiration (ETo) using the FAO Penman-Monteith equation (Figure 14), based on weather data collected from online open sources and a weather station installed at BPH.

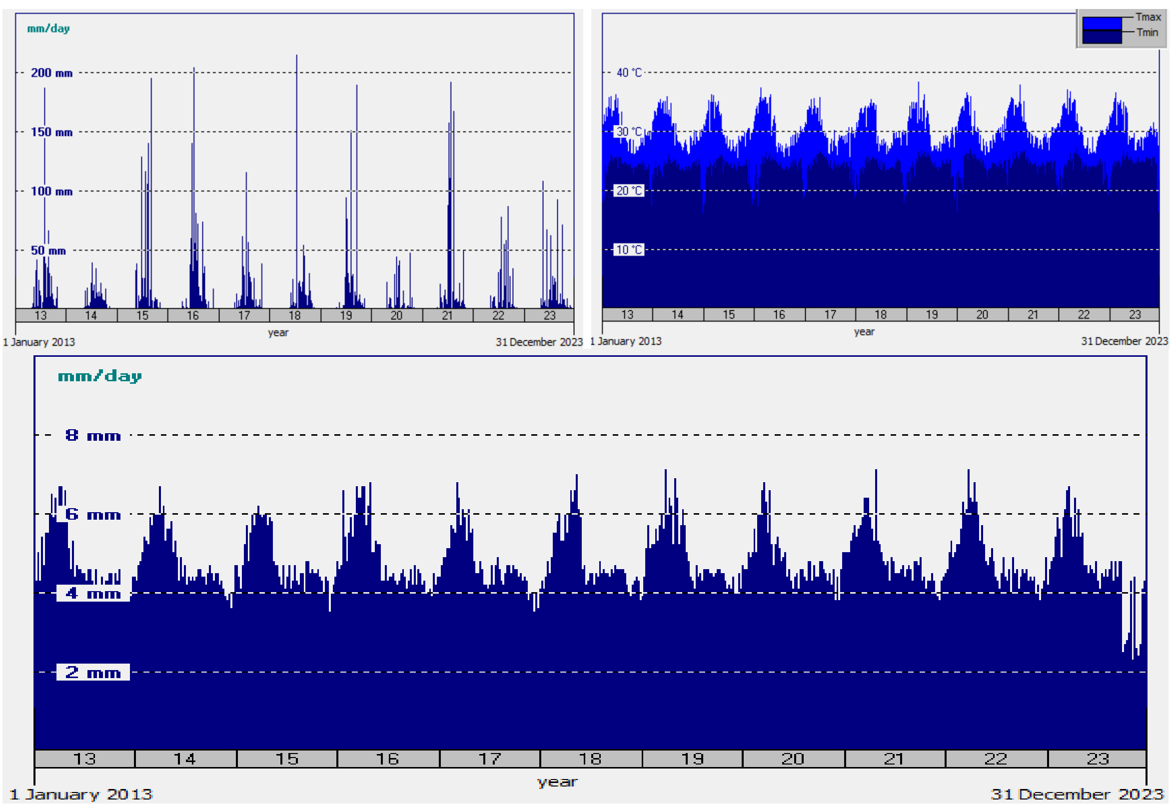


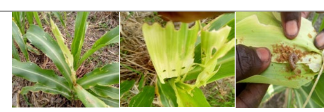
Figure 14: Weather condition (rain and temperature) and the reference evapotranspiration (ETo) estimated by Aquacrop through the FAO Penman-Monteith equation.

3.2.Sorghum

3.2.1. Crop performance and management:

The Sierra Leone Agricultural Research Institute (SLARI) has provided the following crop management details. Effective crop management practices data are crucial for the use of any crop model. These practices encompass various agricultural activities conducted throughout the growing season, including seedbed preparation, sowing, crop maintenance, and harvesting. The collected information is summarized in Table 6.

Table 6: Crop management details in the region of Rokupr, Kambia District in the Northern Province of Sierra Leone.

Operation	Dates and Notes	Photos or remarks from the field
LAND PREPARATION	On February 24th, 2023, the land was prepared by clearing and brushing it.	
SOWING	On March 2nd, 2023, Sorghum and Pearl Millet were seeded. The seeds were pre-germinated to prevent insect and bird issues. Plant spacing was 50cm between plants and 75cm between rows, resulting in a plant population of 226,666 per hectare.	 Farmers participate in the sowing of Sorghum at BPH
IRRIGATION AND MULCHING	Water from the borehole is used twice daily to irrigate the crops, which are also mulched to minimize weed growth and optimize water use. Weekly water samples are taken to test for salinity.	 Irrigating field using the watering can during the dry season cropping period.
WEEDING	The field was weeded twice, on April 18th and 20th, 2023, and then again on May 8th.	 Field weeding by the farmers
FERTILIZATION	May 21st, 2023 $80kgNha^{-1}$, $40kgP_2O_5ha^{-1}$ and $40kgK_2Oha^{-1}$ were made as a recommendation, but on application: the first dose at a rate $40kgNha^{-1}$, $40kgP_2O_5ha^{-1}$and $40kgK_2Oha^{-1}$ was made using 160g NPK 15:15:15. The last two doses were made using Urea at a rate of 20$kgNha^{-1}$ each (22g) as splits as F2.	 Technician demonstrating the application of Fertilizer.
PEST MANAGEMENT	On the May 9th Applying wood ash on newly emerging leaves of the crop plants to control pest attacks.	 Plant affected by stem borer attack
DATA COLLECTION	Colleagues and technicians have collected data periodically since the trial's establishment. Parameters such as plant height, panicle length, panicle weight, and fresh biomass yield were measured in the field. Samples were dried in an oven at 70°C for 3 days before being weighed in a desiccator.	 Field data collection by Technicians

HARVESTING	On the 16th of May 2023 Notes: For the variety grown, the leaves continue to be green even when the crop is mature for harvesting, unlike local varieties, which, upon maturity, become pale and dry, losing the green component.	 Assessing the Pearl millet crop for maturity before harvesting
HARVESTING OF SORGHUM	July 10th 2023	
THE DRYING PROCESSING	Sorghum was sun-dried for five days before being threshed and winnowed to separate seeds from chaff. The seeds were dried again until tested for 11.5% moisture content using a moisture meter.	

3.2.2. Simulation Modeling Results and Development of Different Scenarios

Upon completing model calibration using the available data, the model was utilized to derive various production scenarios, which have been succinctly presented in Table 7. The results are a testament to the effectiveness of the model and its ability to produce valuable insights into the production process.

The simulation results highlighted that one of the main factors causing yield loss in Sierra Leone is the widespread issue of weed infestation. When weeds are present at a moderate level, they can significantly reduce biomass, leading to an estimated decline of 4 tonnes per hectare, as illustrated in Table 7. Another crucial aspect contributing to this problem is low soil fertility, primarily due to insufficient fertilization practices, which is responsible for about 60% of the reductions in crop yields.

The situation worsens when this low soil fertility is further aggravated by the use of saline water, particularly water with a salinity level of 6 dS/m. In these scenarios, the potential crop yield could drop by as much as 20 tonnes per hectare from a possible maximum of 27 tonnes per hectare.

This challenges the common beliefs regarding soil fertility issues in Sierra Leone, underscoring that soil quality is indeed the primary driver of yield losses. Additionally, it is crucial to consider the complicating factors related to salinity, as they further hinder agricultural productivity.

Table 7: Sorghum yield and biomass estimated using Aquacrop model

Scenario	**Estimated**		**Observed**	
	Biomass T/ha	Yield T/ha	Biomass T/ha	Yield T/ha
Sorghum- Sowing during the dry season, with irrigation- fresh water	27.33	5.02	27.25	
Sorghum- Sowing during the dry season, with irrigation- saline water	27.09	4.99	27.51	
Sorghum- Sowing during the dry season without irrigation	25.5	4.8		
Sorghum- Sowing during the dry season, with irrigation- fresh water-medium weed	23.59	4.46		
Sorghum- Sowing during the dry season, with irrigation- fresh water-medium weed-no fertilization	11.85	2.18		
Sorghum- Sowing during the dry season, with irrigation- saline water-medium weed-no fertilization	7.55	1.39		

Figure 15 compares the cumulative crop biomass of sorghum grown under various production conditions. The results indicate that salinity alone does not significantly impact biomass yield. However, the combination of multiple stressors, namely saline water, competing weeds, and the lack of fertilization, greatly diminishes the biomass production of sorghum. This suggests that while salinity by itself may not pose a significant threat, the synergistic effects of these stress factors can substantially impede the crop's growth and productivity.

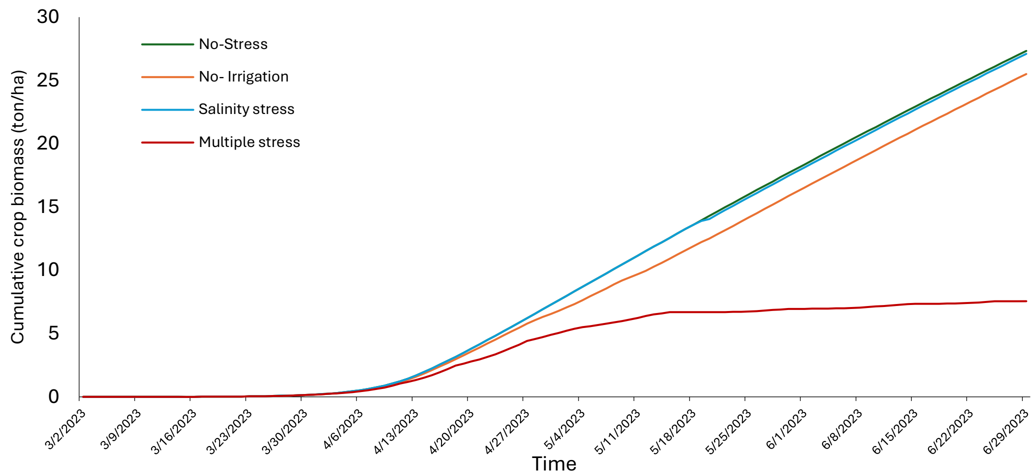


Figure 15: Cumulative crop biomass of sorghum cultivated under different production factors.

3.2.3. Water balance in the soil:

Table 8 summarizes model outputs concerning soil water balance and water productivity for sorghum under various production scenarios. When planted during the dry season, sorghum requires approximately 200 mm of irrigation to satisfy its water requirements. It's important to note that while Sierra Leone experiences significant rainfall during this period, the distribution is not uniform, which may highlight the necessity for supplementary irrigation.

Figure 16 illustrates the soil water content throughout the sorghum growth cycle in the BPH region with complementary irrigation. The results indicate that the irrigation schedule proposed by the model effectively maintains soil water content between the wilting point and field capacity. This ensures an adequate water supply for the sorghum crop while avoiding over-irrigation, ultimately leading to improved crop performance. In mid-May, the onset of the rainy season raised soil moisture levels to saturation at various points during the growth cycle.

Table 8: Model outputs related to soil water balance and water productivity for Sorghum under different production scenarios.

Scenario	Rain	Irri	Ev	Tr	ET0	Infilt	Drain	WPet	Soil ECi	Soil ECf
Sorghum- Sowing during the dry season, with irrigation- fresh water	989.7	195.3	109.6	398.5	654.8	1185	623.6	0.98	0.1	0.1
Sorghum- Sowing during the dry season, with irrigation- saline water	989.7	202.1	11.6	401.7	654.8	1191.8	66.5	0.98	0.1	0.28
Sorghum- Sowing during the dry season without irrigation	989.7	0	76.1	372.4	654.8	989.7	488	1.09	0.1	0.1
Sorghum- Sowing during the dry season, with irrigation- fresh water-medium weed	989.7	202.1	11.6	401.7	654.8	11.91.8	660.5	0.87	0.1	0.1
Sorghum- Sowing during the dry season, with irrigation- fresh water-medium weed-no fertilization	989.7	162.6	202.7	262.2	654.8	1152.3	673.1	0.47	0.1	0.1
Sorghum- Sowing during the dry season, with irrigation- saline water-medium weed-no fertilization	989.7	153.2	100.5	123.3	654.8	849.1	562.0	0.62	0.1	0.5

Rain: Rainfall; Irri: Water applied by irrigation; Ev: Soil evaporation; Tr: Total transpiration of crop and weeds ET: Evapotranspiration; Infilt: Infiltrated water in soil profile; Drain: Water drained out of the soil profile; WPet: ET Water productivity for yield part (kg yield produced per m3 water evapotranspired); Soil Eci: soil salinity before plantation; Soil ECf: soil salinity after the season; EC Electrical conductivity of the saturated soil-paste extract (ECe in dS/m)

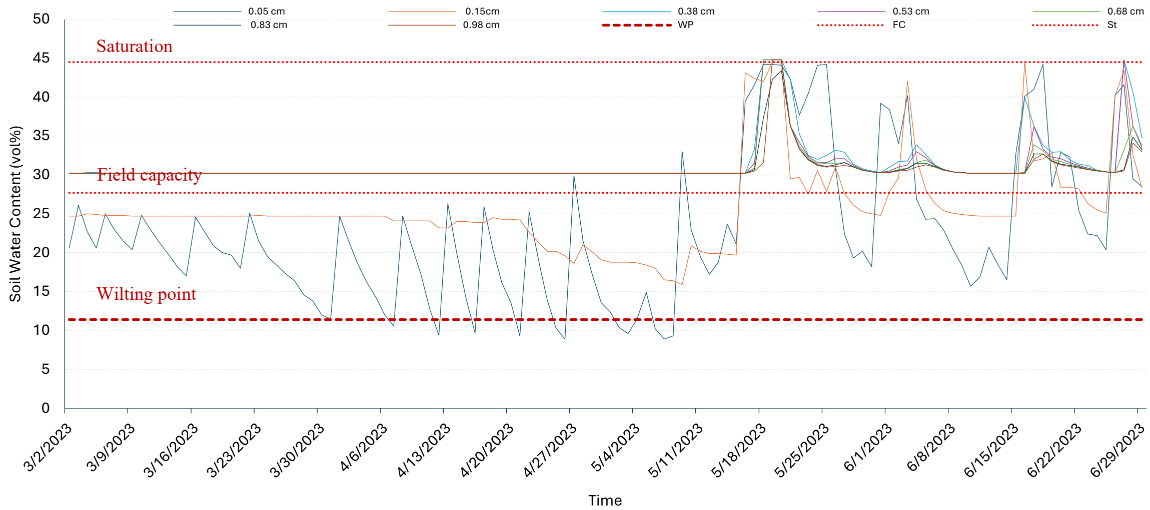


Figure 16: soil water content in case of complimentary irrigation during the sorghum growth cycle in the BPH in the region of Rokupr, Kambia District in the Northern Province of Sierra Leone

In the absence of irrigation, the soil moisture at a depth of 0 to 30 cm drops below the wilting point at the beginning of the crop's growth cycle (Figure 17). If no irrigation is provided, a significant reduction in crop yield is observed.

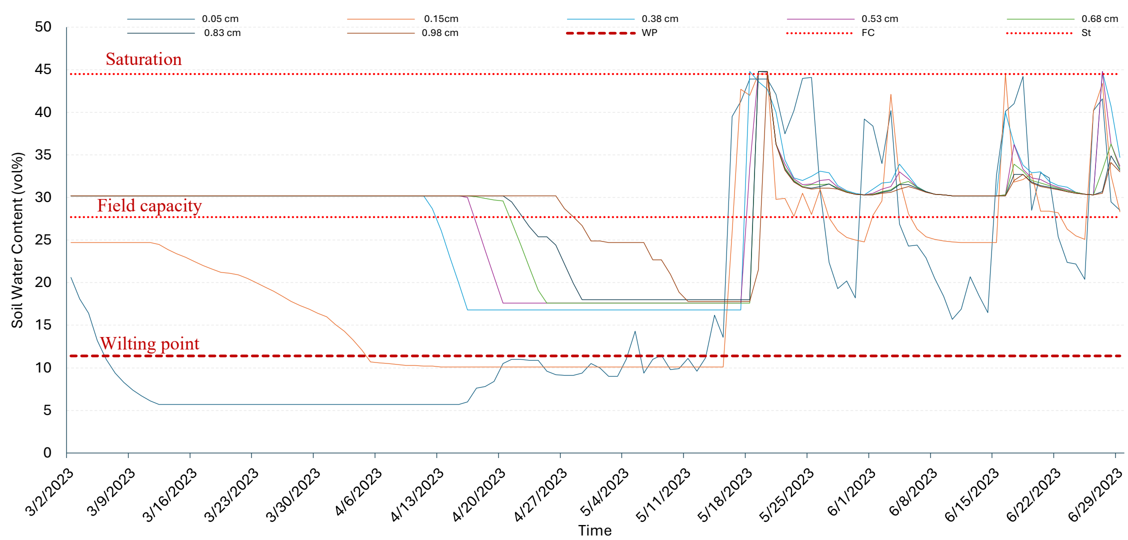


Figure 17: Soil water content in the scenario of the absence of irrigation during the sorghum growth cycle in the BPH in the region of Rokupr, Kambia District in the Northern Province of Sierra Leone.

To guarantee an adequate water supply for the crops, it was essential to implement irrigation systems that could fulfill their hydration needs before the arrival of substantial rainfall (Figure 18). This effective rainfall, which usually begins in May, plays a crucial role in supporting crop growth, but in its absence, timely irrigation is vital to keep the plants healthy and thriving during the dry months leading up to that pivotal season.

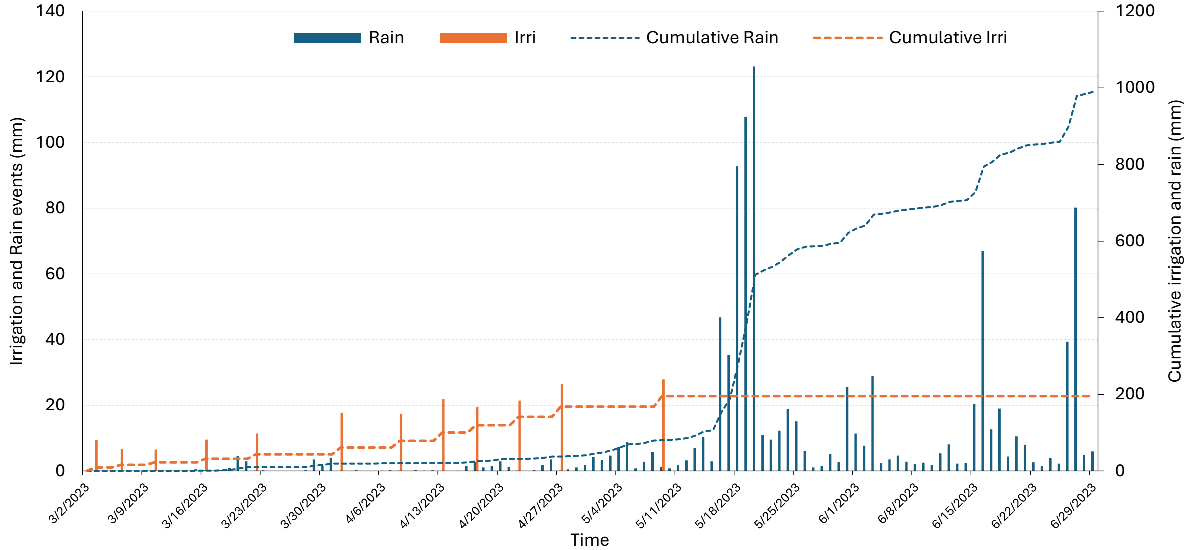


Figure 18: Irrigation and Rain events and their accumulation during the sorghum growth cycle in the BPH in the region of Rokupr, Kambia District in the Northern Province of Sierra Leone.

3.2.4. Salinity build-up risk in case of irrigation with saline water of 6dS/m

The simulation results reveal that specific areas in Sierra Leone are not susceptible to salinity accumulation (Figure 19). When irrigation was conducted using saline water with a conductivity of 6 ds/m, an increase in soil salinity was observed. However, following the initial rainfall in May, there was a notable decrease in salinity levels, as the rain effectively leached away the salt that had built up in the soil profile, reaching depths of up to 1.73 meters.

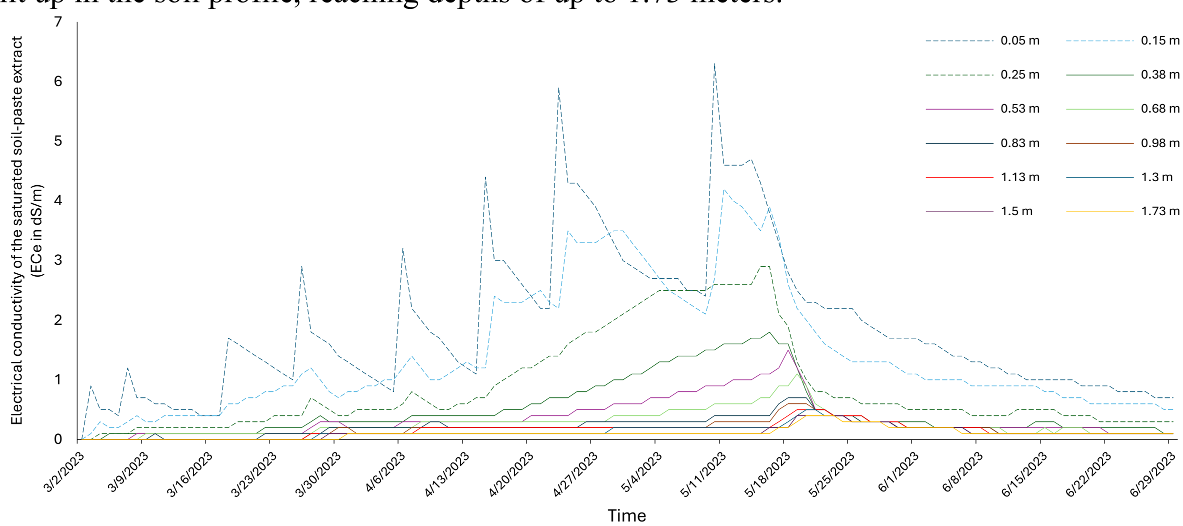


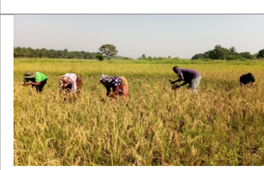
Figure 19: Electrical conductivity of the saturated soil-paste extract (ECe in dS/m) at various depths of the sorghum field irrigated with saline water of 6 dS/m, estimated by the Aquacrop model.

3.3.Rice production and simulation

3.3.1. Crop management

The SLAR-RESADE team has provided comprehensive crop management details. These practices cover various agricultural activities throughout the growing season, including soil preparation, sowing, crop maintenance, and harvesting. The collected information is summarized in Table 9.

Table 9: Crop management details in the region of rice plantation in Sierra Leone.

Operation	Dates and Notes	Photos or remarks from the field
Land preparation	Land was brushed and cleared prior to digging and harrowing.	
Sowing	**TRANSPLANTING** The first batch of one-month-old seedlings (SD1) was uprooted and transplanted on August 1st, 2022, at a spacing of 25cm x 25cm and about two seedlings per hill. The second and third batches were transplanted on September 2nd, 2022, and October 3rd, 2022, respectively.	 Transplanting of young rice seedlings by farmers at the demonstration plot
Fertilization	**FERTILIZER APPLICATION** fertilizer at a rate of **$90kgNha^{-1}$** to **$60kgP_2O_5ha^{-1}$** After the first batch of one-month-old seedlings were transplanted in the three replications, basal fertilizer application was made using **NPK 0:20:20** and the first split of **Urea (46%)**. Application was made at **$30gm^{-2}$** to **$36gm^{-2}$** using **NPK 0:20:20** as **$60kgP_2O_5ha^{-1}$** and **$60kgK_2Oha^{1}$**. Application was also made with Urea (46%) at **$22.5kgNha^{-1}$** as 1st split. At 4 weeks after transplanting, only Urea (**46%)** was again applied at **$4.9\ gm^{-2}$** and **$5.9\ gm^{-2}$** as 2nd split respectively. The 3rd and 4th split doses were applied at the booting and panicle initiation periods using the same quantities with Urea only.	 Rice varieties of trial and demonstration plot are nursed at the BPH.
HARVESTING OF RICE	Manuel harvest	 Farmers took part in the harvesting of rice

The salinity levels of soil and water samples collected during the main season of transplanting were analyzed and documented. The results are in Table 10.

Table 10: salinity results for both soil and water samples taken during Main season transplanting.

Trial	Date of Transplanting	Soil Salinity (dSm^{-1}) (1:5)	Water Salinity (dSm^{-1})
Sowing date 1	21 /08/2023	3.18	6.04
Sowing date 2	23 /09/2023	3.27	5.29
Sowing date 3	24/10/2023	2.98	5.18

3.3.2. Simulation results

Following the calibration of the model with the available data, multiple production scenarios were generated. This iterative approach allowed for the examination of various outcomes and demonstrated the model's robustness and accuracy. The results obtained highlight the model's effectiveness and its capability to provide insights into the complexities of the production process. A summary of the simulation results for these scenarios is presented in Table 11, which is also clearly visualized in Figure 20.

Table 11: Yield and biomass estimated using the AquaCrop model for rice production under different scenarios.

Scenario	Estimated		Observed	
	Biomass t/ha	Yield t/ha	Biomass t/ha	Yield t/ha
Rice- Sowing with irrigation- fresh water, perfect fertilization	11.3	4.41	--	--
Rice- Sowing with irrigation- fresh water	5.71	2.23	--	--
Rice- Sowing with permanent irrigation - Saline water 6 dS/m water-saline soil 3 dS/m	5.6	2.21	--	2.3
Rice- Sowing with permanent irrigation - freshwater - saline soil 0.3 dS/m	5.71	2.23	--	--

The simulation results have convincingly demonstrated that soil fertility is a pivotal factor in boosting rice yields in Sierra Leone (Figure 20). This vital information can greatly benefit farmers in the area, encouraging them to prioritize the maintenance and enhancement of soil fertility to achieve higher rice production. However, the challenges posed by salinity cannot be overlooked. The use of water with a salinity level of 6 dS/m in soils that already exhibit a salinity of 3 dS/m resulted in a noticeable reduction in crop yields. Despite this setback, the findings suggest that there is potential for revitalizing land affected by salinity, particularly in Sierra Leone, where the risk of salinity accumulation in the soil remains minimal due to the region's high precipitation levels. This dynamic relationship between rainfall and soil salinity highlights important opportunities for sustainable agricultural practices, as illustrated in Figure 24. Indeed, in these saline-affected lands, it was possible to produce 2.3 t/ha of rice.

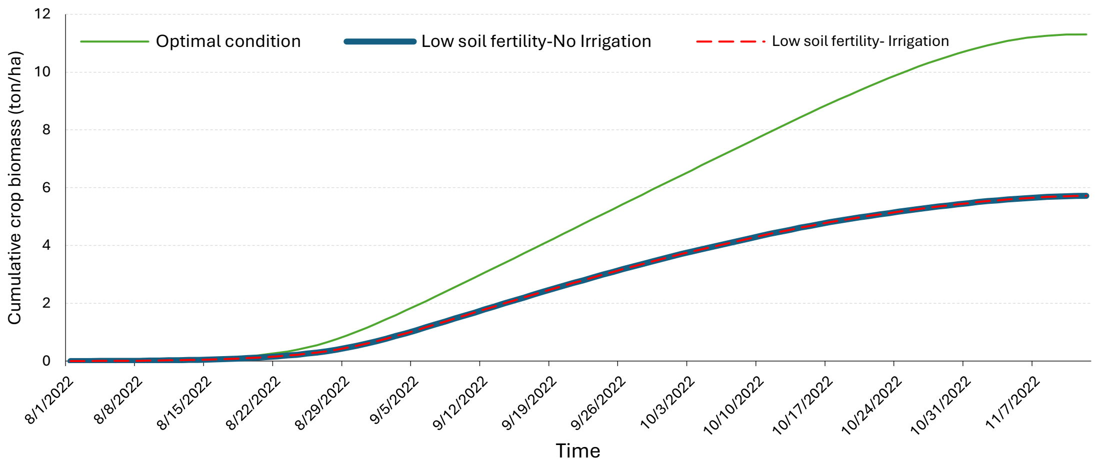


Figure 20: Cumulative crop biomass of rice under different production factors.

3.3.3. Water balance in the soil

Cultivating rice during the rainy season typically does not require additional irrigation, as the natural rainfall is often adequate. This particular season recorded an impressive total precipitation of 1567.1 mm, providing ample moisture for the crop. The simulation results for soil water content (Figure 21) in Sierra Leone, considering a scenario without irrigation during the rice growth cycle, indicate that soil moisture in the effective root zone consistently remains around the field capacity level.

Conversely, employing traditional irrigation methods or permanent flood irrigation, which keeps the soil surface continuously saturated throughout the rice-growing period, results in minimal changes to soil moisture levels. This approach can necessitate a significant 6240 mm of water, highlighting the large volume required for optimal rice growth. However, utilizing saline water for irrigation can pose a serious threat to soil health, as the increased water volume may lead to elevated soil salinity levels, potentially jeopardizing future crop yields.

Table 12: Model outputs regarding soil water balance and water productivity for rice under various production scenarios.

Scenario	Rain	Irri	Ev	Tr	ET0	Infilt	Drain	WPet	Soil ECi	Soil ECf
Rice- Sowing with irrigation- fresh water, perfect fertilization	1567.1	0	142.1	327.0	469.2	905.0	381.6	0.94	0.1	0.1
Rice- Sowing with irrigation- fresh water	1567.1	0	217.8	258.0	469.2	910.1	381.9	0.47	0.1	0.1
Rice- Sowing with permanent irrigation - Saline water 6 dS/m water-saline soil 3 dS/m	1567.1	6240	223.8	251.3	469.2	7807.1	7118.8	0.47	3.0	0.4
Rice- Sowing with permanent irrigation - fresh water -saline soil 0.3 dS/m	1567.1	62.8	221.2	258.8	469.2	1694.2	1079.3	0.47	0.21	0.1

Rain: Rainfall; Irri: Water applied by irrigation; Ev: Soil evaporation; Tr: Total transpiration of crop and weeds ET: Evapotranspiration; Infilt: Infiltrated water in soil profile; Drain: Water drained out of the soil profile; WPet: ET Water productivity for yield part (kg yield produced per m3 water evapotranspired); Soil Eci : soil salinity before plantation; Soil ECf: soil salinity after the season; EC Electrical conductivity of the saturated soil-paste extract (ECe in dS/m)

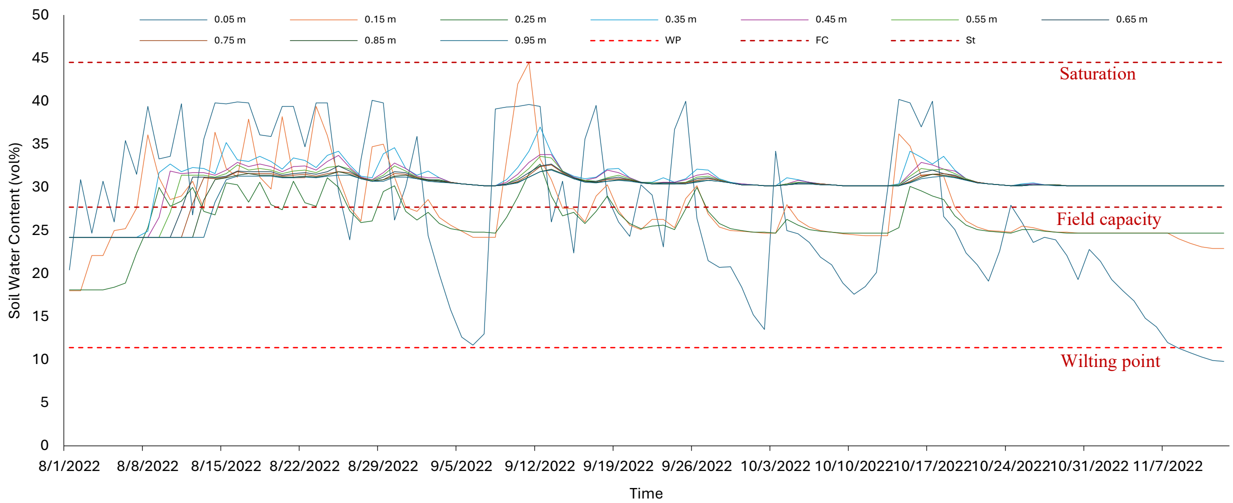


Figure 21: Soil water content in the scenario of the absence of irrigation during the rice growth cycle in Sierra Leone.

In Sierra Leone, the agricultural landscape largely depends on the natural rainfall during the rainy season, which typically provides sufficient moisture for crops to thrive without the need for irrigation. This reliance on rainfall is characteristic of the region's farming practices. Nevertheless, detailed assessments of the water need for rice cultivation have indicated that implementing supplementary irrigation at certain critical periods can significantly enhance crop yields (Figure 22). This strategic approach to watering allows farmers to achieve the best possible results, ensuring that their rice production is both fruitful and sustainable.

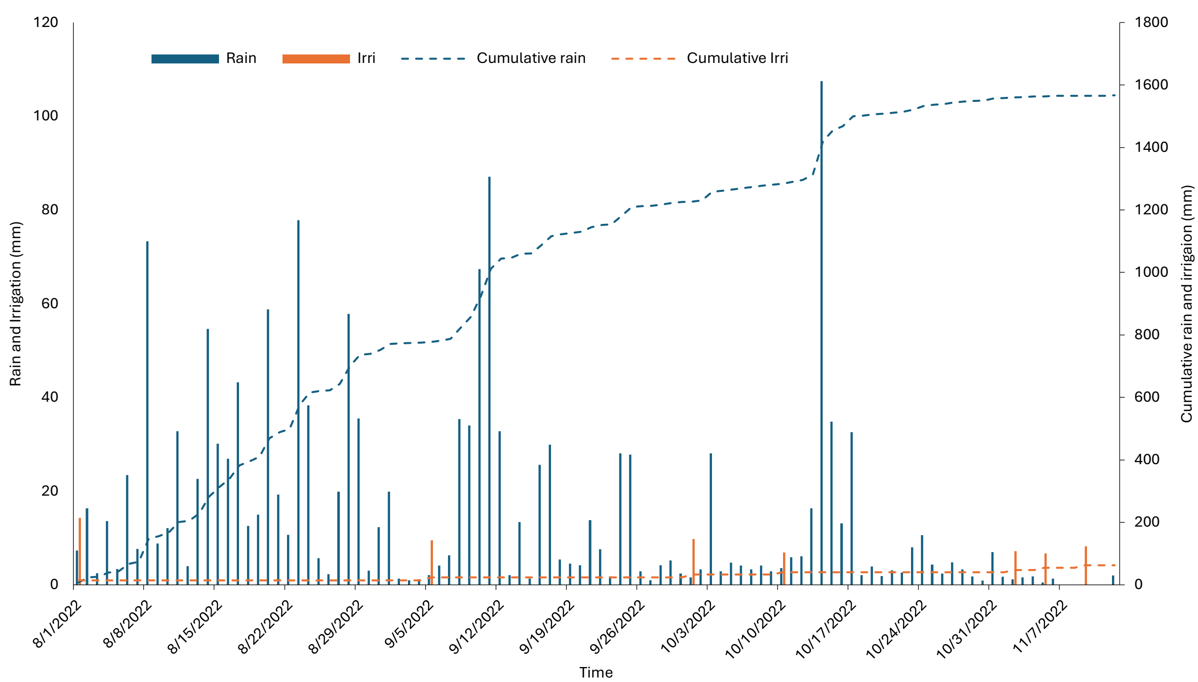


Figure 22: Irrigation and Rain events and their accumulation during the rice growth cycle in Sierra Leone.

3.3.4. Water budget

During the rice growth cycle in Sierra Leone, the water budget is influenced by various factors, including rainfall, irrigation, soil evaporation, total transpiration from crops and weeds, evapotranspiration, the amount of water infiltrated into the soil profile, and the water drained from it. The water budget assesses the volume of water that enters, exits, and is stored in the soil, particularly in the root zone. A specific equation is employed to calculate a field's water budget, with the results presented in Figure 23. The data clearly demonstrates that the water budget during the rice growth cycle in Sierra Leone is positive, largely due to the plentiful rainfall.

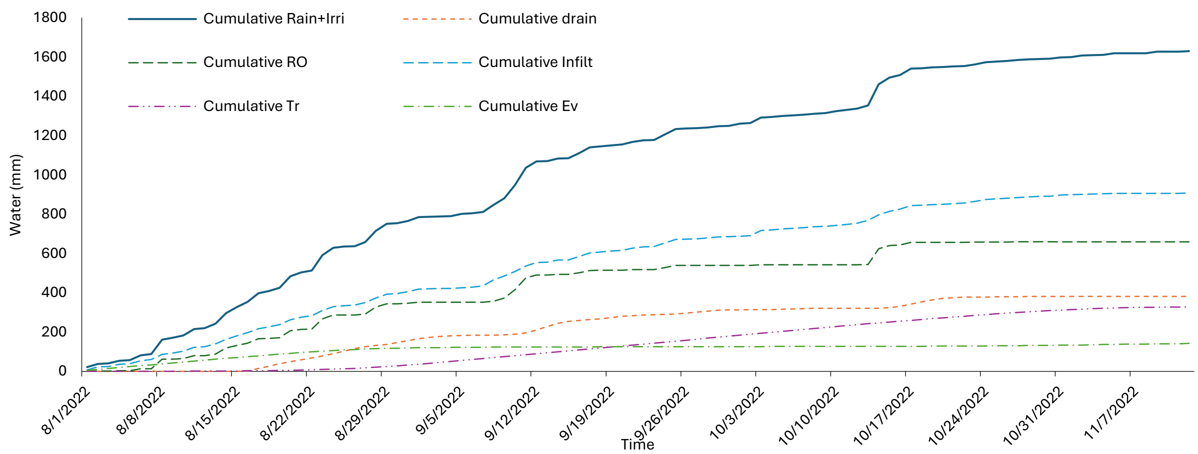


Figure 23: Water budget during the rice growth cycle in Sierra Leone.
Rain: Rainfall; Irri: Water applied by irrigation; Ev: Soil evaporation; Tr: Total transpiration of crop and weeds ET: Evapotranspiration; Infilt: Infiltrated water in soil profile; Drain: Water drained out of the soil profile;

3.3.5. Salinity build-up risk in case of irrigation with saline water of 6dS/m

According to the AquaCrop model, the Electrical Conductivity (ECe in dS/m) of saturated soil-paste extracts at various depths of the rice field irrigated with saline water (6 dS/m) does not present any risk in Sierra Leone (Figure 24). This assessment takes into account the soil type and the region's annual precipitation levels, which amounted to 1567.1 mm during this rice growing cycle.

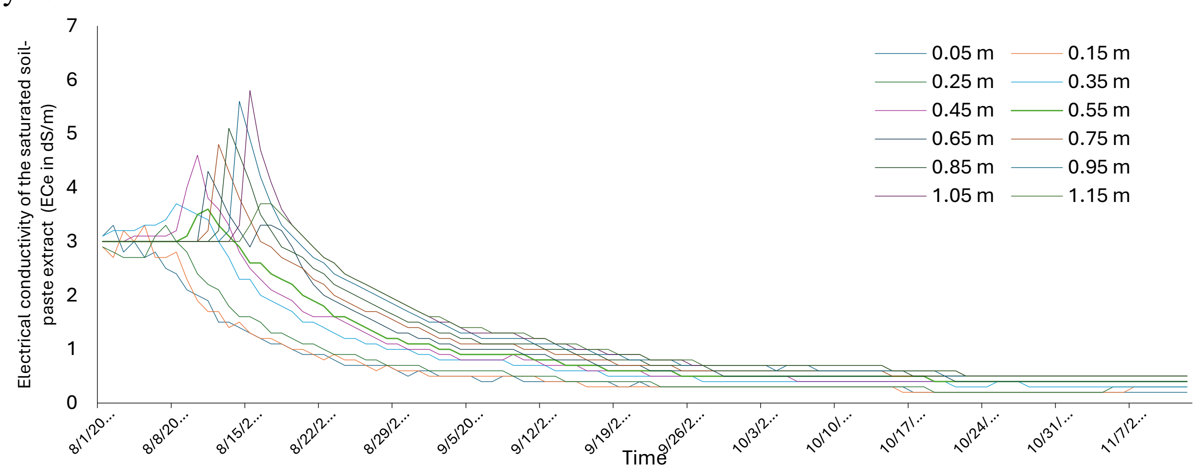


Figure 24: Electrical conductivity of the saturated soil-paste extract (ECe in dS/m) at various depths of the rice field irrigated with saline water of 6 dS/m, estimated by Aquacrop model

4. Conclusion

In summary, the findings regarding the optimal allocation of irrigation and drainage in irrigated regions of Sierra Leone (case of study), as informed by comprehensive soil-water-plant modeling, can be encapsulated in the following points:

- The tools implemented by RESADE related to precision agriculture, as well as the modeling and computer science approach, facilitate data-driven irrigation scheduling, accurately determine water needs, and lead to significant water and energy savings. It estimates atmospheric demand and soil moisture, allowing for adjustments in crop coefficients to boost crop productivity and potentially conserve resources.
- This will contribute to improved crop management and may enhance crop growth efficiency, emphasizing profitability, sustainability, and environmental protection.
- Following model calibration, various production scenarios were generated, demonstrating its effectiveness. Key findings suggest that weed infestation and low soil fertility due to inadequate fertilization are major contributors to yield loss. Weeds are associated with an estimated reduction of 4 tonnes per hectare in biomass. The use of saline water (6 dS/m salinity) could further decrease potential yield by up to 20 tonnes per hectare from a maximum of 27 tonnes per hectare.
- These findings challenge existing beliefs regarding soil fertility issues in Sierra Leone, highlighting that soil quality may be the primary factor in yield losses. Salinity also affects agricultural productivity.
- Enhancing soil fertility is essential to improving crop water productivity and increasing yield and profitability from underutilized water resources.
- The generated data can improve irrigation and fertilization practices and underscores the need for supplementary irrigation during the dry season for enhanced yield and water productivity. Sorghum is identified to require approximately 200 mm of irrigation during the dry season. Despite significant rainfall in Sierra Leone, its uneven distribution necessitates supplementary irrigation.
- To maintain an adequate water supply, the implementation of irrigation systems is crucial before substantial rainfall begins in May. Timely irrigation is important for crop health during the dry months preceding the rainy season.
- The findings highlight the importance of soil fertility in increasing rice yields in Sierra Leone. Emphasis is placed on enhancing soil fertility despite the challenges posed by salinity. The use of saline water on already saline soils is associated with reduced yields, though high rainfall levels may mitigate salinity risks. This relationship suggests a trend towards sustainable agricultural practices, enabling potential rice production of 2.3 tonnes per hectare on affected lands.
- Simulation results indicate that certain areas in Sierra Leone are not susceptible to salinity accumulation. Applying saline water (6 dS/m) raised soil salinity; however, the high rainfall effectively leached away accumulated salts.

- During the rainy season, rice typically does not require additional irrigation due to sufficient natural rainfall, averaging 1567.1 mm. Simulation results for soil water content indicate that soil moisture remains around field capacity in the effective root zone without supplementary irrigation. However, supplementary irrigation has the potential to enhance rice yields during critical growth periods. Assessments indicate that irrigating with saline water does not pose significant risks to soil health, considering the region's soil types and average annual rainfall during the rice growing cycle.
- Traditional irrigation methods for rice cultivation, such as permanent flood irrigation, maintain continuous soil saturation and require a substantial 6240 mm of water for optimal growth. However, irrigation with saline water may pose a risk of increasing soil salinity, which could threaten future crop yields.

The Gambia

1. General information about The Gambia

The Gambia is a West African country with a population of 1,882,450. It has a significant poverty challenge, with most of the population living below the poverty line. The agricultural sector employs 75% of the country's population, and it accounts for 29% of GDP. Agricultural production is primarily rainfed, and the country relies heavily on food imports. The Gambia River is the primary surface water source in the country, suitable for tidal and pump irrigation. The country's economy is characterized by its small size, narrow base, and large re-export trade. The agricultural sector contributes 30% to the country's economy. The climate is Sudano-Sahelian, characterized by a short rainy season from June to October and a long dry spell from November to May with scattered vegetation and forest cover. The country has a total arable land area of 558,000 ha, and only about 6% of the irrigation potential has been used.

The agricultural sector in The Gambia contributes significantly to the economy, accounting for 29% of GDP, employing 75% of the population, and meeting half of the country's food requirements. It's also the main source of income for poor rural households. The sector mainly comprises small-scale, subsistence rainfed crop production, traditional livestock rearing, semi-commercial groundnut, horticultural, and small cotton production. The Gambia is classified as a Low-Income Food-Deficit Country (LIFDC), producing only about 50% of the total food consumption needs, with rice being a major staple food. Despite increasing cereal production, the gap between supply and demand has widened due to the increasing population, leading to an increased food deficit.

The Gambia's water resources include surface waters (such as The Gambia River and its tributaries) and sub-surface waters in multiple aquifers throughout the country. The river is highly seasonal, with flows ranging from 5 m3/s in April and May to 1,000 m3/s in the rainy season. The country also has phreatic and deep sandstone aquifers. The hydrological processes and water resources engineering impact land degradation at both the watershed and farm levels. Soil salinization, acidification, and erosion occur due to changes in the flow components of the hydrological cycle.

Due to climate change and variability, water resources in The Gambia are being affected by pollution and saline intrusion. This has led to a decrease in the quantity and quality of both surface and groundwater resources and the salinization of the Gambia River.

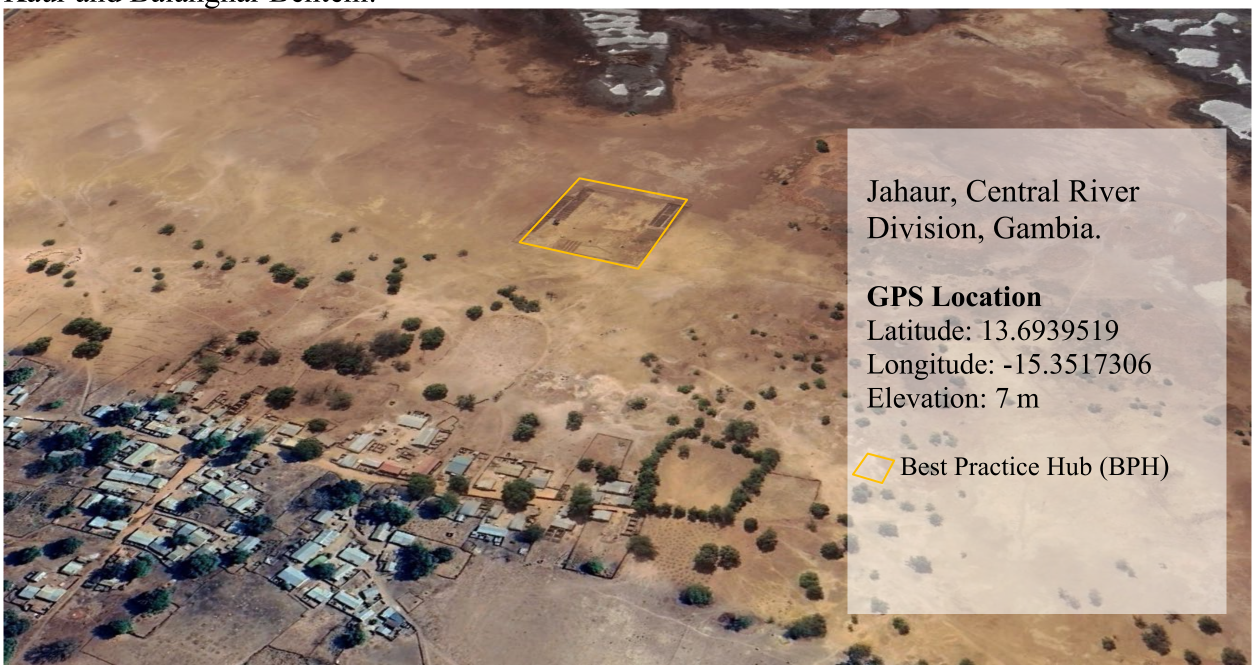
The Gambia has untapped water resources for food production, including the Gambia River and abundant groundwater. The Sambangalou dam is expected to increase water availability, but it is difficult to anticipate due to unknown water availability.

Different irrigation methods are used in The Gambia. Small low-lift pump-irrigated areas are used near the main river or its tributaries. Tidal irrigation is used in low-lying marshy areas, where ocean tides are used to force river water onto fields. Sprinkler irrigation is used in private and community garden projects, primarily using groundwater. Mangrove and freshwater swamps are used to grow rice from August to January by constructing protection dikes. Groundwater systems are used to rehabilitate boreholes, wells, and pumping systems. Irrigated lowland rice has also been successful. Although tidal irrigation is cheaper, it can cause uneven water distribution to fields, leading to conflicts among farmers. Drip irrigation is not yet widely used, but on-farm demonstrations and intensive capacity building could help convince farmers to adopt this technology.

2. Study site characterization.

1.1.Site name

RESADE- HUB, The Gambia
Location: Jahaur
Jahaur is a village in the Central River Division of the Gambia. It is situated near the villages of Kaur and Balanghar Bentenl.



Best Practice Hub (BPH), in Jahaur, Central River Division, The Gambia.

1.2.Soil data

One of the most accurate ways to gain a thorough understanding of your soil is by collecting soil samples and analyzing them in a laboratory. However, if this method is not feasible, other alternatives can still be useful. For instance, we obtain valuable data from the FAO soil portal (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/.)

Table 13: Physical & Chemical Properties of Soil of the Hub in the region of Jahaur, Central River Division, The Gambia.

	Soil type 1		**Soil type 2**	
Parameters	Topsoil (0-30 cm)	Subsoil (30-60)	Topsoil (0-30 cm)	Subsoil (30-60)
Sand Fraction (%)	67	58	42	45
Silt Fraction (%)	20	17	27	23
Clay Fraction (%)	13	25	31	32
USDA Texture Classification	sandy loam	sandy clay loam	clay loam	clay loam
Reference Bulk Density (kg/dm3)	1.52	1.4	1.35	1.35

Bulk Density (kg/dm3)	1.44	1.5	1.15	1.11
Gravel Content (%)	10	11	6	6
Organic Carbon (% weight)	0.18	0.3	0.4	0.27
pH (H2O)	6.4	6.1	9	8.8
CEC (clay) (cmol/kg)	16	5	78	75
CEC (soil) (cmol/kg)	3	2	25	25
Base Saturation (%)	72	82	100	100
TEB (cmol/kg)	1.9	1.9	25	24.7
Calcium Carbonate (% weight)	0.7	0	35.8	59.3
Gypsum (% weight)	0	0	9.5	19.7
Sodicity (ESP) (%)	1	1	65	72
Salinity (ECe) (dS/m)	0	0	8	6.6

Data collected from the FAO soil portal, https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/.

To determine the soil-water status of the Hub, it is necessary to have access to data pertaining to the water content characteristics of the soil, such as θsat, θcc, and θpfp. If such data is unavailable, it may be estimated using pedo transfer functions based on soil particle size analysis results. Among the most widely used functions for this purpose is one developed by Saxton et al. in 1986 and 2005. Notably, the USDA's SPAW software relies on these pedo transfer functions to estimate these values. The SPAW Hydrology software is employed to determine the Soil-Water Status, and it can be accessed at https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/drainage/?cid=stelprdb1045331 .

Table 14: Soil-Water Status of the Hub in the region of Jahaur, Central River Division, The Gambia.

		Soil type 1		**Soil type 2**	
Parameters	Unit	Topsoil (0-30 cm)	Subsoil (30-60)	Topsoil (0-30 cm)	Subsoil (30-60)
Wilting point	% vol	9.8	16.6	19.8	20.4
Field capacity	% vol	19.0	27	32.5	32.6
Saturation	% vol	44.4	43.7	45.7	45.2
Available water	in/ft	1.11	1.26	1.53	1.47
Salt hydraulic conductivity	in/ha	1.58	0.44	0.23	0.2
Matric bulk density	Ib/ft3	92.04	93.21	89.89	90.65

1 in/ft=83.33 millimeter/meter

1.3.Weather condition

General description of the Gambian weather:

The mean annual rainfall in the country exhibits significant variability, ranging from 900 mm in the southwest to approximately 500 mm in the northeast. The mean temperatures also exhibit a degree of variability, ranging from 14 to 40C, with the eastern part of the country typically experiencing higher temperatures. This short duration and the unpredictable nature of rainfall make crop and livestock production a challenging undertaking. The lack of adequate water control and irrigation structures that ensure a consistent production of food and cash crops has significantly impeded the progress of agriculture in the country over the years.

Site weather conditions

In situations where actual climate data is not available, it is possible to obtain climate parameters from satellite models that provide a good level of agreement. For this purpose, we used the site developed by the Worldwide Energy Resource (POWER) Project. This project is being funded by the National Aeronautics and Space Administration (NASA) Applied Sciences Program under the Earth Science Division of the Science Mission Directorate (https://power.larc.nasa.gov/data-access-viewer/.). The weather data required by Aqua Crop includes maximum and minimum temperature (in Celsius), mean relative humidity (in percentage), wind speed (in meters per second), and solar radiation (in megajoules per square meter per day).

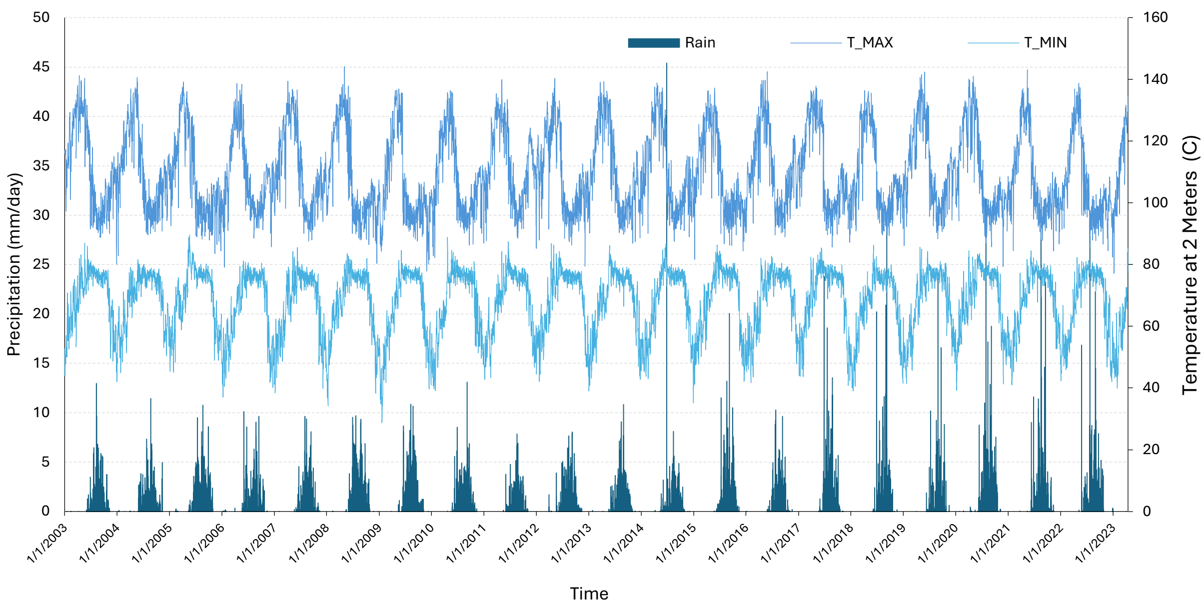


Figure 25: Daily precipitation and maximum and minimum temperature in the region of Jahaur, Central River Division, The Gambia, from January 1st, 2013, to December 31st, 2023.

The FAO Penman-Monteith method is the standard for calculating reference evapotranspiration (ETo) in various fields. In this report, we use the AQUACROP model to calculate ETo using RESADE countries' BPH site climate data. The average monthly ETo was found to be highest in February -March at 8.6 mm day-1, while the lowest average ETo was observed in July- August (3.8-4.2 mm day-1). The mean daily reference evapotranspiration ranged from 4 mm day-1 to 10 mm day-1 for all the years.

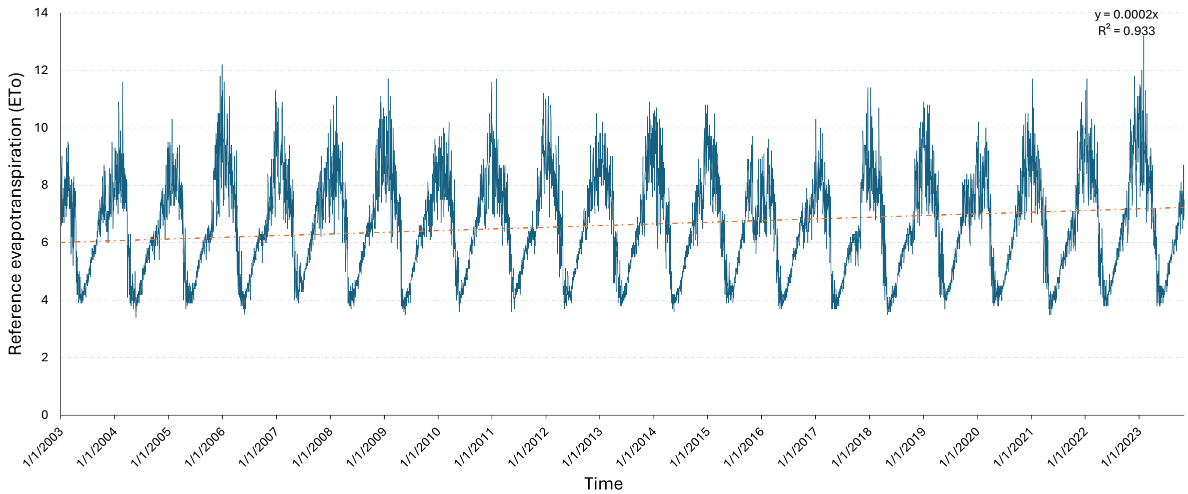


Figure 26: Daily Reference evapotranspiration (ETo) in the region of Jahaur in Central River Division, Gambia, from January 1st, 2013, to December 31st, 2023.

Data collection from the sensors installed in the BPH

The RESADE project has successfully deployed a state-of-the-art weather station, equipped with a wide range of sensors that monitor key atmospheric parameters, including precipitation, barometric pressure, solar radiation, and more. These sensors provide real-time data, which is now accessible through the Zentra Cloud platform offered by the METER Group. This innovative system allows the RESADE project to continuously monitor atmospheric conditions, as data can be gathered and recorded remotely at any time (Figure 27). Additionally, the station is utilized to estimate evapotranspiration (ETo) directly, as illustrated in the figure below.

Figure 27: data collected by the sensor installed in BPH, in the BPH in the region of Jahaur in Central River Division, Gambia.

3. Simulation modeling results

3.1. Estimation of the reference evapotranspiration (ETo) and data visualization using the Aquacrop model

The accurate estimation of evapotranspiration is essential for the effective management and allocation of water resources. The Penman-Monteith method, which has been adopted by the Food and Agriculture Organization (FAO) of the United Nations, is a widely used global standard for estimating reference crop evapotranspiration (ETo). In our study, we utilized the Aquacrop model to estimate the FAO Penman-Monteith reference evapotranspiration for the BPH region. Daily weather data, including maximum and minimum temperatures, precipitation, relative humidity, wind speed, and solar radiation, were collected from 2003 to 2023 for input data into the Aquacrop model. Various statistical parameters were employed to characterize the spatial and temporal variability of ETo.

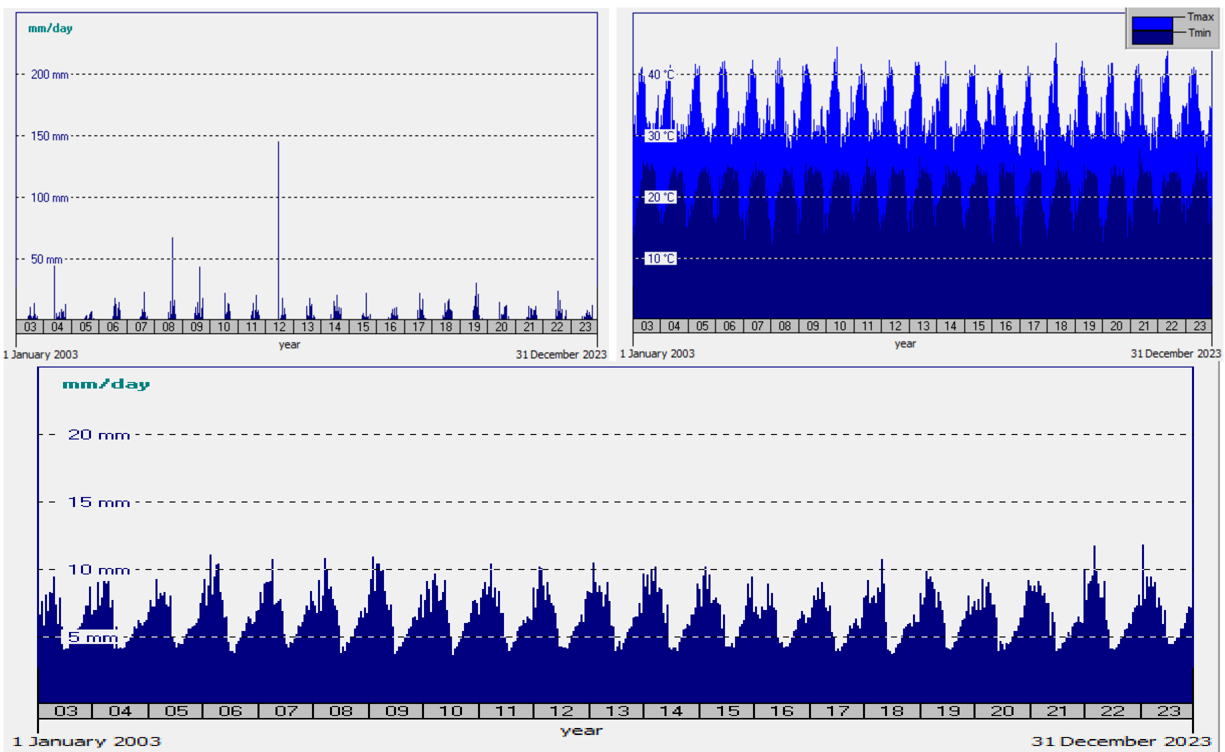


Figure 27: Weather condition (rain and temperature) and the reference evapotranspiration (ETo) estimated and visualized by Aquacrop through the FAO Penman-Monteith equation.

3.2.Modelling results for sorghum

3.2.1. Crop management.

Crop management practices are essential to operating a successful crop model. These practices involve agricultural activities carried out throughout the season, such as seedbed preparation, sowing, maintaining, and harvesting the crop.

The NARI-RESADE team has provided crop management details. Trials for salt and drought-tolerant crops began in July, right after the onset of the rainy season, at the Best Practice Hub (BPH) in Jahurr village.

Table 15: Crop management adopted in the BPH in the region of Jahaur in Central River Division, Gambia.

Operation	Dates and Notes	Photos or remarks from the field
LAND PREPARATION	On February 24th, 2023, the land was prepared by clearing and brushing it.	 Field preparation
SOWING	Sorghum The spacing used was 25cm and 50cm intra and inter-rows, respectively, resulting in a plant population of 8 plants per meter square.	 sowing of Sorghum by the farmers at the Jahur site
IRRIGATION AND MULCHING	Water from the borehole is used twice daily to irrigate the crops, which are also mulched to minimize weed growth and optimize water use. Weekly water samples are taken to test for salinity.	 Irrigating field using the watering can during the dry season cropping period.
WEEDING	The first weeding commenced 2 weeks after emergence, The second weeding and fertilizer application took place four weeks after the first weeding.	 Plot after weeding and ensure all weeds were removed.
FERTILIZATION	75 kg/ha of NPK 15:15:15 as basal application and 75 kg/ha of NPK 15:15:15 during the cycle	
PEST MANAGEMENT	Application of wood ash on newly emerging leaves of the crop plants to control pest attack.	

DATA COLLECTION	Colleagues and technicians have collected data periodically since the trial's establishment. Parameters such as plant height, panicle length, panicle weight, and fresh biomass yield were measured in the field. Samples were dried in an oven at 70°C for 3 days before being weighed in a desiccator.	 Field data collection by Technicians
HARVESTING OF SORGHUM		
THE DRYING PROCESSING	Sorghum was sun-dried for five days before being threshed and winnowed to separate seeds from the chaff. The seeds were dried again until tested for 11.5% moisture content using a moisture meter.	

3.2.2. Development of Different Scenarios for sorghum

The AquaCrop model was utilized to evaluate the performance of various crops under differing environmental conditions, including climate, soil type, water salinity, water scarcity, and irrigation management practices. This approach is particularly advantageous for researchers, technicians, extension service agents, and indirectly for farmers. By employing this model, they can enhance crop yields and optimize water productivity.

Simulation results indicated that sorghum yield reaches its peak when its water needs are met with freshwater. While the use of saline water does not affect yield in the first year, significant declines occur in the second and third years, with yields dropping nearly to zero. This decrease is primarily attributed to salt accumulation in the soil, especially in the absence of an appropriate drainage system (Figure 33)

Table 16: Model outputs related to biomass and yield production for Sorghum under different production scenarios.

Scenario	**Estimated**		**Observed**	
	Biomass	Yield	Biomass	Yield
Sorghum- Sowing during the dry season, with irrigation- fresh water	27.32	5.03		
Sorghum- Sowing during the dry season, with irrigation- saline water- year 1 of saline water use.	27.1	4.97		
Sorghum- Sowing during the dry season, with irrigation- saline water- year 2 of saline water use.	3.80	0.69		
Sorghum- Sowing during the dry season, with irrigation- saline water- year 3 of saline water use.	0.87	0.16		
Sorghum- Sowing during the dry season, without irrigation	3.93	0		
Sorghum- Sowing during the dry season, with irrigation- fresh water-medium weed	23.57	4.47		
Sorghum- Sowing during the dry season, with irrigation- fresh water-medium weed-no fertilization	14.49	2.71		
Sorghum- Sowing during the dry season, with irrigation- saline water-medium weed-no fertilization	14.3	2.69		
Sorghum- Sowing during the wait season and g**ood** field condition	25.28	5.29		

The figures presented below depict the projected cumulative biomass of sorghum cultivated during the dry season, taking into account various production factors. The simulation results reveal that sorghum achieves its maximum yield when its water requirements are adequately satisfied with freshwater. Interestingly, while the initial year of using saline water shows no detrimental impact on yields, a notable decline is observed in the subsequent second and third years. During this period, crop yields plummet almost to zero. This alarming decrease is primarily caused by the accumulation of salt in the soil, particularly in situations where an effective drainage system is lacking.

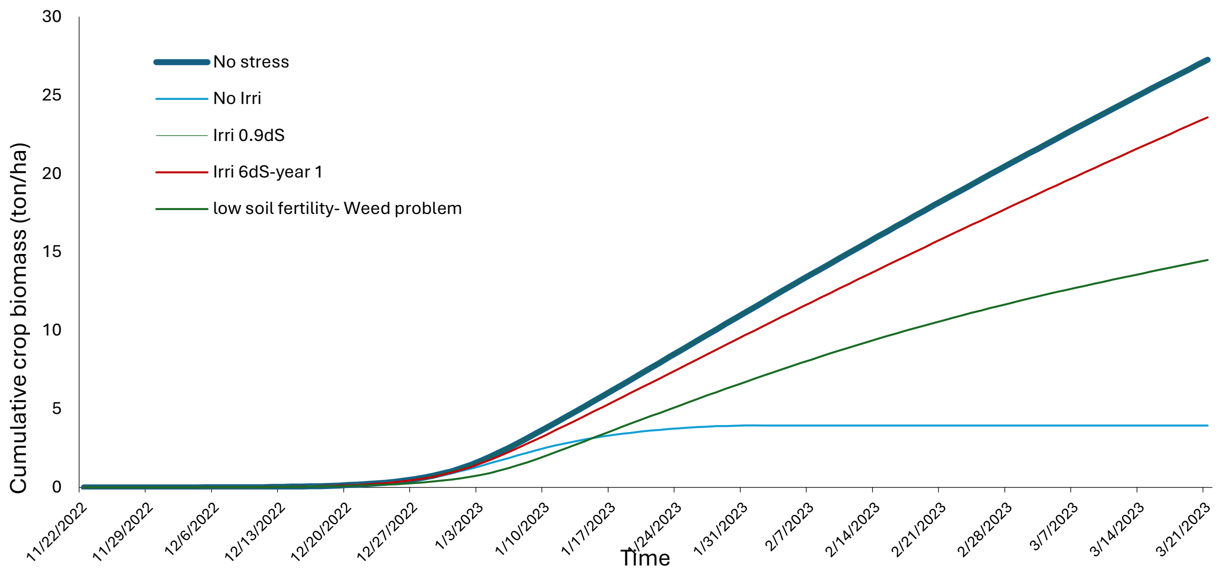


Figure 28: Cumulative biomass of sorghum under different production factors.

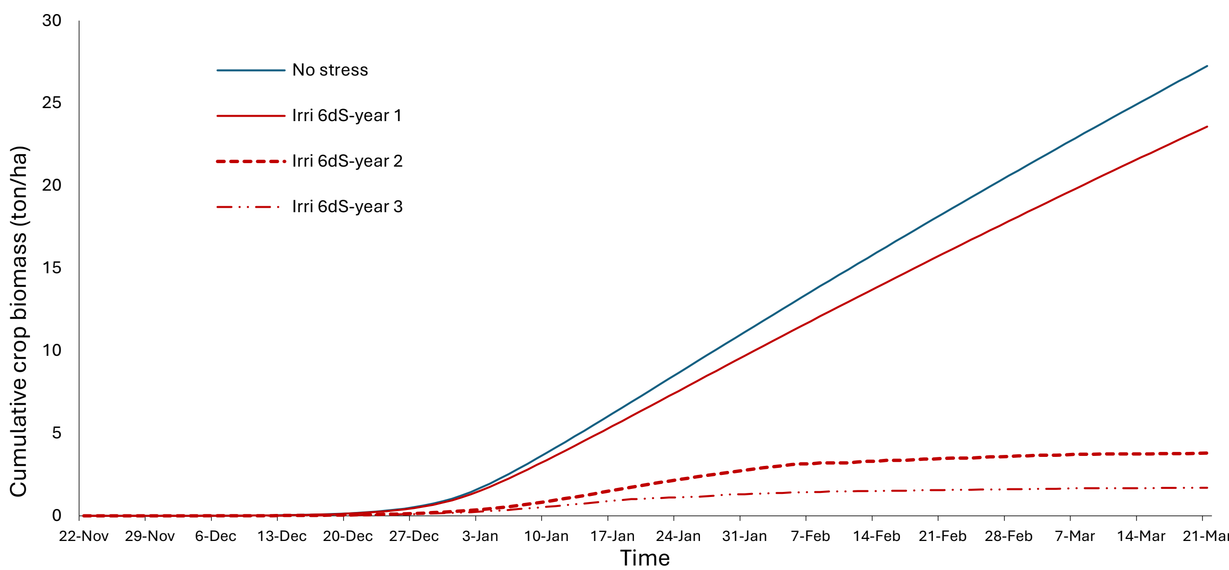


Figure 29: Cumulative biomass of sorghum under irrigation with saline water of 6dS/m during 3 years with the absence of appropriate management (2021-2023).

3.2.3. Water balance in the soil

During the dry season, the region experienced an unprecedented absence of rainfall, necessitating the irrigation of crops with approximately 800 mm of water to meet their essential moisture requirements. Interestingly, using saline water for irrigation resulted in a lower water demand due to a reduced transpiration rate in the plants. Nonetheless, it is crucial to incorporate a leaching fraction to effectively wash away the accumulated salts from the root zone.

The results from the actual simulations revealed a concerning finding: the volume of water drained was recorded as zero. This indicates that all the salt applied over the three-year period had been trapped within the root zone, ultimately accumulating to toxic levels that could harm the plants. This alarming situation underscores the urgent need for an effective drainage system to be implemented prior to the use of saline water for irrigation in The Gambia. A proper drainage solution is vital to prevent salt accumulation, ensuring that crops can thrive without the detrimental effects of toxicity.

Table 17: Model output related to water balance and productivity for Sorghum under different production scenarios.

Scenario	Rain	Irri	Ev	Tr	ET0	Infilt	Drain	WPet	Soil ECi	Soil ECf
Sorghum- Sowing during the dry season, with irrigation- fresh water	0.1	812.2	81.7	738.6	1054.6	818.3	4.6	0.61	0	2.3
Sorghum- Sowing during the dry season, with irrigation- saline water- year 1 of saline water use.	0.1	804.8	80.8	735.0	1054.6	804.1	6.2	0.61	0	9.72
Sorghum- Sowing during the dry season, with irrigation- saline water- year 2 of saline water use.	01	428.2	197.6	101.4	1054.6	428.9	0	0.23	7.9	12.24
Sorghum- Sowing during the dry season, with irrigation- saline water- year 3 of saline water use.	0.1	350.5	215.3	23.4	1054.6	350.6	0	0.07	12.4	14.63
Sorghum- Sowing during the dry season, without irrigation	0.1	0	24.3	99.8	1054.6	0.1	0	0	0	0
Sorghum- Sowing during the dry season, with irrigation- fresh water-medium weed	0.1	818.8	80.2	738.6	1054.6	818.9	6.7	0.55	0	0
Sorghum- Sowing during the dry season, with irrigation- fresh water-medium weed-no fertilization	0.1	668.2	108.2	557.8	1054.6	668.3	97.9	0.41	0	0
Sorghum- Sowing during the dry season, with irrigation- saline water-medium weed-no fertilization	0.1	666.6	108.2	557.6	1054.6	666.7	95.9	0.41	0	8.4
Sorghum- Sowing during the wait season and **good** field condition	636.6	0	108.2	390.2	612.3	636.6	252.2	0.98	0	0

Rain: Rainfall; Irri: Water applied by irrigation; Ev: Soil evaporation; Tr: Total transpiration of crop and weeds ET: Evapotranspiration; Infilt: Infiltrated water in soil profile; Drain: Water drained out of the soil profile; WPet: ET Water productivity for yield part (kg yield produced per m3 water evapotranspired); Soil Eci : soil salinity before plantation; Soil ECf: soil salinity after the season; EC Electrical conductivity of the saturated soil-paste extract (ECe in dS/m)

Figures 30 and 31 present a detailed comparison of soil water content during the growth cycle of sorghum in the BPH region of Jahaur, located in the Central River Division of Gambia. Figure 30 demonstrates the impact of complementary irrigation, showcasing how this method effectively maintains optimal moisture levels in the soil. In contrast, Figure 31 illustrates the conditions when irrigation is absent, revealing a significant drop in soil moisture.

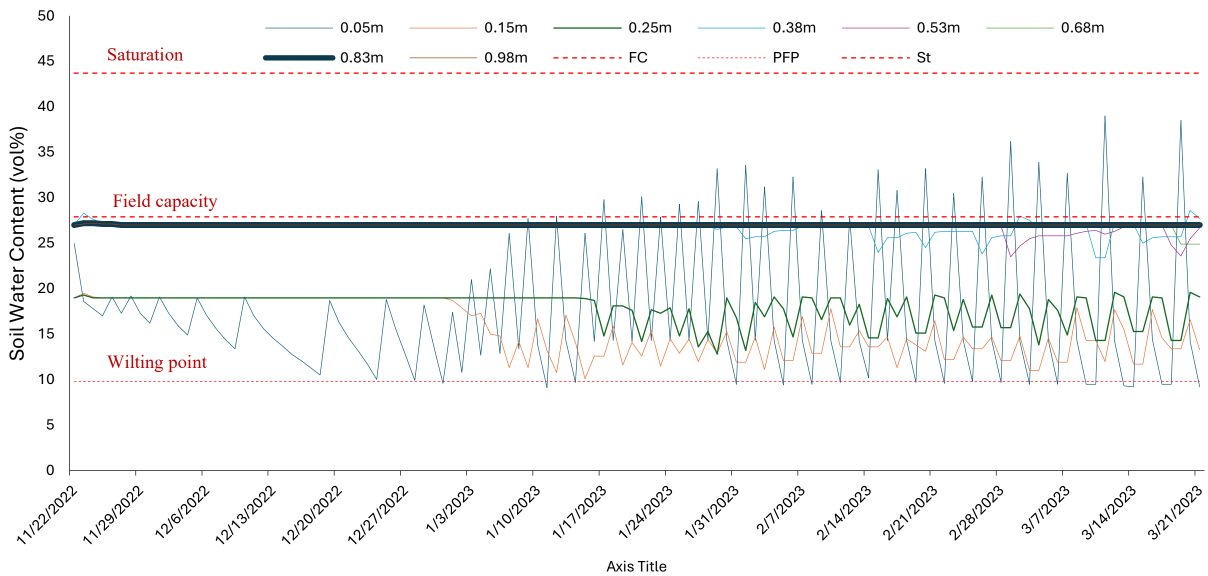


Figure 30: Soil water content in case of complimentary irrigation during the sorghum growth cycle in the BPH in the region of Jahaur in Central River Division, Gambia.

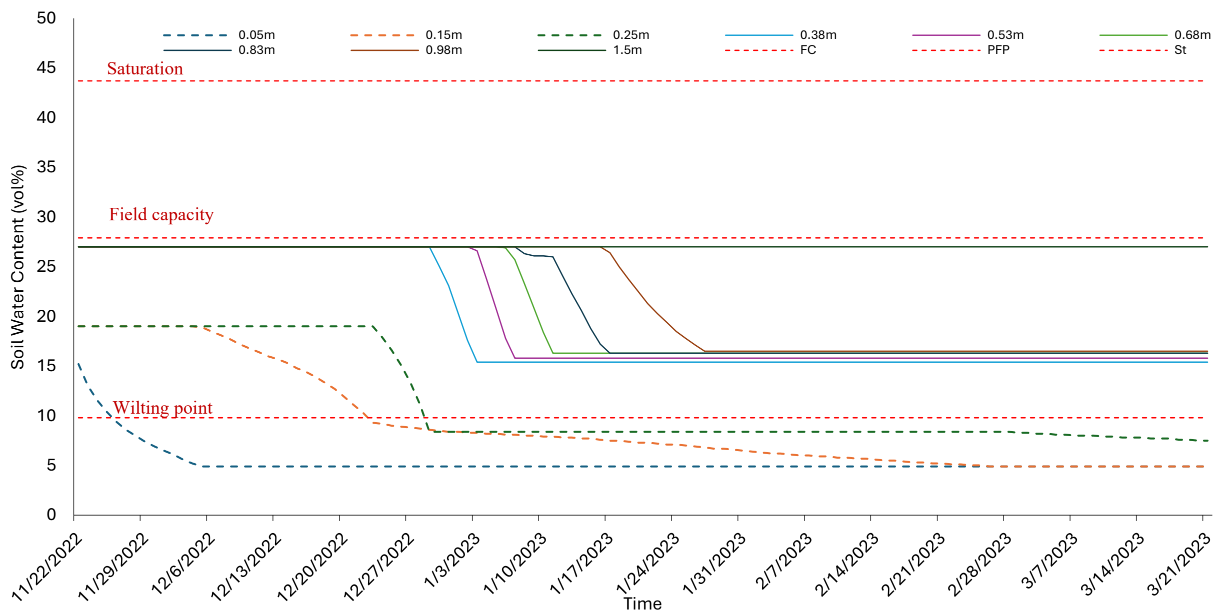


Figure 31: Soil water content in the scenario of absence of irrigation during the sorghum growth cycle in the BPH in the region of Jahaur in Central River Division, Gambia.

The data illustrated in these figures highlights the critical importance of the proposed irrigation scheduling depicted in Figure 32. This scheduling approach plays a key role in maintaining soil moisture levels within an optimal range essential for robust crop growth. Efficiently managing the water supply not only fosters healthy plant development but also significantly enhances yield potential. The results demonstrate a clear connection between soil moisture management and the overall success of agricultural production.

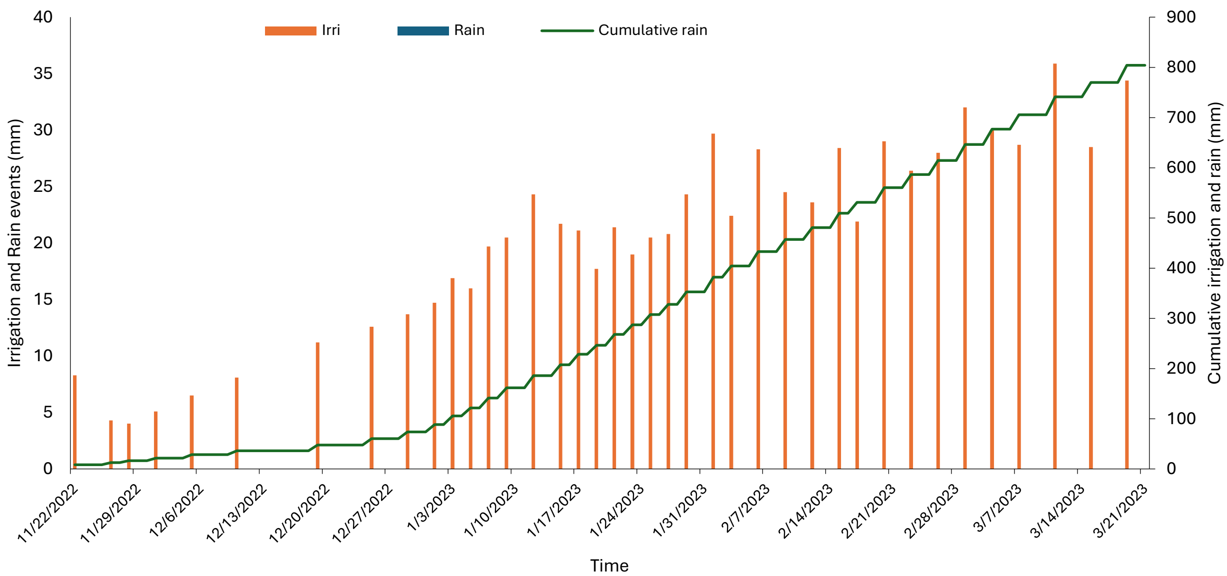


Figure 32: Irrigation and Rain events and their accumulation during the sorghum growth cycle during the dry season in the BPH in the region of Jahaur in Central River Division, Gambia.

3.2.4. Salinity builds up risk in case of irrigation with saline water of 6dS/m

The outcomes of the simulation conducted with the proposed model vividly demonstrated that, without a proper drainage system in place and without rain, salinity levels in the soil will progressively build up over time. This accumulation can eventually reach a point where it becomes toxic for plant life. Consequently, it is crucial to manage irrigation effectively, especially when using saline water, to mitigate this risk and ensure the health and growth of the plants.

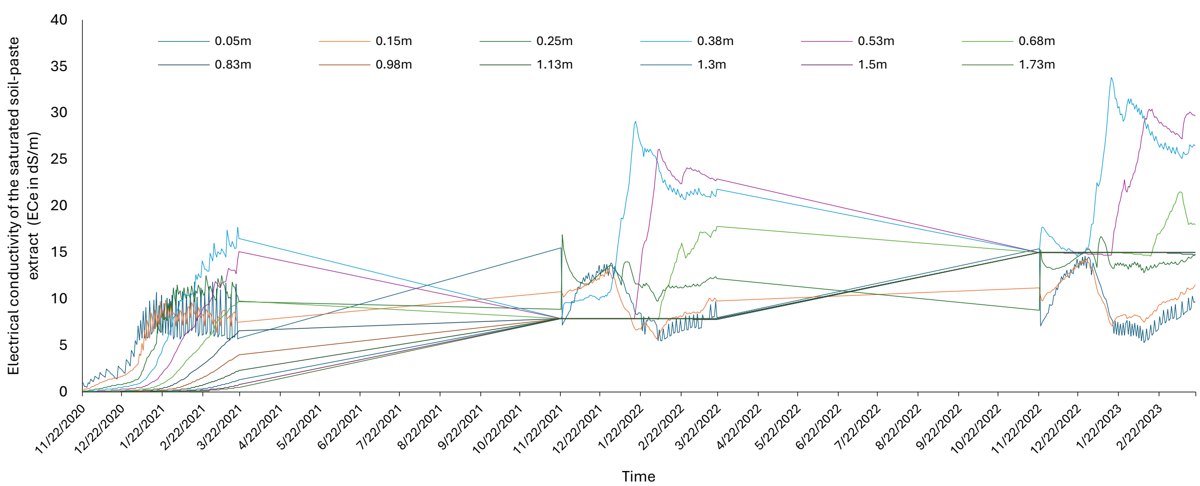


Figure 33: Electrical conductivity of the saturated soil-paste extract (ECe in dS/m) at various depths of the sorghum field irrigated with saline water of 6 dS/m during 3 consecutive dry seasons estimated by the Aquacrop model.

3.3. Rice

3.3.1. Rice in The Gambia

Rice was not part of the project at first, but later it was conducted in a village called Kaiaf. The Gambia has a high per capita consumption of rice, with a deficit of 179,000 MT which is met through importation. Rice in the country is grown in upland rainfed, lowland rainfed, lowland irrigated, and mangrove swamps. Most of the rice is grown in tidal and pump-irrigated perimeters. Saltwater intrusion has affected rice production areas upstream. A possible solution is to introduce salt-tolerant rice varieties to mitigate the issue.

A trial was conducted as part of the RESADE project to assess rice's resilience to salinity conditions. The main objective of the trial was to identify and select rice varieties that could thrive in salt-affected areas of The Gambia and that were highly tolerable to salinity stress.

The trial took place in Kaiaf village, which is a significant rice-growing community in The Gambia. This area is subject to salt intrusion due to its location in the Sudano-Sahelian zone, where precipitation volumes are low, ranging from 600 to 900mm per annum. The growing season in the area lasts between 80-119 days.

3.3.2. Site Characteristics

The study that was conducted mainly focused on the four test varieties' agronomic and yield performances. However, not much focus was given to the soil parameters as previous studies conducted by NARI and post-graduate students indicated that the electrical conductivity remained consistently high, ranging from 1.5 to 2 dS/m, indicating a saline condition. The soil of the site is sandy loamy with an average organic matter content (OM) of 0.54%.

3.3.3. Crop management.

The NARI-RESADE team has provided information on rice management, which is illustrated in the table below.

Table 18: Crop management adopted for the rice

Operation	Dates and Notes	Photos or remarks from the field
Land Preparation and Planting	The land was cleared and plowed using a tractor provided by the Regional Agricultural Directorate in the Lower River Region. The community women help with the leveling and planting.	 Plowing of the trial plots at Kaiaf
Sowing	**TRANSPLANTING** Planting was done by directly seeding the dried seeds. Planting robes were laid to make sure the rice was planted on straight rows at a planting distance of 20 cm between plants and between rows	 Women planting the rice at the experiment under the supervision of the technicians
Irrigation and mulching		

Weeding	The first weeding was carried out immediately after fertilizer application so that the fertilizer could be incorporated.	
Fertilization	**FERTILIZER APPLICATION** Fertilizer was applied at the recommended rate of 200 kg/ha NPK and 200 kg/ha Urea in three split applications. At two weeks after planting, the first dose of fertilizer NPK 15:15:15 was applied. The second application, comprising 50% of the Urea, was carried out two weeks after the first application. The final application of the remaining 50% of the Urea was carried out immediately after flowering was completed.	 Salt tolerant rice varieties in their mid-vegetative stage in the fields
Pest management	Not mentioned	
HARVESTING OF rice	Manuel harvest	
The drying processing		

3.3.4. Development of Different Scenarios

The findings from the simulation results strongly underscore the importance of employing freshwater for crop irrigation to achieve optimal yields (Table 19; Figure 34). Nonetheless, the analysis also revealed that it is feasible to attain satisfactory crop yields even when using moderately saline water, with a salinity level of 2 dS/m. This can be accomplished by implementing the best agricultural practices tailored to this specific region, highlighting a valuable approach for farmers facing freshwater limitations.

Table 19: Yield and biomass estimated using the AquaCrop model for rice production under different scenarios.

Scenario	Estimated		Observed	
	Biomass	Yield	Biomass	Yield
Rice- with irrigation- fresh water, perfect fertilization	15.81	6.85		
Rice- with irrigation- fresh water, local condition	7.61	3.28		
Rice- No irrigation-	7.067	2.89		2.68
Rice- with permanent irrigation - Saline water 2 dS/m water-saline soil 0.1 dS/m	7.54	3.27		
Rice- with permanent irrigation -2 dS/m -saline soil 0.3 dS/m	7.12	2.91		

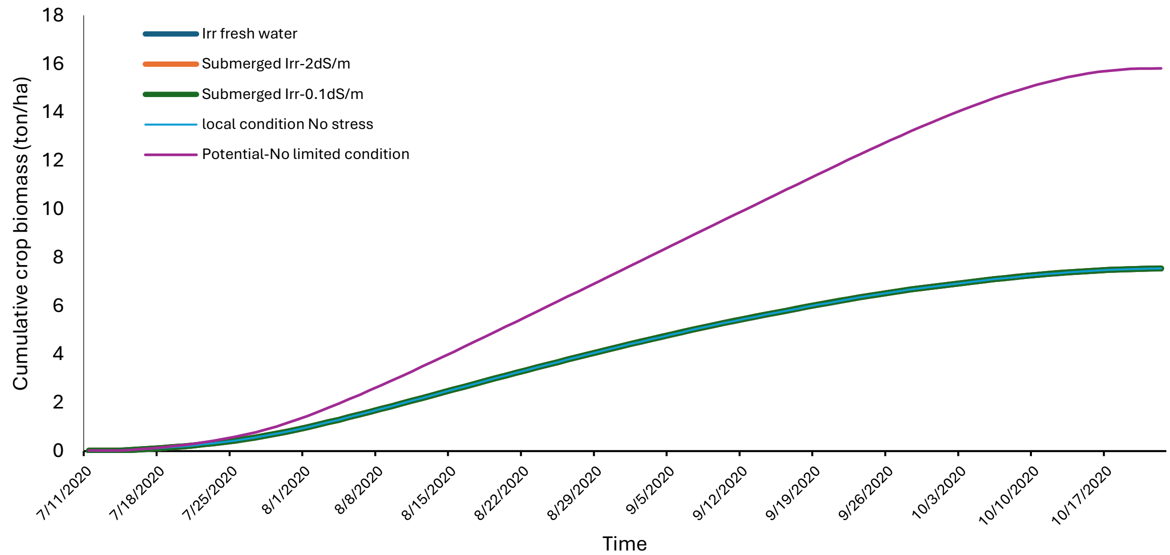


Figure 34: Cumulative crop biomass of rice under different production factors.

3.3.5. Water balance in the soil

A detailed examination of the water balance in rice fields cultivated during the rainy season revealed that with a total precipitation of 656 mm, it is indeed possible to grow rice successfully. However, the irregular distribution of rainfall during critical developmental phases of the rice plants may necessitate supplementary irrigation to ensure optimal growth conditions.

Figure 35 illustrates the soil water content throughout the irrigation cycles (figure 36) during the rice growth period in The Gambia, highlighting how timely irrigation events can prevent soil moisture levels from dropping to the wilting point. This preventative measure is crucial in mitigating adverse effects on the crop's performance, ensuring a healthier yield. The findings also underscore the significance of precise fertilization strategies, which enhance water productivity and enable more efficient use of the available water resources. By employing these methods, farmers can maximize the benefits of both water and nutrients, ultimately leading to improved agricultural outcomes.

Table 20: Model output related to water balance and productivity for rice under different production scenarios.

Scenario	Rain	Irri	Ev	Tr	ET0	Infilt	Drain	WPet	Soil ECi	Soil ECf
Rice- with irrigation- fresh water, perfect fertilization	656.5	107.1	108.1	406	524.1	739.1	234.01	1.33	0	0.1
Rice- with irrigation- fresh water, local condition	656.5	124.3	189.5	389.9	524.1	780.8	970.2	0.63	0	0
Rice- NO irrigation- fresh water	656.5	0	175	286	524.1	656.5	241.5	0.63	0	0.08
Rice- with permanent irrigation - Saline water 6 dS/m water-saline soil 3 dS/m	656.5	124.3	189.5	3898.9	524.1	780.8	970.2	0.63	0	0.88
Rice- with permanent irrigation - 2dS/m -saline soil 0.3 dS/m	656.5	20280	203.2	329.1	524.1	20669.9	20181.6	0.61	0	2.01
Rice- with permanent irrigation - 2dS/m -saline soil 0.3 dS/m-other soil	656.5	4743.6	202.9	329.1	524.1	5333.6	4769.5	0.61	0	2.06

Rain: Rainfall; Irri: Water applied by irrigation; Ev: Soil evaporation; Tr: Total transpiration of crop and weeds ET: Evapotranspiration; Infilt: Infiltrated water in soil profile; Drain: Water drained out of the soil profile; WPet: ET Water productivity for yield part (kg yield produced per m3 water evapotranspired); Soil Eci : soil salinity before plantation; Soil ECf: soil salinity after the season; EC Electrical conductivity of the saturated soil-paste extract (ECe in dS/m)

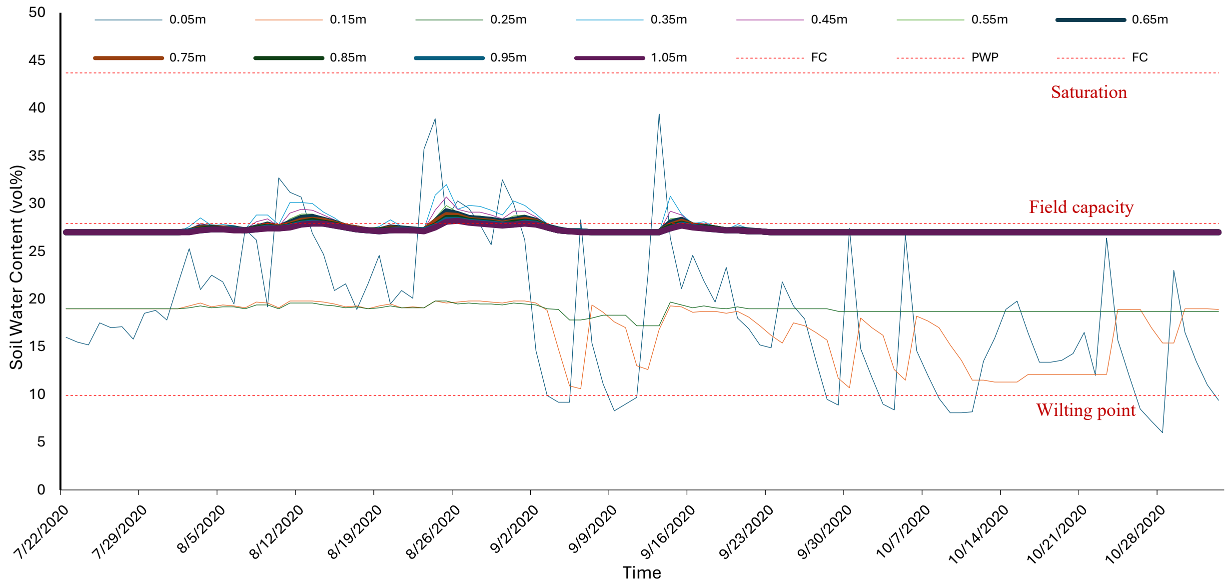


Figure 35: Soil water content in the irrigation scenario during the rice growth cycle in The Gambia.

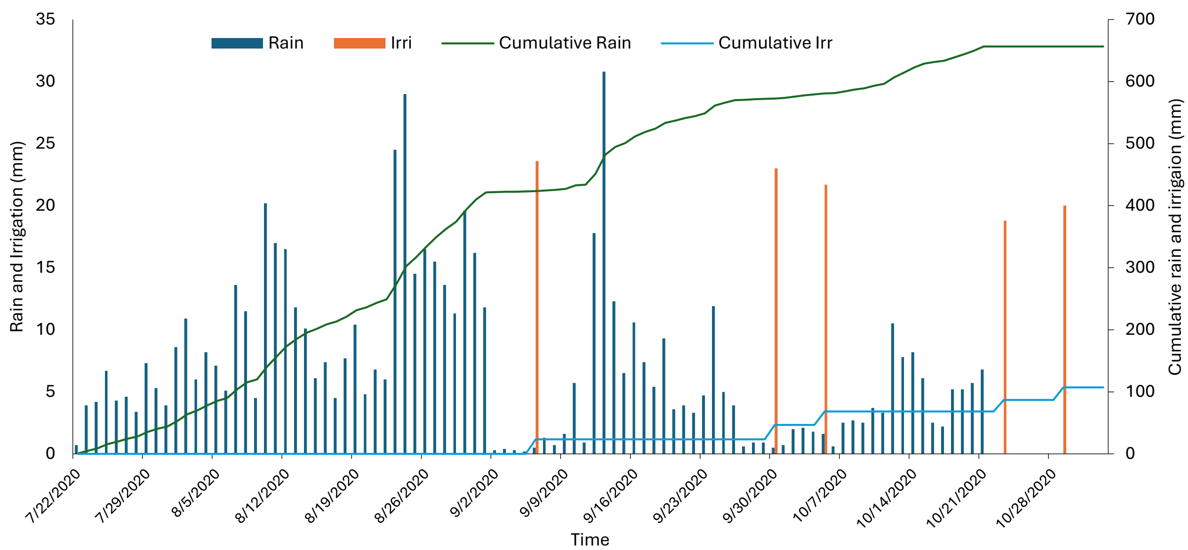


Figure 36: Irrigation and Rain events and their accumulation during the rice growth cycle in THE Gambia.

3.3.6. Water budget

The water budget is a crucial framework for understanding the dynamics of water within the soil, particularly in relation to the rooting zones of plants. It quantifies the various inflows and outflows of water, as well as the amounts retained in the soil. During the rice growth cycle in The Gambia, an analysis of the water budget revealed the importance of effective management of both rainfall and irrigation (figure 37). These two sources of water were carefully monitored and tailored to maintain a favorable water balance in the rice-growing soils. Ensuring an optimal water balance is essential for promoting healthy rice growth, maximizing yields, and efficiently using available water resources throughout the growth period.

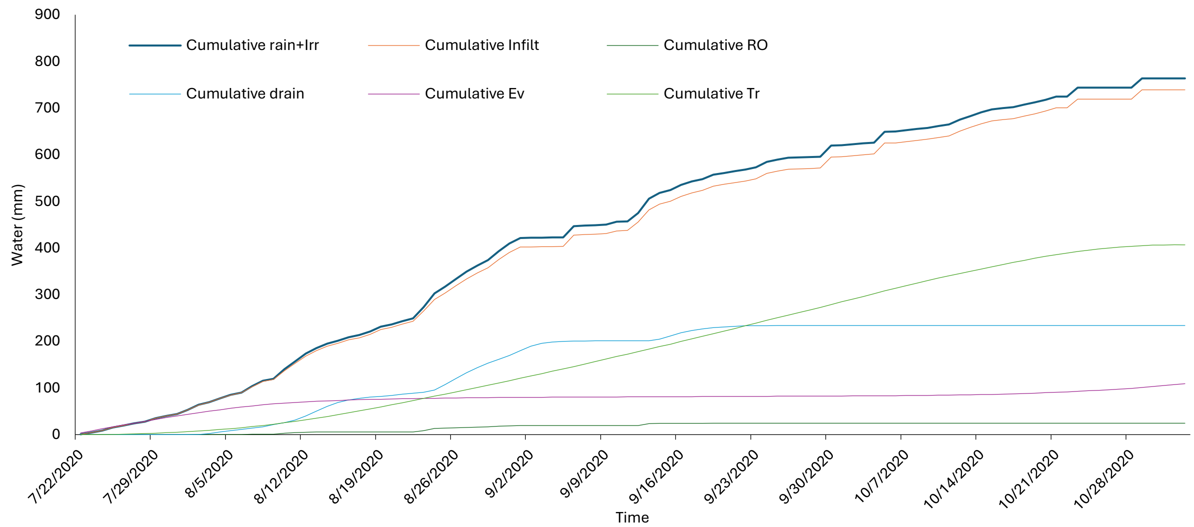


Figure 37: Water budget during the rice growth cycle in The Gambia.

Rain: Rainfall; Irri: Water applied by irrigation; Ev: Soil evaporation; Tr: Total transpiration of crop and weeds ET: Evapotranspiration; Infilt: Infiltrated water in soil profile; Drain: Water drained out of the soil profile.

3.3.7. Salinity builds up risk in case of irrigation with saline water of 2 dS/m

Figure 38 presents a detailed illustration of the electrical conductivity of the saturated soil-paste extract (ECe, measured in dS/m) at different depths within a rice field that is irrigated with saline water, specifically with a salinity level of 2 dS/m. These measurements were estimated using the Aquacrop model, which simulates crop yield and water management. The findings from this analysis indicate that it is indeed feasible to maintain soil salinity within acceptable limits by applying a leaching fraction. This approach helps to mitigate the impact of salinity on crop growth by facilitating the removal of excess salts from the root zone, thereby promoting healthier soil conditions and supporting the sustainability of rice production in saline environments.

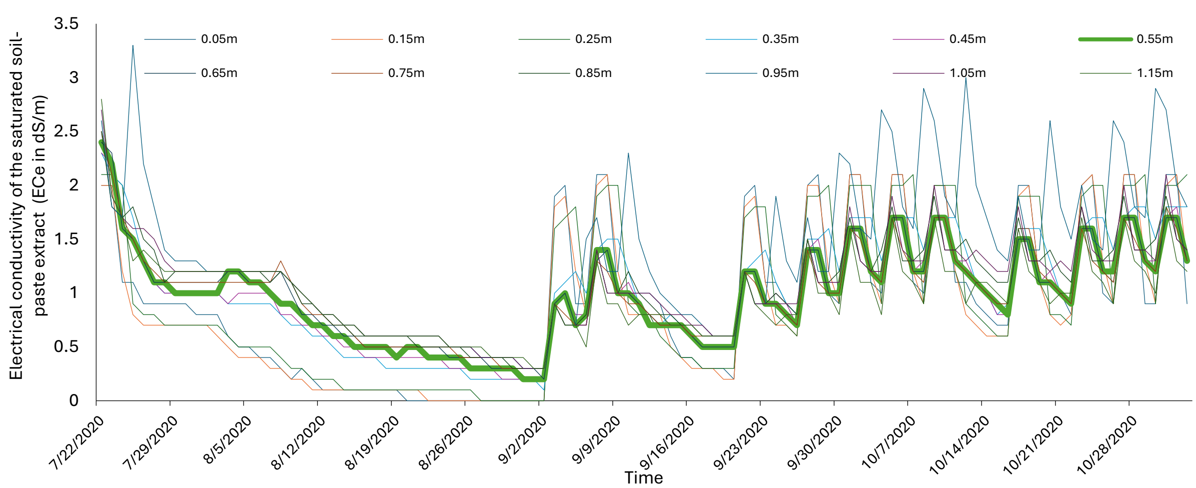


Figure 38: Electrical conductivity of the saturated soil-paste extract (ECe in dS/m) at various depths of the rice field irrigated with saline water of 2 dS/m, estimated by Aquacrop model.

4. Conclusion

In summary, the insights derived from the soil-water-plant modeling study on the optimal allocation of irrigation and drainage in the irrigated regions (case of study) of The Gambia can be summarized as follows:

- Sorghum yield peaks when irrigated with freshwater; saline water initially has no effect but leads to drastic yield declines in subsequent years due to salt accumulation, particularly without proper drainage.
- During dry seasons, about 800 mm of irrigation water is needed, and while saline water reduces transpiration, a leaching fraction is necessary to remove accumulated salts.
- The model simulation showed zero water drainage, indicating salt buildup in the root zone to toxic levels, highlighting the urgent need for an effective drainage system when using saline water.
- Without an effective drainage system, salinity levels will increase over time, posing risks to plant health, emphasizing the importance of managing irrigation, especially with saline water.
- Proper irrigation scheduling is crucial for maintaining optimal soil moisture levels, which enhances crop growth and yield potential.
- The findings from the rice simulation results strongly underscore the importance of - Freshwater use for crop irrigation is essential for optimal yields, but satisfactory yields can also be achieved with moderately saline water (2 dS/m) through best agricultural practices.
- The study on rice fields during the rainy season (656 mm of precipitation) suggests that supplemental irrigation may be needed during some critical growth phases due to irregular rainfall.
- Timely irrigation can prevent soil moisture from reaching wilting points, which is crucial for crop performance, and precise fertilization can enhance water productivity.
- The water budget is vital for understanding water dynamics in plant rooting zones, and effective management of rainfall and irrigation is necessary for maintaining a favorable water balance during rice growth in The Gambia.
- Modeling results indicate that maintaining acceptable soil salinity levels is achievable using a leaching fraction, which supports healthier soil conditions and sustainable rice production in saline environments.

TOGO

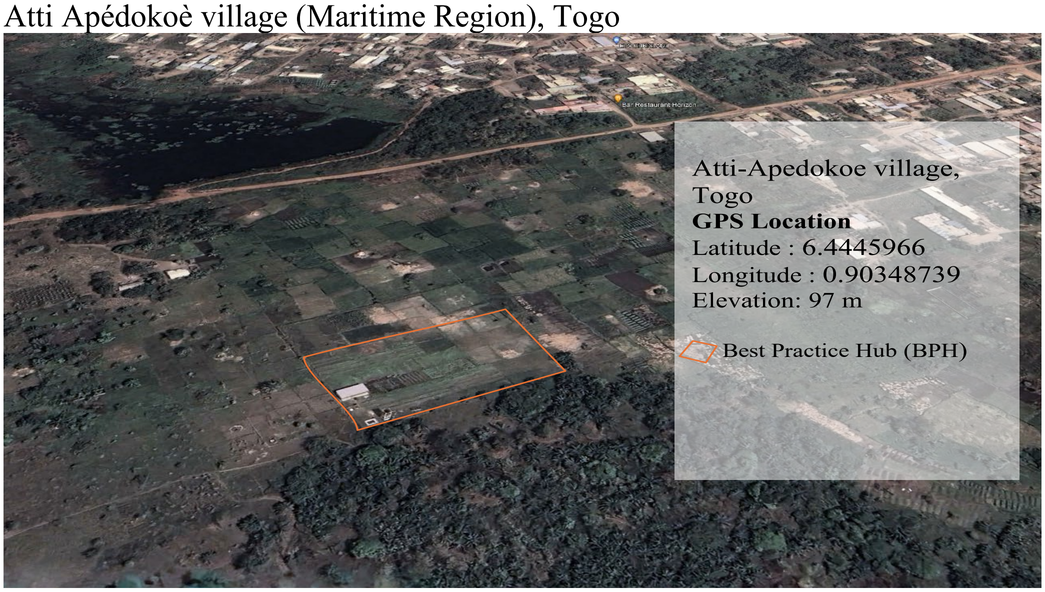
1. General information

Togo is a country with an extensive hydrographic system that covers its territory. The hydrographic system is composed of three main river basins, namely Volta, Mono, and Lac Togo. Agriculture is the most critical sector in Togo, contributing 40% of the country's GDP, according to ITRA. Two-thirds of the active population in Togo work on small land (0.5 ha) for agriculture. Food crops are the most produced and make up two-thirds of the total production. These crops are mainly used domestically for consumption. Togo produces both cash crops and food crops. Food crops such as maize, rice, millet, sorghum, yam, cassava, peanut, bean, and vegetables are cultivated on 44% of the cultivated land. These are usually grown during the rainy season. On the other hand, cash crops such as cotton, coffee, cocoa, and cashews are grown on 15% of the cultivated land.
In recent years, Togo has made significant efforts towards water control in the production areas, particularly in irrigation infrastructure. This infrastructure was established through specific strategic projects, which supported different types of irrigation depending on the production area and targeted crops. However, information and documentation about this infrastructure are dispersed in each project's reports, making it difficult to create an accurate irrigation map of Togo. It is essential to take stock of this infrastructure to determine the primary factors that influence irrigation, irrigation management, and drainage effluent elimination.

2. Study site characterization.

2.1.Site name

Country name: TOGO
Site name: ATTI-APEDOKOE- RESADE- ITRA-HUB
Atti Apédokoè village (Maritime Region), Togo



Best Practice Hub (BPH), in Atti-Apedokoe village, Togo.

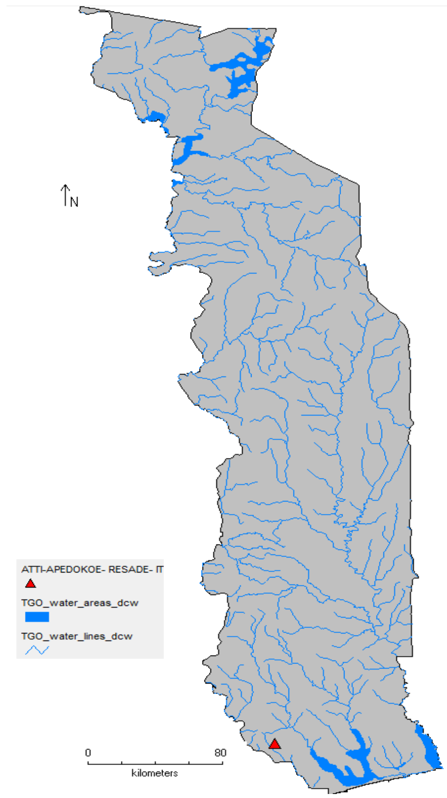


Figure 39: Togo map with the geographical distribution of water and rivers as well as the Best Practice Hub location.
DIVA-GIS software (version 7.5) was used to create the maps.

2.2.Soil data

One of the most precise methods for gaining a comprehensive understanding of your soil is to collect soil samples and have them analyzed in a laboratory. For this exercise, we used data from a soil analysis conducted at ICBA for samples taken from the PBH site in Togo.

Table 21: Soil physical properties for BPH-Atti-Apedok-Togo, laboratory results.

Sample	Depth (cm)	pH 1:1	EC 1:1 ms/cm	Clay (%)	Silt (%)	Sand (%)	% OM	% C
Togo1	0-20	5.14	0.243	8.352	22.6	69.048	2.02	1.17
Togo1	20-40	5.54	0.325	10.072	25.32	64.608	1.67	0.97
Togo1	40-60	5.63	0.494	15.992	21.12	62.888	2.46	1.43
Togo1	60-80	5.54	0.700	17.992	16.80	65.208	2.63	1.53
Togo1	80-100	5.18	1.016	24.672	16.48	58.848	3.50	2.03
Togo2	0-20	5.20	0.192	9.032	13.76	77.208	2.76	1.60
Togo2	20-40	5.50	0.088	8.192	11.60	80.208	1.62	0.94
Togo2	40-60	5.92	0.059	4.552	11.28	84.168	0.79	0.46
Togo2	60-80	5.96	0.094	17.232	9.52	73.248	2.60	1.51
Togo2	80-100	5.83	0.180	28.032	8.72	63.248	3.92	2.27

Table 22: Soil chemical properties: Ca Mg, Cl, Na, available K, P, and N.

Sample	Depth (cm)	Ca (meq/L)	Mg (meq/L)	Cl (meq/L)	Na (mg/L)	Na (meq/L)	K (mg/L)	K (meq/L)	P (mg/kg)	N (ppm)
Togo1	0-40	2.82	2.10	72.00	174.20	7.57	1.19	0.03	1.87	3.64
Togo1	40-80	3.44	2.02	118.50	323.84	14.08	1.19	0.03	0.62	2.80
Togo1	80-100	3.92	11.56	169.50	441.03	19.18	1.78	0.05	10.27	4.34
Togo 2	0-40	1.48	6.70	10.50	50.99	2.22	0.86	0.02	3.11	2.66
Togo 2	40-80	0.56	0.90	19.00	59.12	2.57	0.86	0.02	1.25	1.82
Togo 2	80-100	0.74	0.64	13.50	63.81	2.77	0.86	0.02	14.32	1.96

Nevertheless, if this method is not feasible, other alternatives can still be useful. For instance, we obtain valuable data from the FAO soil portal (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/.)

Table 23: Physical & Chemical Properties of Soil of the BPH in Atti-Apedokoe , Togo.

Parameters	Topsoil (0-30 cm)	Subsoil (30-60)
Sand Fraction (%)	49	38
Silt Fraction (%)	28	23
Clay Fraction (%)	23	39
USDA Texture Classification	loam	clay loam
Reference Bulk Density (kg/dm3)	1.4	1.31
Bulk Density (kg/dm3)	1.49	1.54
Gravel Content (%)	10	5
Organic Carbon (% weight)	0.58	0.4
pH (H2O)	6.2	6.3
CEC (clay) (cmol/kg)	32	41
CEC (soil) (cmol/kg)	9	15
Base Saturation (%)	81	82
TEB (cmol/kg)	7.2	9.4
Calcium Carbonate (% weight)	0	0
Gypsum (% weight)	0	0
Sodicity (ESP) (%)	1	1
Salinity (ECe) (dS/m)	0.1	0.1

Data collected from the FAO soil portal, https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/.

To determine the soil-water status of the Hub, it is necessary to have access to data pertaining to the water content characteristics of the soil, such as θsat, θcc, and θpfp. If such data is unavailable, it may be estimated using pedo transfer functions based on soil particle size analysis results. Among the most widely used functions for this purpose is one developed by Saxton et al. in 1986 and 2005. Notably, the USDA's SPAW software relies on these pedo transfer functions to estimate these values. The SPAW Hydrology software is employed to determine the Soil-Water Status, and it can be accessed at https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/drainage/?cid=stelprdb1045331.

Table 24: Soil-Water Status of the BPH in Atti-Apedokoe, Togo.

Parameters	Unit	Topsoil (0-30 cm)	Subsoil (30-60)
Wilting point	% vol	15.4	24.1
Field capacity	% vol	27.6	36.7
Saturation	% vol	44.9	46.5
Available water	in/ft	1.46	1.51
Salt hydraulic conductivity	in/ha	0.51	0.09
Matric bulk density	Ib/ft3	91.23	88.46

1 in/ft=83.33 millimeter/meter

2.3.Weather condition

In situations where actual climate data is not available, it is possible to obtain climate parameters from satellite models that provide a good level of agreement. For this purpose, we used the site developed by the Worldwide Energy Resource (POWER) Project. This project is being funded by the National Aeronautics and Space Administration (NASA) Applied Sciences Program under the Earth Science Division of the Science Mission Directorate (https://power.larc.nasa.gov/data-access-viewer/.)

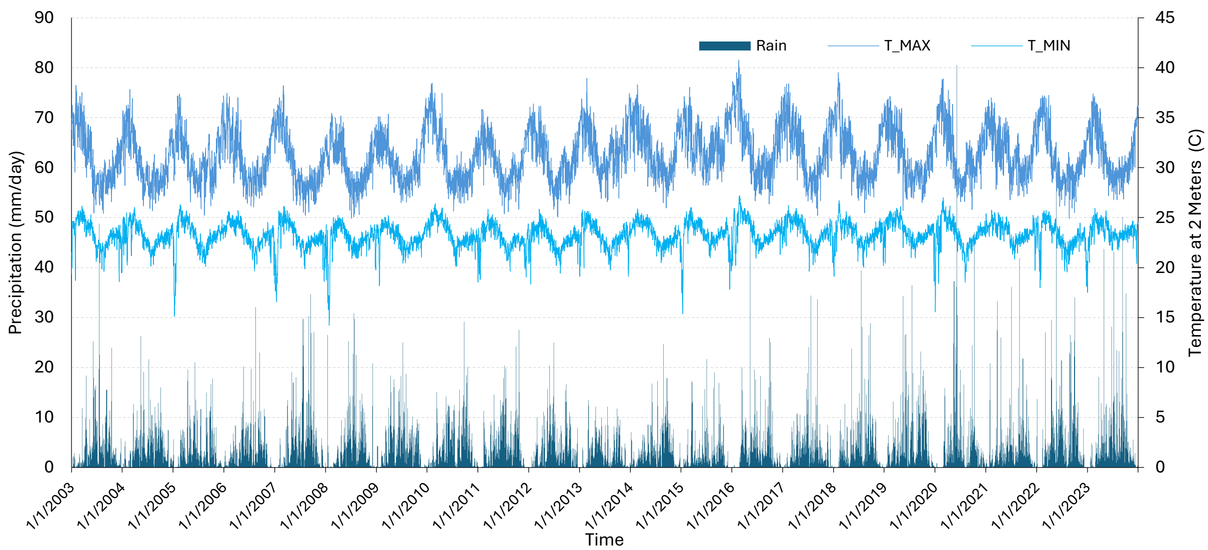


Figure 40: Daily precipitation and maximum and minimum temperature in the region of Atti-Apedokoe, Togo, from January 1st, 2013, to December 31st, 2023.

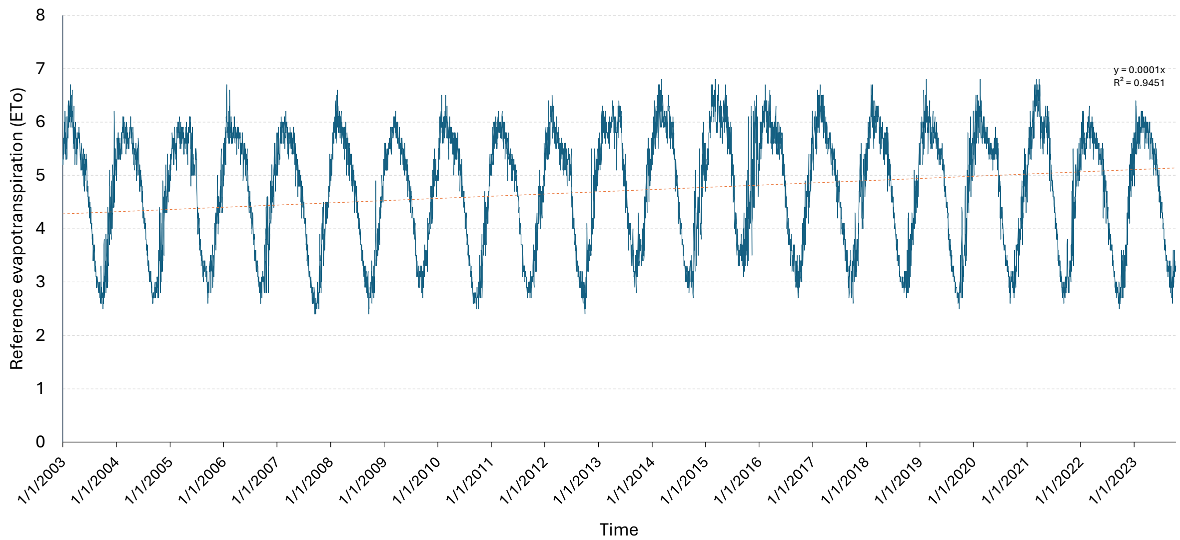


Figure 41: Daily Reference evapotranspiration (ETo) in the region of Atti-Apedokoe, Togo, from January 1st, 2013, to December 31st, 2023.

Data collection from the sensors installed in the BPH

The RESADE project has installed a state-of-the-art weather station with sensors that monitor key atmospheric parameters such as precipitation, barometric pressure, and solar radiation. Real-time data is accessible via the Zentra Cloud platform from the METER Group, enabling continuous remote monitoring. The station is also connected to a platform that estimates evapotranspiration (ETo) directly (Figure 42).

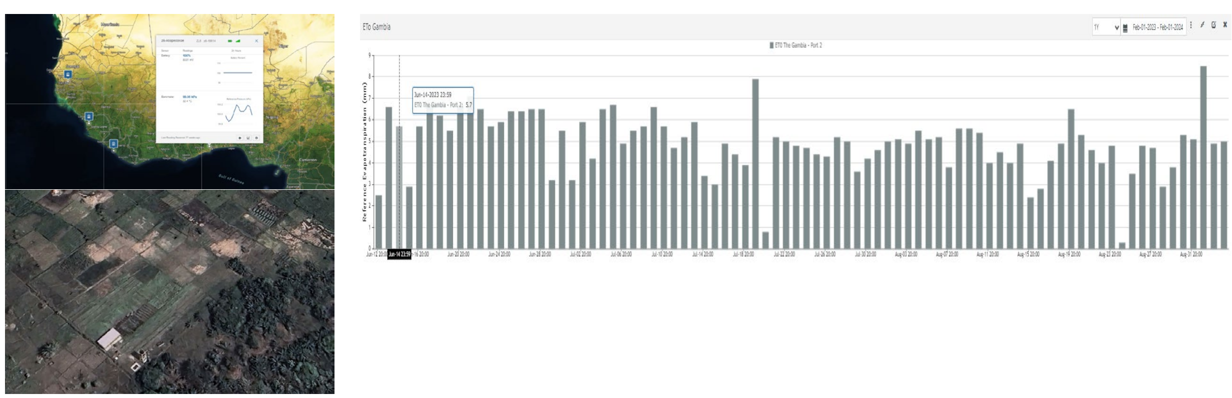


Figure 42: data collected by the sensor installed in BPH, the BPH in the region of Jahaur in Central River Division, Gambia.

3. Simulation modeling results

AquaCrop is a user-friendly tool suitable for RESADE target countries. It requires essential inputs such as weather data, crop characteristics, and soil attributes. It provides an overview of field and irrigation management practices, categorizing soil characteristics into soil profile and water properties. This comprehensive approach hopes to enhance crop management planning and decision-making.

3.1.Calculation of the reference evapotranspiration (ETo)

AquaCrop was used in this report to calculate the reference evapotranspiration (ETo) using the FAO Penman-Monteith equation (Figure 43) based on weather data collected from online open sources and a weather station installed at BPH.

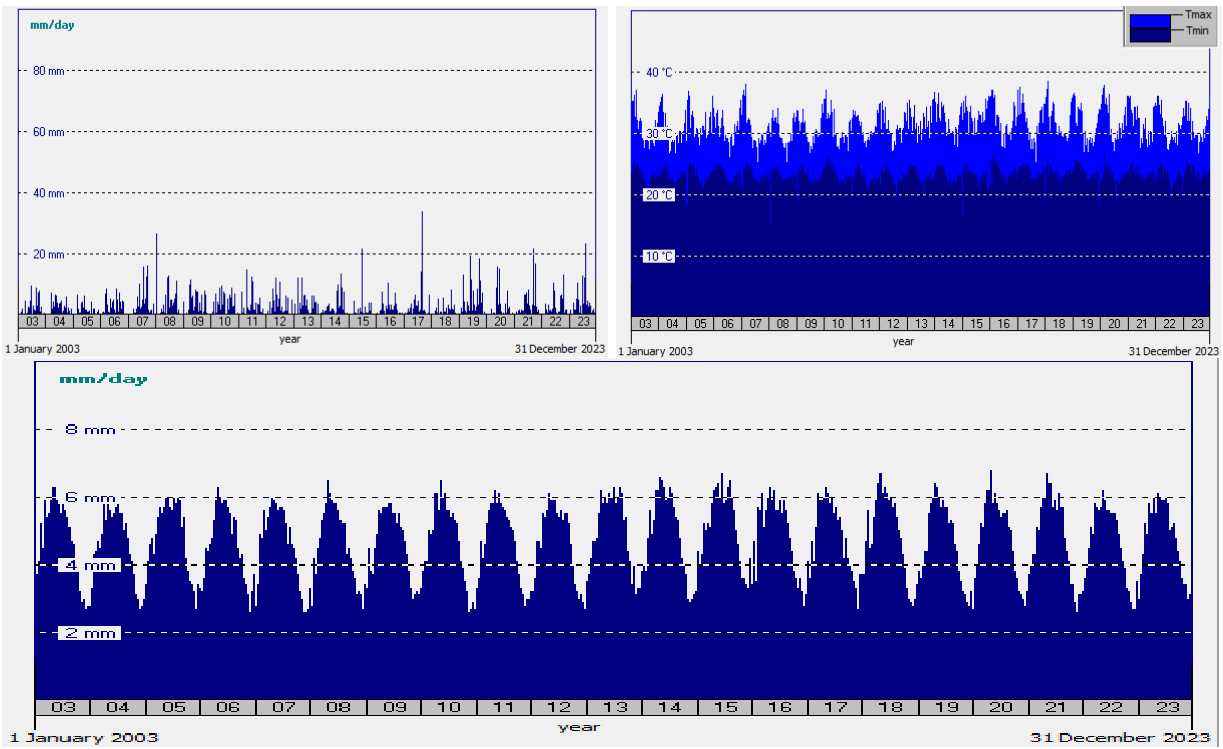


Figure 43: Weather condition (rain and temperature) and the reference evapotranspiration (ETo) estimated by Aquacrop through the FAO Penman-Monteith equation.

3.2.Sorghum

3.2.1. Crop performance and management

The ITRA team has provided details on crop management in the annual report. During the off-season of 2022, trials were conducted on the Atti-Apedokoe hub for soil amendment and crop fertilization. For the experiment and current crop modeling exercise, the sorghum variety ICSV-700 was chosen for its salt-tolerant capacity and yield potential.

Table 25: Crop management adopted for the sorghum

Operation	Dates and Notes	Photos or remarks from the field
LAND PREPARATION	In 2023, the land was prepared by clearing and brushing it.	 Field preparation and plots Amending

SOWING	Sorghum The sowing of sorghum was on 19/01/2023	 sowing of Sorghum and Pearl millet by the farmers at the Atti-Apedokoe site
IRRIGATION AND MULCHING	Irrigation regime: water is supplied in 2-day turns, depending on crop needs and in relation to the modalities	 Irrigating field using the watering can during the dry season cropping period.
WEEDING	weeding operations were done every two weeks	
FERTILIZATION	Sorghum Fertilization: NPK fertilizer (15-15-15) and urea were applied at a dose of 100kg/ha on the 35th day after sowing.	 
PEST MANAGEMENT	insecticide treatments against caterpillars were done by applying EMACOT with a sprayer.	
DATA COLLECTION	Since the trial's establishment, the ITRA team has collected data periodically. In the field, parameters such as plant height, panicle length, panicle weight, and fresh biomass yield were measured.	
HARVESTING OF SORGHUM	2023	
THE DRYING PROCESSING		

3.2.2. Development of Different Scenarios for the Sorghum

The analysis conducted through various scenarios by the model highlighted the critical requirement for supplementary irrigation, particularly during the dry season, to sustain optimal sorghum productivity. According to the simulation results, in Togo, the challenge of weed infestation in agricultural fields poses a significant threat to crop yields, potentially leading to a reduction of up to 50%. Moreover, in conditions where low soil fertility is coupled with weed presence, the yield reduction could escalate to approximately 60%. This underscores the pressing need for effective weed management and improved soil fertility practices to enhance sorghum cultivation outcomes.

Table 25: Yield and biomass estimated using the AquaCrop model for Sorghum production under different scenarios.

Scenario	Estimated		Observed	
	Biomass T/ha	Yield T/ha	Biomass T/ha	Yield T/ha
Sorghum- Sowing during the dry season, No irrigation perfect condition	19.19	4.41		
Sorghum- Sowing during the dry season, with irrigation- saline water- year 1 of saline water use.	15.57	2.47		
Sorghum- Sowing during the dry season without irrigation	10.82	1.96		
Sorghum- Sowing during the dry season, with irrigation- fresh water-medium weed	15.63	2.49		
Sorghum- Sowing during the dry season, with irrigation- freshwater medium weed-low soil **fertility**	9.64	1.50		
Sorghum- Sowing during the dry season, with irrigation- saline water- medium weed-no fertilization	9.64	1.5		

The graph below illustrates the cumulative biomass of sorghum as influenced by various production factors. It clearly demonstrates that low soil fertility has a detrimental effect on the crop's performance, leading to reduced biomass accumulation. This negative impact on sorghum growth highlights the importance of maintaining optimal soil conditions for achieving better agricultural outcomes.

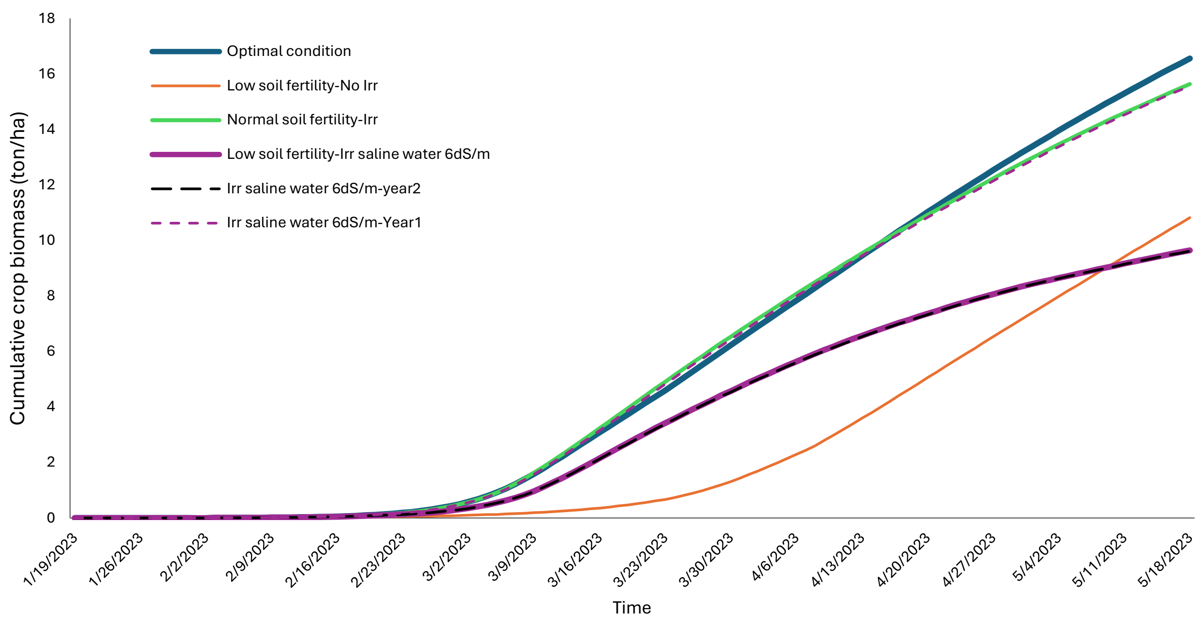


Figure 44: Cumulative biomass of sorghum under different production factors.

3.2.3. Water balance in the soil

The water balance simulation (Table 26) underscores the crucial role of irrigation in achieving optimal growth across various agricultural scenarios. Specifically, findings indicate that an irrigation volume of 200 to 250 mm is necessary to adequately meet the water requirements of sorghum plants. In the context of the BPH region of Atti-Apedokoe, Togo, a comparative analysis of soil water content simulations reveals significant disparities between irrigation and non-irrigation scenarios throughout the sorghum growth cycle. The data emphasize the vital importance of irrigation in maintaining sufficient soil moisture levels, which are essential for the healthy development of sorghum crops. This highlights the necessity of implementing effective irrigation strategies to ensure consistent soil hydration and enhance productivity in the region.

Table 26: Model output related to crop and water balance and productivity for Sorghum under different production scenarios.

Scenario	Rain	Irri	Ev	Tr	ET0	Infilt	Drain	WPet	Soil ECi	Soil ECf
Sorghum- Sowing during the dry season, no irrigation	368.4	0	123.6	395.6	621.4	368.4	0	0.85	0	0
Sorghum- Sowing during the dry season, with irrigation- saline water- year 1 of saline water use.	368.4	223.5	174.6	375.6	621.4	591.9	35.4	0.45	0	5.30
Sorghum- Sowing during the dry season, without irrigation	368.4	0	199.6	236.2	621.4	368.4	0	0.45	0	0
Sorghum- Sowing during the dry season, with irrigation- fresh water-medium weed	368.4	258.2	173.1	379.2	621.4	626.6	68.0	0.45	0	0
Sorghum- Sowing during the dry season, with irrigation- fresh water-medium weed-no fertilization	368.4	201.4	260	277.3	621.4	569.8	50.2	0.45	0	0
Sorghum- Sowing during the dry season, with irrigation- saline water-medium weed-no fertilization	368.4	202.6	262.4	277.3	621.4	571.0	49.0	0.45	0	3.97

Rain: Rainfall; Irri: Water applied by irrigation; Ev: Soil evaporation; Tr: Total transpiration of crop and weeds ET: Evapotranspiration; Infilt: Infiltrated water in soil profile; Drain: Water drained out of the soil profile; WPet: ET Water productivity for yield part (kg yield produced per m3 water evapotranspired); Soil Eci : soil salinity before plantation; Soil ECf: soil salinity after the season; EC Electrical conductivity of the saturated soil-paste extract (ECe in dS/m)

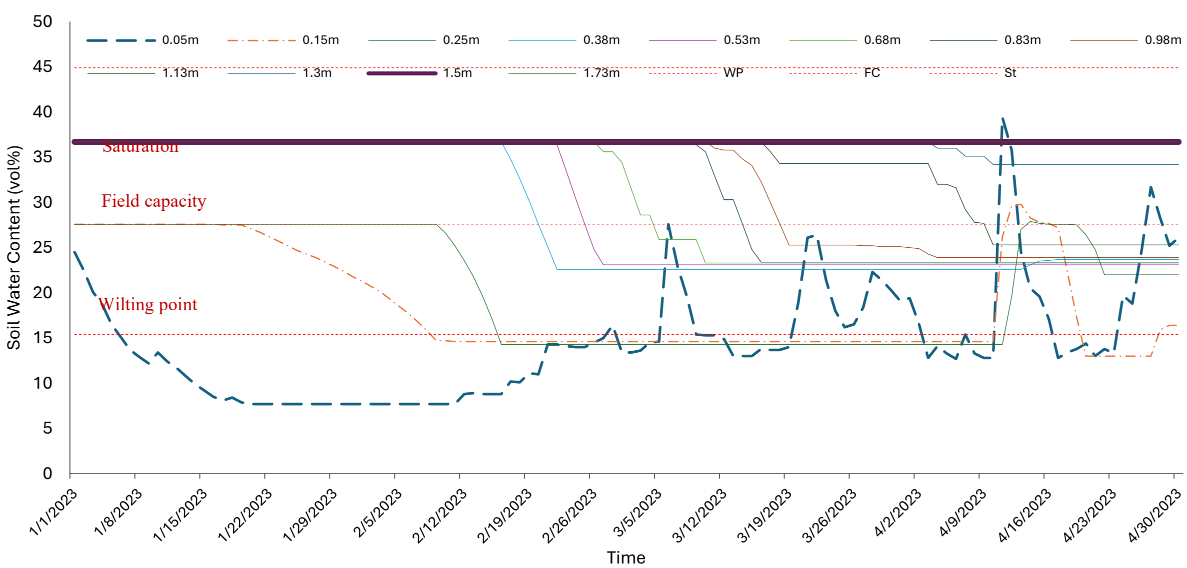


Figure 44: Soil water content in the scenario of the absence of irrigation during the sorghum growth cycle in the BPH in the region of Atti-Apedokoe, Togo.

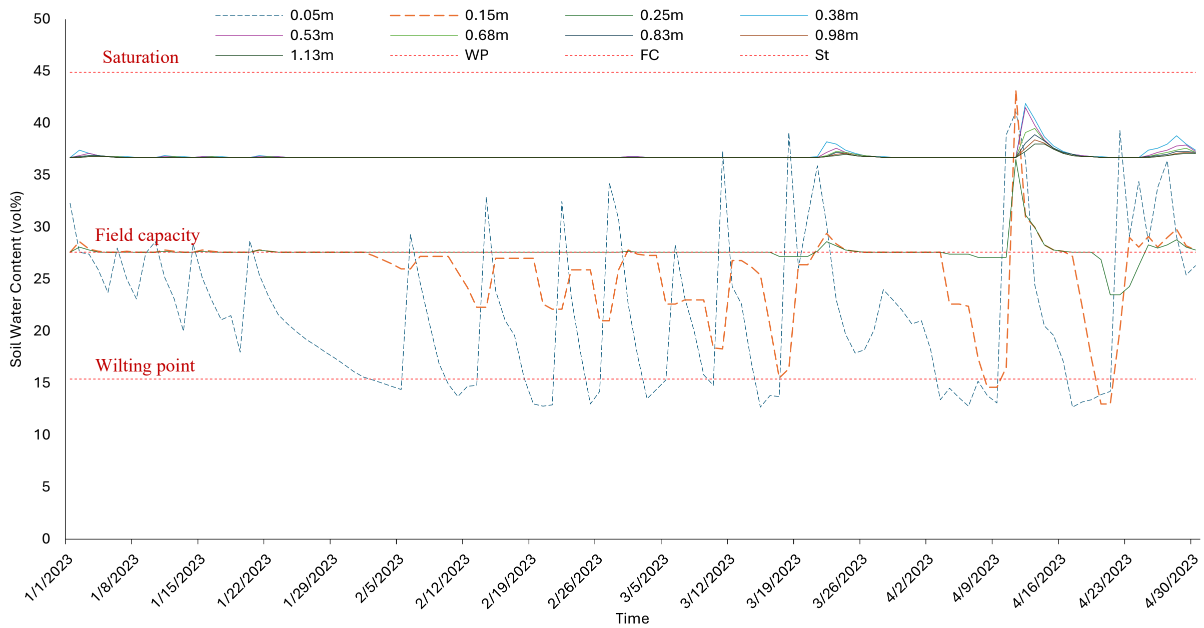


Figure 45: Soil water content in case of complimentary irrigation during the sorghum growth cycle in the BPH in the region of Atti-Apedokoe, Togo.

Considering the specific weather and soil conditions in the Atti-Apedokoe region of Togo, the irrigation schedule depicted in Figure 46 has been prepared. During the sorghum growth cycle, a total rainfall of 360 mm was recorded. However, to enhance the growth and yield of the sorghum crop, an additional water supply of 260 mm through irrigation will be required. This combination of natural rainfall and supplemental irrigation is crucial to meet the water needs of the sorghum plants during their critical growth phases, ensuring they flourish in the provided environmental conditions.

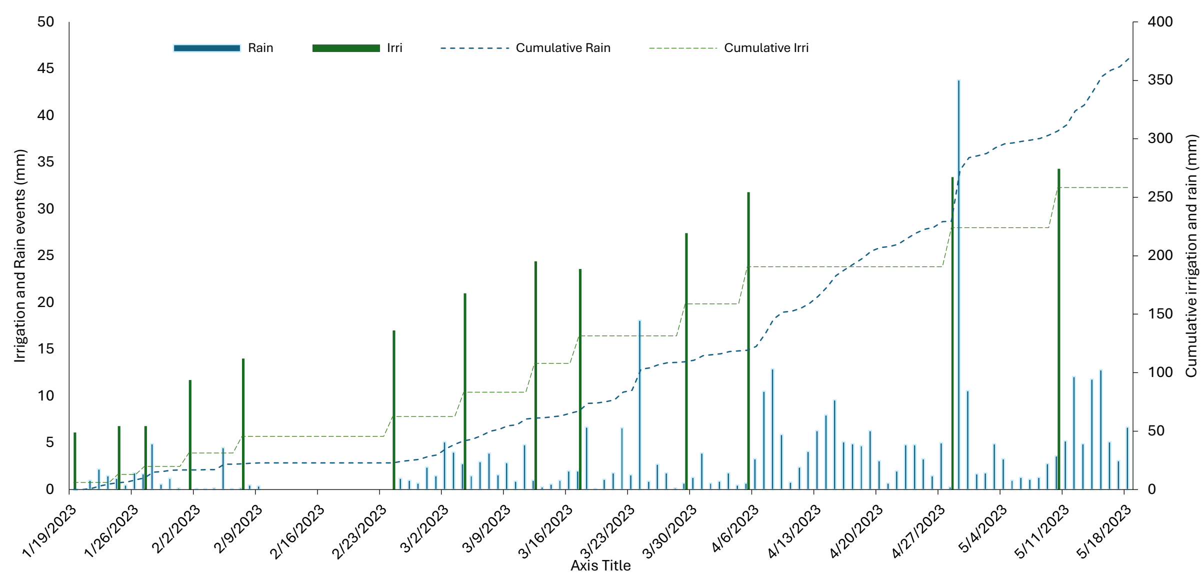


Figure 46: Irrigation and Rain events and their accumulation during the sorghum growth cycle during the dry season in the BPH in the region of Atti-Apedokoe, Togo.

3.2.4. Salinity builds up risk in case of irrigation with saline water of 6dS/m

The risk of salinity accumulation in soil due to irrigation with saline water, particularly at a concentration of 6 dS/m, is significant in Togo, as indicated by model results. This issue is especially pronounced in clay loam soil conditions, where the natural drainage capacity is limited. Without effective soil leaching strategies, such as implementing a targeted leaching fraction or establishing an appropriate drainage system, the likelihood of salt buildup in the soil increases considerably. Over time, this accumulation can adversely affect soil health, crop productivity, and the overall sustainability of agriculture in the region. Therefore, it is crucial to take these factors into account when planning irrigation practices to mitigate the risks associated with salinity.

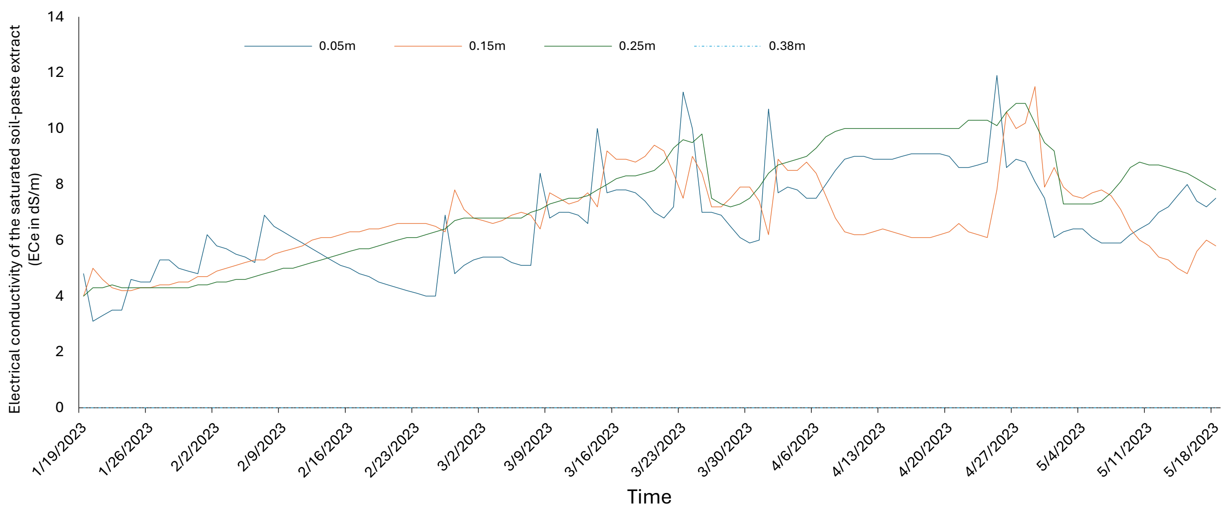


Figure 47: Electrical conductivity of the saturated soil-paste extract (ECe in dS/m) at various depths of the sorghum field irrigated with saline water of 6 dS/m during the dry seasons estimated by the Aquacrop model.

3.3. Rice

3.3.1. Rice in Togo

Rice is one of the most consumed grains in Togo and is ranked as the third staple food after corn and sorghum. In 2018, the country produced 140,519 tons of paddy, which covered a little less than half of the annual demand. However, rice production is limited by several abiotic constraints, including soil salinity, which affects production across the country. Observers have noted that rice is consumed every day by households in both rural and urban areas, and it is consumed in various forms, such as cooked with tomato or peanut sauce, as rice porridge, and as a rice paste that is highly appreciated by some communities.

According to reports, Togo currently relies on imports for approximately 70% of their rice consumption. In 2021, Togo produced around 100,000 tons of milled rice, which only covers about 30% of the country's demand.

3.3.2. Site Characteristics

Site The trial was conducted on the soil salinity hotspot in Atti Apédokoè (Maritime Region).

3.3.3. Crop management.

Table 27: Crop management adopted for the rice

Operation	Dates and Notes	Photos or remarks from the field
Land Preparation and Planting	The land was cleared and plowed using a tractor provided by the Regional Agricultural Directorate in the Lower River Region. The community women help with the leveling and planting.	Plowing of the trial plots
Sowing	**TRANSPLANTING** The nursery was installed on the 10th of July 2020. Transplanting: 25th of July.	 Picture of the nursery seven days after sowing and Transplanting of the seedlings
Irrigation and mulching		
Weeding	Hand weeding was done whatever was needed.	
Fertilization	**FERTILIZER APPLICATION** In terms of fertilizer application, 200 kg/ha of $N_{15}P_{15}K_{15}$ was applied at the transplanting, and 100 kg/ha of Urea in two applications (50 kg/ha at the tillering stage and 50 kg/ha at panicle initiation).	 **View of the trial at the vegetative phase**
Pest management	Not mentioned	
HARVESTING OF rice	Manuel harvest	 View of the trial at the reproductive phase
The drying processing		

3.3.4. Development of Different Scenarios Rice

The simulation of biomass and yield of rice across various production scenarios revealed insightful findings. It was determined that the most effective method for achieving a high rice yield involves using freshwater irrigation combined with optimal fertilization practices. This approach fosters a healthy growing environment for the rice plants, promoting robust development and productivity (Figure 48). In stark contrast, the study found that employing a continuous flooding technique with saline water at a salinity level of 6 dS/m resulted in significantly reduced yields. This highlights the detrimental effects of salinity on rice growth, underscoring the importance of water quality in agricultural practices.

Table 28: Model output related to biomass and Yield production for Rice under different production scenarios.

Scenario	Estimated		Observed	
	Biomass	Yield	Biomass	Yield
Rice- with irrigation- fresh water, good fertilization	9.2	3.95		
Rice- with irrigation- fresh water, local condition	5.78	2.48	Total yield= 8.42	
Rice- No irrigation-	3.9	1.71		
Rice- irrigation - Saline water 6 dS/m water-saline soil 0.1 dS/m	5.76	2.48		
Rice- Continuous flooding-0 dS/m - soil	5.7	2.4		
Rice- Continuous flooding - Saline water 6 dS/m water-saline soil 0.1 dS/m	5.43	2.33		

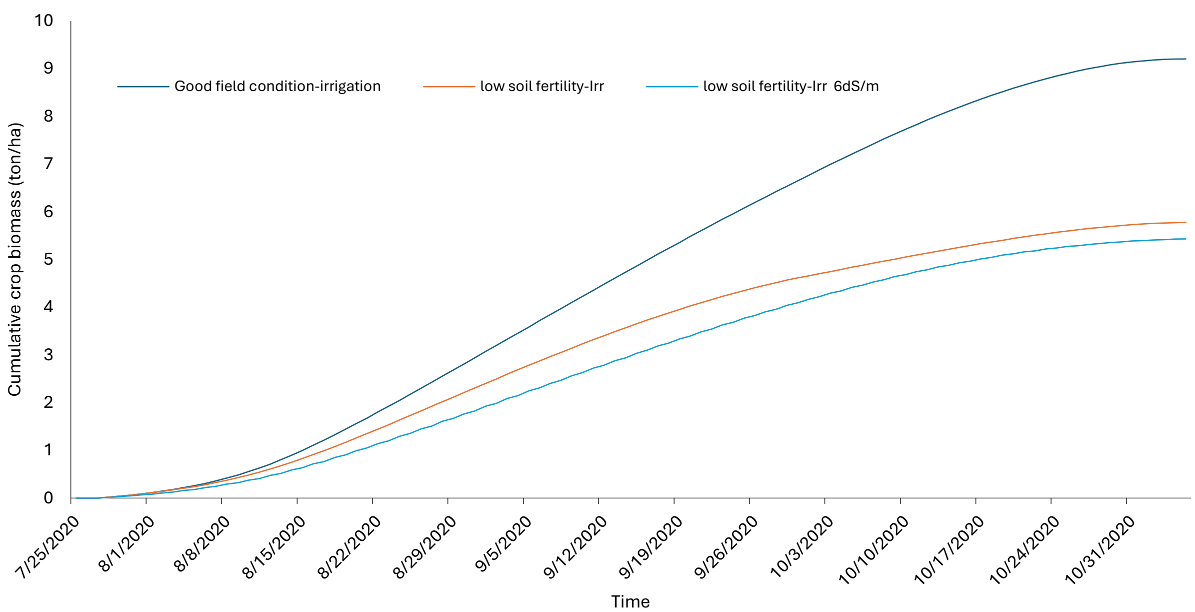


Figure 48: Cumulative crop biomass of rice under different production factors.

3.3.5. Water balance in the soil

The comprehensive analysis of water balance in rice cultivation across various production scenarios yielded valuable insights into effective agricultural practices. It became evident that the most efficient approach to optimize rice water productivity is to implement freshwater irrigation in conjunction with carefully managed fertilization techniques.

To establish an ideal soil-water balance throughout the growing cycle, it is essential to provide an irrigation volume of 213 mm, supplemented by an additional 352 mm derived from rainfall (Figure

50). Together, these water inputs are instrumental in maintaining soil moisture levels close to field capacity (Figure 49) ensuring that the rice plants receive the necessary hydration throughout their growth.

On the other hand, the method of continuous flooding demands a substantially higher volume of water, signifying the need for a more significant management effort to sustain such an irrigation strategy. This approach required 10600 mm of water, highlighting the challenges associated with water resource allocation in rice farming (Figure 51).

Table 29: Model output related to crop and water balance and productivity for rice under different production scenarios.

Scenario	Rain	Irri	Ev	Tr	ET0	Infilt	Drain	WPet	Soil ECi	Soil ECf
Rice- with irrigation- fresh water, perfect fertilization	352.7	218.6	126.6	346.1	487.8	571.3	103.1	0.84	0	0
Rice- with irrigation- fresh water, local condition	352.7	213.6	199.8	270.2	487.8	566.3	95.8	0.53	0	0
Rice- NO irrigation- fresh water	352.7	0	212.6	113.9	487.7	352.7	39.6	0.52	0	0
Rice- irrigation - Saline water 6 dS/m water-saline soil 0.1 dS/m	352.7	217.3	199.8	269.0	487.7	570.0	100.9	0.53	0	1.25
Rice- Continuous flooding -0 dS/m - soil	352.7	10600	237.9	270.0	487.8	106208	10235.8	0.49	0.1	0.1
Rice- Continuous flooding - Saline water 6 dS/m water-saline soil 0.1 dS/m	352.7	10600	229.7	219.5	487.8	10674.1	10292.5	0.52	0	5.12

Rain: Rainfall; Irri: Water applied by irrigation; Ev: Soil evaporation; Tr: Total transpiration of crop and weeds ET: Evapotranspiration; Infilt: Infiltrated water in soil profile; Drain: Water drained out of the soil profile; WPet: ET Water productivity for yield part (kg yield produced per m3 water evapotranspired); Soil Eci : soil salinity before plantation; Soil ECf: soil salinity after the season; EC Electrical conductivity of the saturated soil-paste extract (ECe in dS/m)

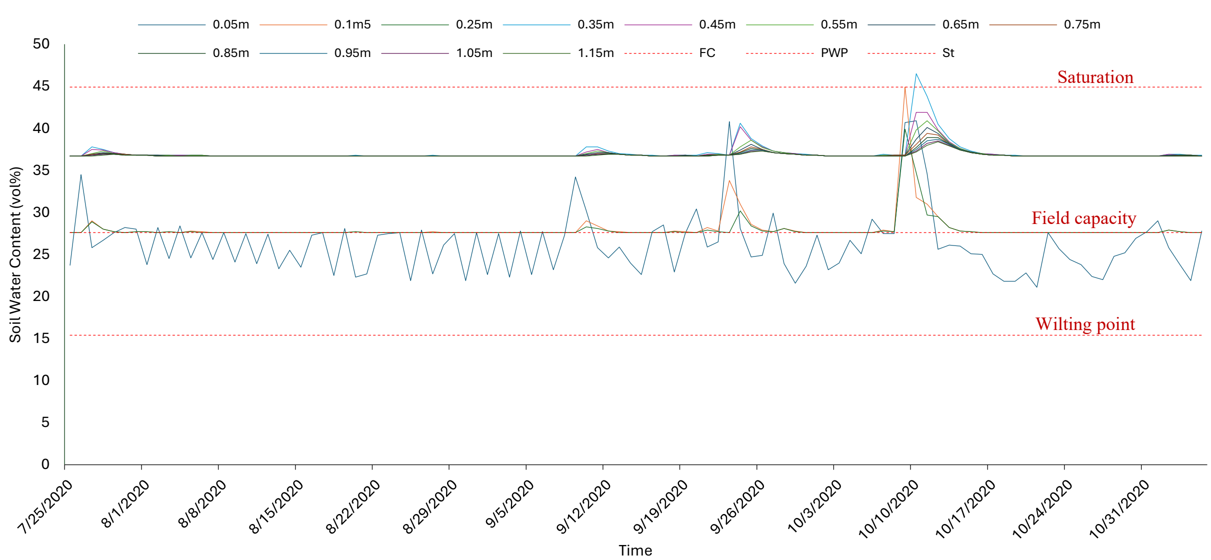


Figure 49: Soil water content in the scenario of irrigation during the rice growth cycle in the BPH in the region of Atti-Apedokoe, Togo.

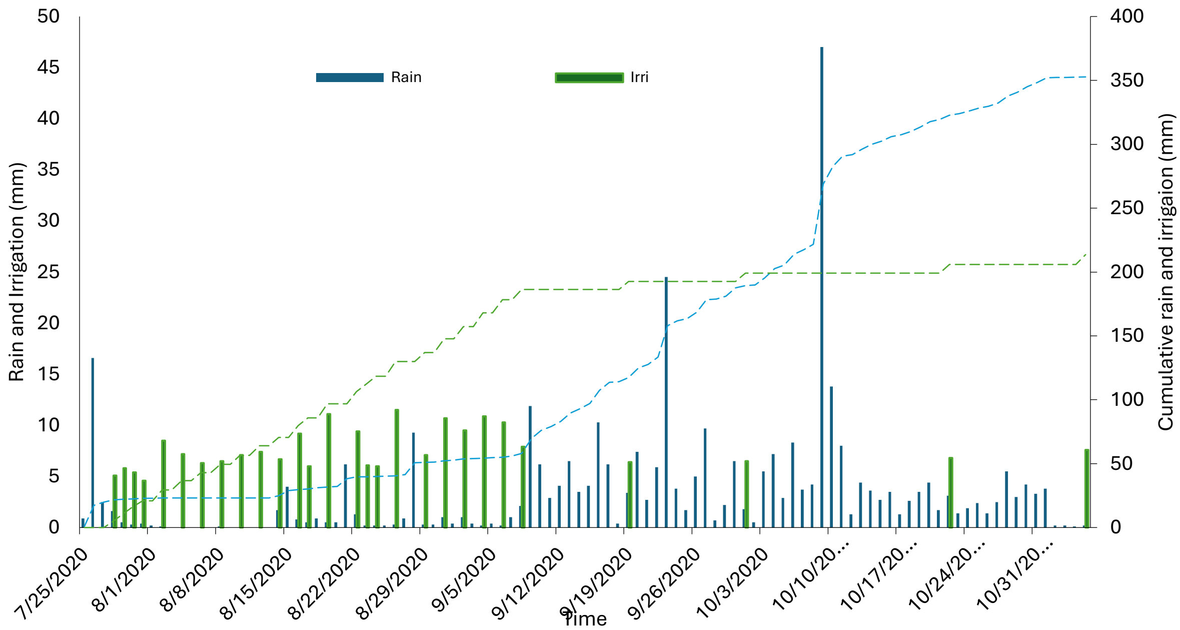


Figure 50: Irrigation and Rain events and their accumulation during the rice growth cycle in the BPH in the region of Atti-Apedokoe, Togo.

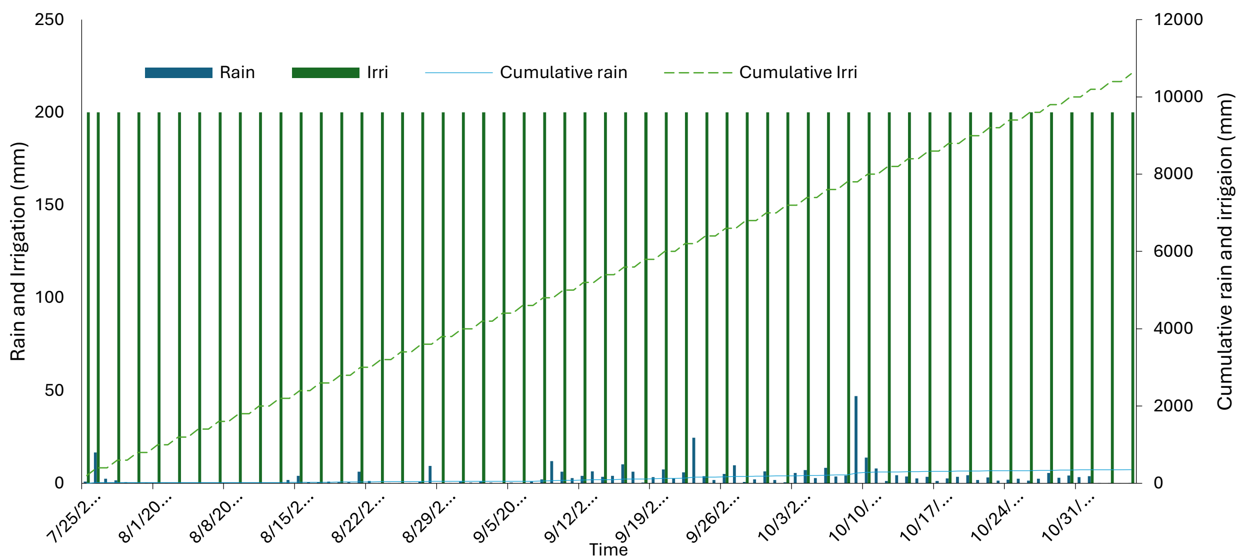


Figure 51: Irrigation and Rain events and their accumulation for Continuous flooding rice during the rice growth cycle in the BPH in the region of Atti-Apedokoe, Togo.

3.3.6. Water budget

The water budget is a critical concept that tracks the dynamics of water entering, exiting, and being stored within the soil, particularly within the root zone where plants absorb moisture. The results from the simulation indicated that the soil possesses favorable characteristics for water infiltration, allowing it to be readily available for plant uptake. Furthermore, any surplus water can be efficiently drained away, minimizing the risk of waterlogging. For rice cultivation, the water utilized by the plants, which is represented by the process of transpiration, is vital for achieving acceptable yields. Research suggests that with adequate water supply (Figure 50), rice can produce impressive yields ranging from 2.5 to 3.5 tonnes per hectare.

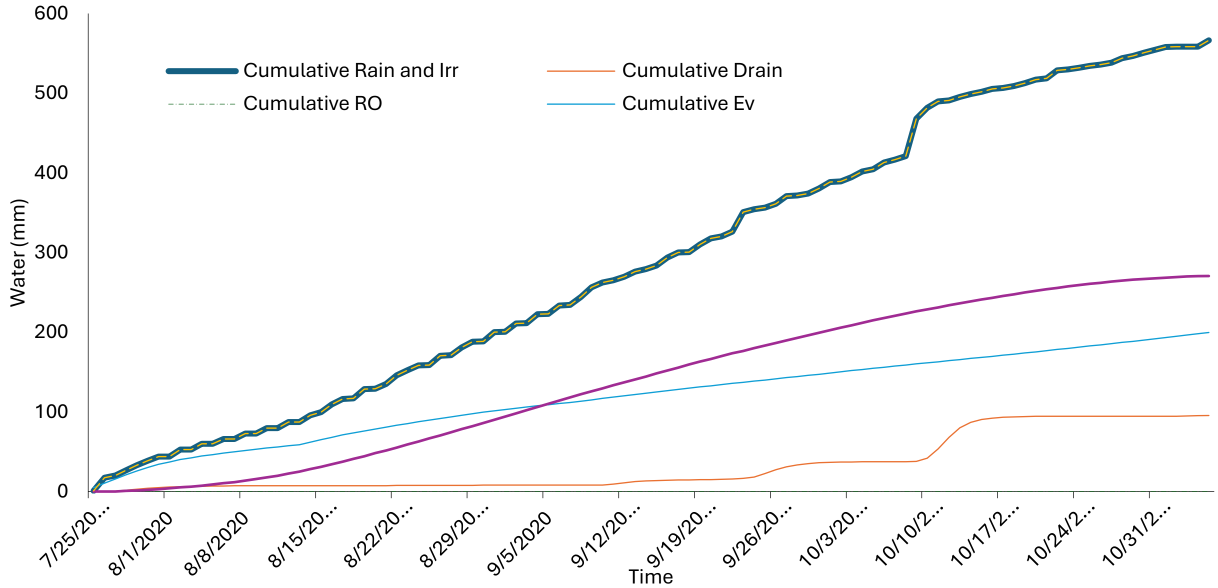


Figure 52: Water budget during the rice growth cycle, irrigated with fresh water in the BPH in the region of Atti-Apedokoe, Togo.

Rain: Rainfall; Irri: Water applied by irrigation; Ev: Soil evaporation; Tr: Total transpiration of crop and weeds ET: Evapotranspiration; Infilt: Infiltrated water in soil profile; Drain: Water drained out of the soil profile.

3.3.7. Salinity builds up risk in case of irrigation with saline water of 6dS/m

The risk of salt building up in the soil from irrigating with salty water, especially at a concentration of 6 dS/m, is a major concern in Togo. This problem is worse in clay loam soils, which do not drain well. If we do not use effective methods to leach the soil, such as a targeted leaching fraction or proper drainage systems, salt accumulation in the soil will likely increase. Over time, this can harm soil quality, reduce crop yields, and threaten the sustainability of farming in the area. Therefore, it's important to consider these factors when planning irrigation practices to reduce salinity risks.

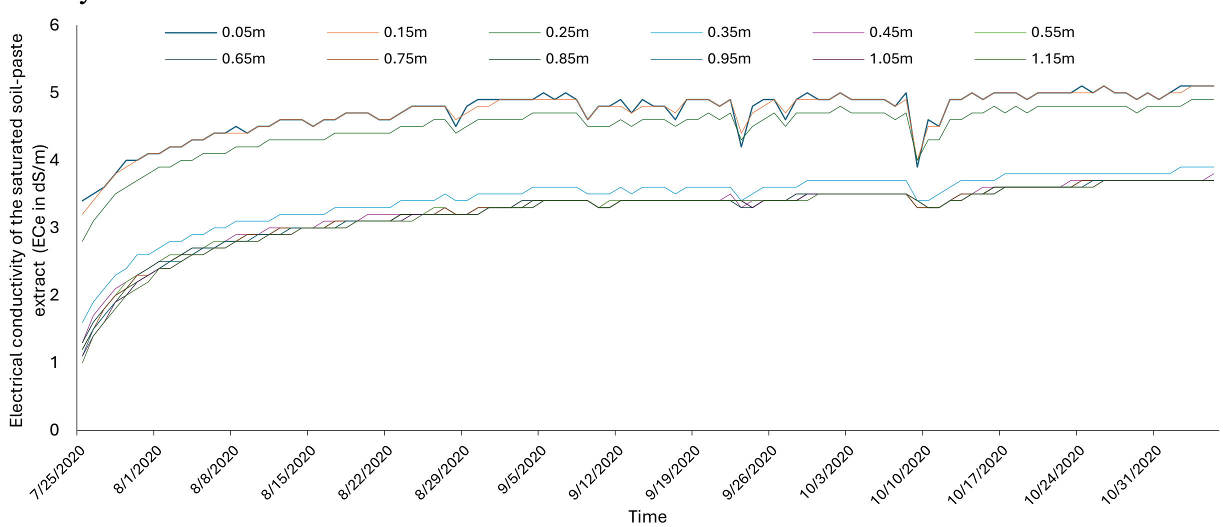


Figure 53: Electrical conductivity of the saturated soil-paste extract (ECe in dS/m) at various depths of the rice field irrigated with saline water of 6 dS/m, estimated by Aquacrop model.

4. Conclusion

In conclusion, the findings from the soil-water-plant modeling study concerning the optimal allocation of irrigation and drainage in the irrigated regions of Togo can be summarized as follows:

- The analysis emphasizes the critical need for supplementary irrigation during the dry season to maintain optimal sorghum productivity in Togo. Key findings include:
  - ✓ Weed infestation can reduce crop yields by up to 50%, escalating to around 60% with low soil fertility, highlighting the necessity for effective weed management and improved soil practices.
  - ✓ Low soil fertility negatively impacts sorghum biomass accumulation, underscoring the importance of maintaining optimal soil conditions for better agricultural outcomes.
  - ✓ An irrigation volume of 200 to 250 mm is essential for adequate sorghum growth, with significant differences observed between irrigation and non-irrigation scenarios throughout the growth cycle.
  - ✓ In Atti-Apedokoe, a total of 360 mm of rainfall is complemented by an additional 260 mm of irrigation water needed for optimal sorghum development during critical growth phases.
  - ✓ There is a significant risk of soil salinity accumulation from using saline water (6 dS/m) in clay loam soils without proper drainage and leaching strategies, adversely affecting soil health and agricultural sustainability. Thus, careful irrigation planning is crucial to mitigate salinity risks.
- The simulation of biomass and rice yield highlighted the effectiveness of using freshwater irrigation combined with optimal fertilization for achieving high yields, and better water productivity. In contrast, continuous flooding with saline water (6 dS/m salinity) significantly reduced yields, emphasizing the importance of water quality.
- The analysis showed that an irrigation volume of 213 mm, plus an additional 352 mm from rainfall, is essential for maintaining soil moisture at field capacity. Continuous flooding requires much higher water volumes, indicating greater management challenges.
- The water budget tracks the dynamics of moisture in the soil, crucial for plant uptake and transpiration, with potential yields of 2.5 to 3.5 tonnes per hectare when water supply is adequate.
- In Togo, the risk of salt accumulation from using salty water, particularly in clay loam soils, threatens soil quality and crop yields. Effective leaching methods and drainage systems are necessary to mitigate salinity risks and ensure sustainable farming practices.

Liberia

1. General information

Liberia, located in West Africa, has a notable agricultural sector that contributes significantly to its economy. Agriculture accounts for between 25% and 35% of Liberia’s GDP, making it a crucial component of its financial stability. Furthermore, over 75% of the population relies on agriculture for their livelihood, highlighting the sector's importance in providing employment and sustenance for a majority of Liberians.

One of Liberia's key assets for agricultural development is its extensive arable land, which spans over 4 million acres. Despite this abundance, Liberia still imports over half of its food, indicating a potential for increased domestic production to meet the country's nutritional needs and reduce reliance on imports.

The fertile soil, favorable climatic conditions, and abundant water resources in Liberia form a solid foundation for enhancing agricultural activities. However, there is underutilization of arable land and limited irrigation, which present opportunities for investment and development to boost productivity and food security in the country.

Water resources are also integral to Liberia's agricultural landscape. The country is endowed with six principal river basins and numerous smaller rivers and streams, all of which ultimately flow into the Atlantic Ocean to the south. However, the proximity to the ocean results in frequent sea intrusion and salinization of freshwater resources in coastal regions, posing challenges for agricultural activities. Nevertheless, the abundance of water resources provides an opportunity for irrigation and agricultural development. It's worth noting that despite an estimated 600,000 hectares of land with irrigation potential, less than 1% of it is currently under irrigation (LNRDS, 2012). This underutilization represents an area with potential for growth and improvement in agricultural productivity.

Rice and cassava have traditionally been the primary staple crops in Liberia. While rice is a highly consumed commodity, it is imported on a large scale, indicating an opportunity for increased domestic production to meet local demand.

2. Study site characterization

2.1. Site name

Site name: RESADE-Libiran HUB

Location: The Best Practice Hub (BPH) is located near the Mechlin River in the plunker community, Grand Bassa County along Liberia's coastal belt. The river's salinity level (EC) is approximately 6.23 ds/m. This salinity level decreases during the rainy season and increases during the dry season when the water level decreases and the sea intrudes into the river.

Best Practice Hub (BPH), near the Mechlin River in Grand Bassa County, Liberia.

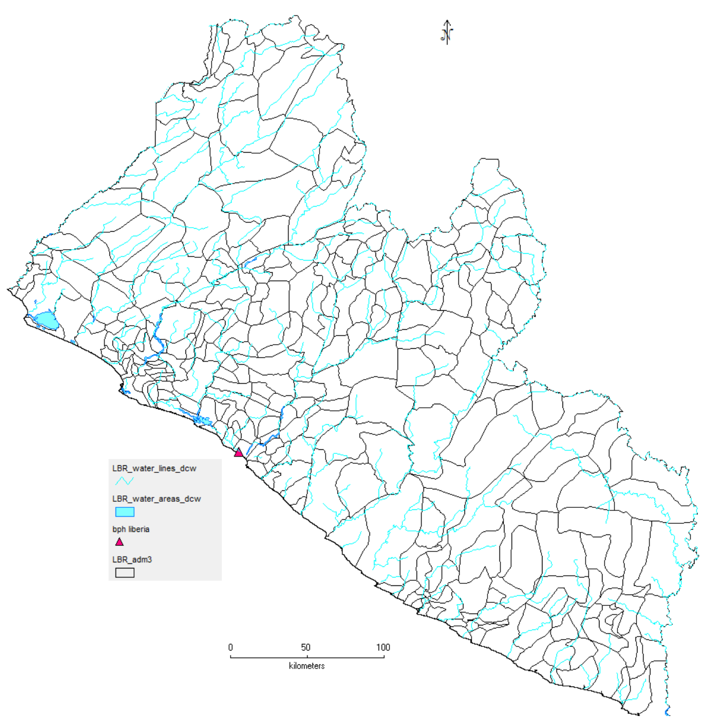


Figure 54: Liberian map with the geographical distribution of water and rivers and the Best Practice Hub location.

DIVA-GIS software (version 7.5) was used to create the maps.

2.2.Soil characteristics

The data presented in Table 30 pertains to the physical and chemical properties of soil and the soil-water status in the area of Hub, Grand Bassa, Liberia. This information has been sourced from the FAO portal and analyzed using the Soil Water Characteristics software to determine the anticipated Soil Water Properties.

Table 30: Physical and Chemical Properties of the Soil of the Hub in the region of Grand Bassa, Liberia.

	BPH site		**Other soil**	
Parameters	Topsoil (0-30 cm)	Subsoil (30-60)	Topsoil (0-30 cm)	Subsoil (30-60)
Sand Fraction (%)	82	81	40	41
Silt Fraction (%)	10	11	39	34
Clay Fraction (%)	8	8	21	25
USDA Texture Classification	loamy sand	loamy sand	loam	loam
Reference Bulk Density (kg/dm3)	1.62	1.62	1.4	1.38
Bulk Density (kg/dm3)	1.4	1.5	1.33	1.36
Gravel Content (%)	19	10	2	4
Organic Carbon (% weight)	0.7	0.31	1.25	0.4
pH (H2O)	5.4	5.2	5.1	5.2
CEC (clay) (cmol/kg)	27	22	24	31
CEC (soil) (cmol/kg)	4	3	11	10
Base Saturation (%)	38	79	47	47
TEB (cmol/kg)	1.7	2.8	5.5	6.1
Calcium Carbonate (% weight)	0	0	0	0
Gypsum (% weight)	0	0	0	0
Sodicity (ESP) (%)	3	4	1	1
Salinity (ECe) (dS/m)	0.1	0.1	0.1	0.1

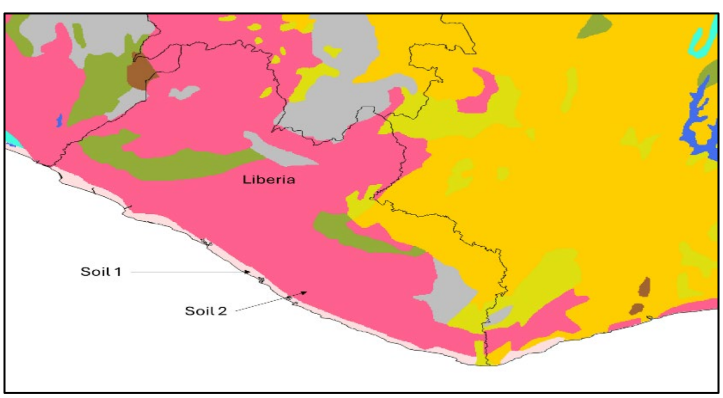


Figure 55: Soil 1 represents the loamy sand soil of the BPH site (coastal areas), and the soil 2 sample represents the loam soil of another region.

A soil sample was taken for analysis before installing the BPH. The results of the analysis of the soil's physical and chemical properties are presented in Tables 31 and 32.

Table 31: Soil physical properties for BPH-Liberia, laboratory results.

Sample	**Depth (cm)**	**pH 1:1**	**EC 1:1 ms/cm**	**Clay (%)**	**Silt (%)**	**Sand (%)**	**% OM**	**% C**
Liberia	0-20	4.05	0.041	1.35	6.64	92.008	2.51	1.46
Liberia	20-40	4.01	0.037	1.91	5.60	92.488	2.53	1.47
Liberia	40-60	4.19	0.030	4.19	7.44	88.368	3.15	1.83
Liberia	60-80	4.00	0.022	12.11	6.72	81.168	2.92	1.69
Liberia	80-100	3.96	0.021	13.07	5.48	81.448	2.57	1.49

Table 32: Soil chemical properties: Ca Mg, Cl, Na, available K, P, and N.

Sample	**Depth (cm)**	**Ca (meq/L)**	**Mg (meq/L)**	**Cl (meq/L)**	**Na (mg/L)**	**Na (meq/L)**	**K (mg/L)**	**K (meq/L)**	**P (mg/kg)**	**N (ppm)**
Liberia 1	0-40	0.56	0.66	12.50	19.75	0.86	0.86	0.02	2.18	1.68
Liberia 2	40-100	0.82	1.04	11.00	23.93	1.04	0.42	0.01	1.25	1.82

Table 33: Soil-Water Status of the Hub in the region of Grand Bassa, Liberia

Parameters	Unit	Topsoil (0-30 cm)	Subsoil (30-60)
Wilting point	% vol	7.3	7.3
Field capacity	% vol	28.4	28.4
Saturation	% vol	47.4	47.4
Available water	in/ft	2.53	2.53
Salt hydraulic conductivity	in/ha	0.96	0.96
Matric bulk density	Ib/ft3	86.94	86.94

1 in/ft=83.33 millimeter/meter

2.3.Weather condition

Climate data for daily precipitation and maximum and minimum temperature in the region of BPH in Grand Bassa, Liberia, was collected between January 1st, 2013, and December 31st, 2023. This data was obtained from the Worldwide Energy Resource (POWER) Project, which is funded by the National Aeronautics and Space Administration (NASA) Applied Sciences Program. The POWER website is a dependable source of climate data and can be easily accessed through https://power.larc.nasa.gov/data-access-viewer/.

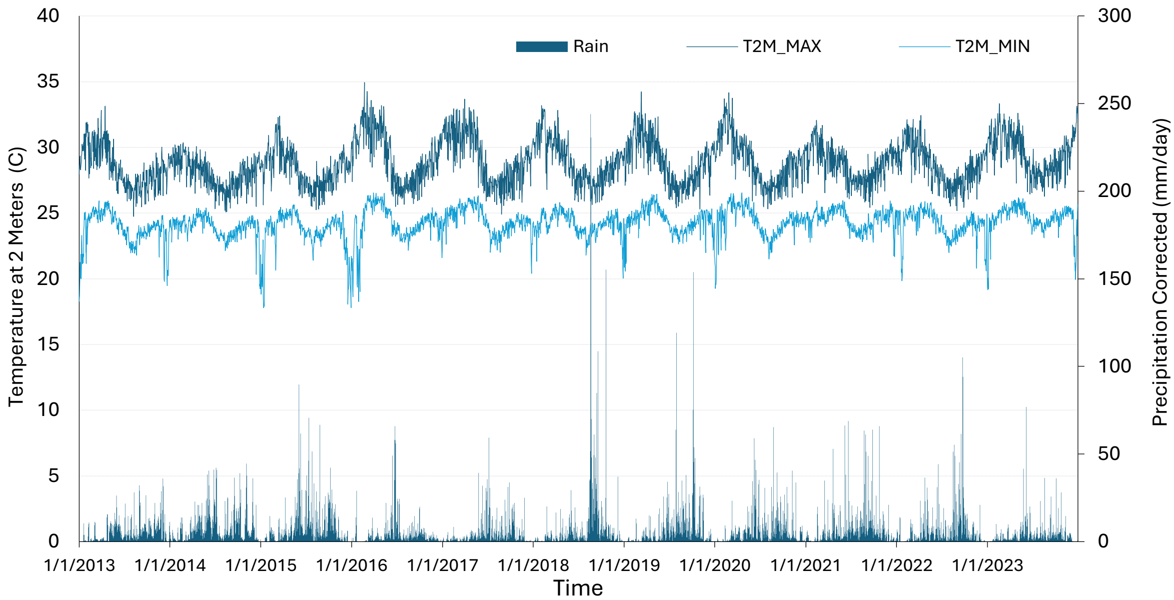


Figure 56: Daily precipitation, maximum and minimum temperature in the region of Grand Bassa, Liberia, f 57rom January 1st, 2013, to December 31st, 2023.

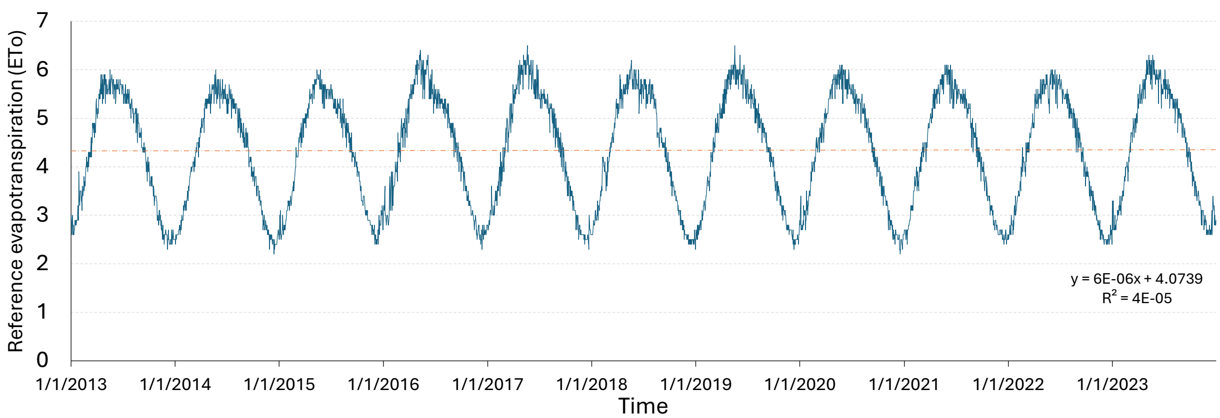


Figure 57: Daily Reference evapotranspiration (ETo) in the region of BPH-Liberia, during the period of January 1st, 2013, to December 31st, 2023.

The sensing system integrated into the BPH has collected essential data on the field's weather conditions. These real-time data are utilized to refine and calibrate the online data obtained from satellites, thereby ensuring enhanced accuracy and precision.

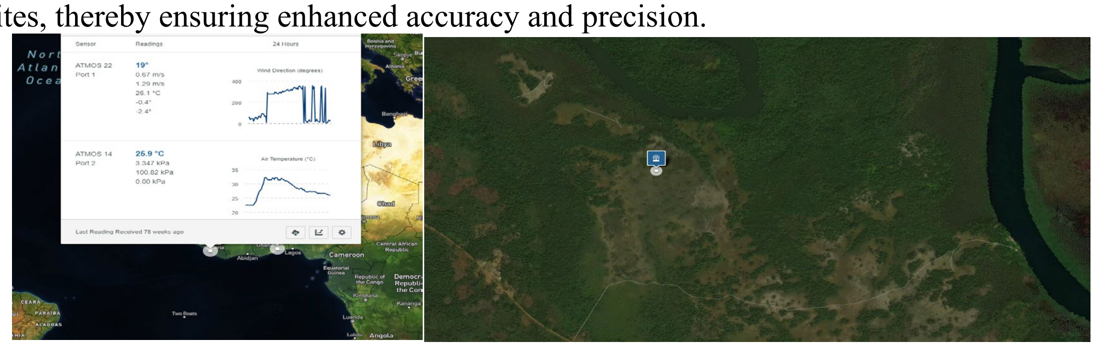


Figure 58: Climatic data collected and analyzed in real-time using the sensor installed in the BPH Analyzed.

2.4.Soil sensors data

Precision agriculture is a farming management technique aimed at enhancing the accuracy and efficiency of crop growth. Its primary goal is to achieve efficiency, profitability, and sustainability while safeguarding the environment. This system facilitates data-driven irrigation scheduling, enabling the determination of actual water requirements for selected grasses and forages, with the potential for significant on-farm water and energy savings. In BPH, a sensing system has been installed to collect crucial real-time soil data on the water-soil balance in the field. Sensory system platforms are designed to estimate atmospheric evaporative demand, below-ground data, and plant data. This allows for measuring a plant's response to atmospheric water demand and soil water supply, ultimately fine-tuning crop coefficients required for irrigation and other management practices. This, in turn, enhances forage productivity while conserving natural resources, particularly water and soil. The system also improves irrigation and fertilization practices, provides quantitative data for water-saving and capacity-building efforts, and supports water security.
Below is the estimated soil water content data and percent plant available water for Hub-Liberia during 2022-2023 using TEROS 12 Moisture/Temp/EC sensors.

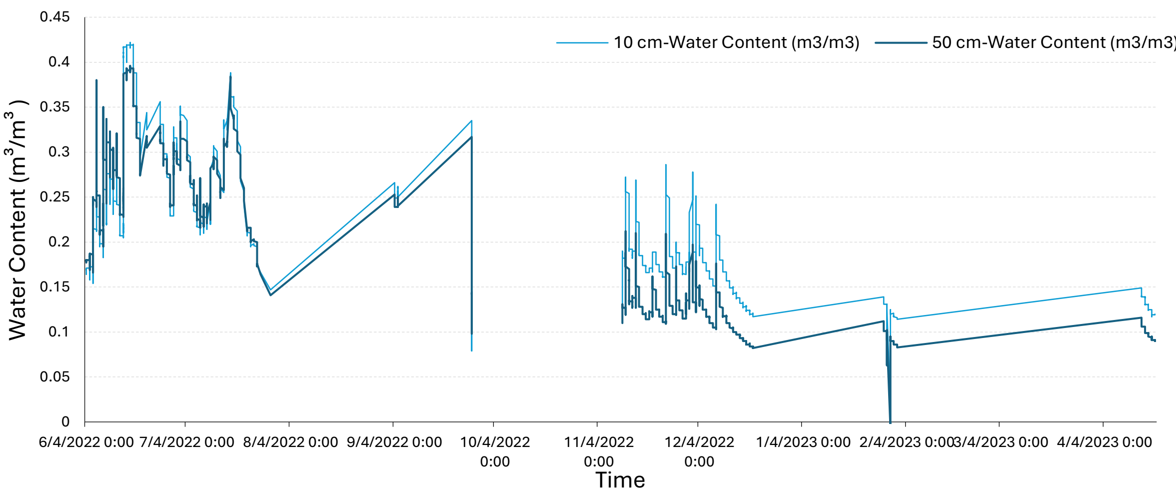


Figure 59: Soil Water Content during the 2022-2023 in the Hub- Liberia, estimated using TEROS 12 Moisture/Temp/EC sensors.

3. Simulation modeling results

The Model is a tool that can be used easily in the RESADE target countries. It only requires a few specific parameters and mostly straightforward input variables that can be determined using simple methods. The inputs consist of weather data, crop and soil characteristics, and a description of field and irrigation management practices that define the environment in which the crop will grow. Soil characteristics are further divided into soil profile and groundwater characteristics.

3.1.Calculation of the reference evapotranspiration (ETo)

AquaCrop includes a calculator that uses weather station data to calculate the reference evapotranspiration (ETo) through the FAO Penman-Monteith equation.

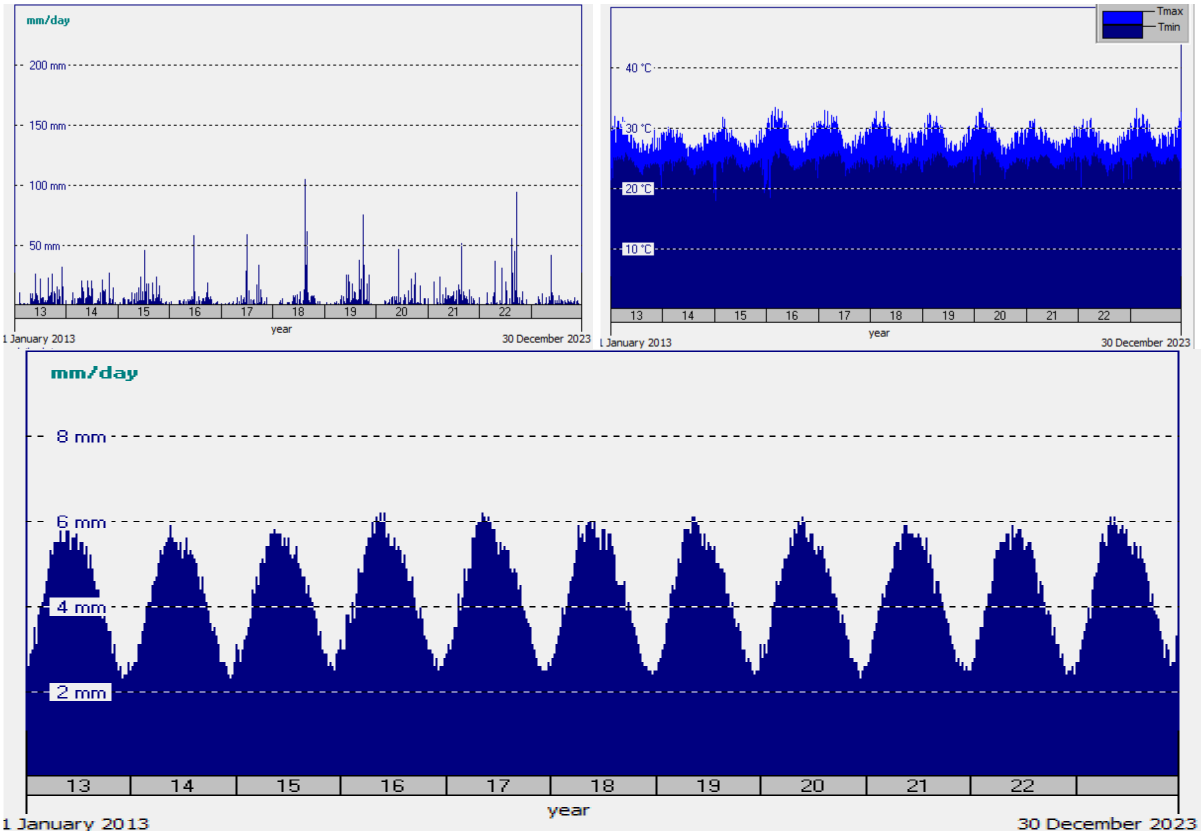


Figure 60: Weather condition (rain and temperature) and the reference evapotranspiration (ETo) estimated by Aquacrop through the FAO Penman-Monteith equation.

3.2.Crop performance of Sorghum.

3.2.1. Crop management

The RESADE-CARI team has provided valuable insights into crop management, highlighting essential practices for a crop model's success. These practices cover a range of agricultural activities carried out throughout the season, such as seedbed preparation, seed sowing, crop maintenance, and harvesting, and all the associated problems, such as floods.

Table 34: Crop management adopted for the sorghum.

Operation	Dates and Notes	Photos or remarks from the field
LAND PREPARATION	On February 24th, 2023, the land was prepared by clearing and brushing it.	 land preparation
SOWING	On July 19, 2021, Sorghum and Pearl Millet were seeded. The plant spacing was 50cm between plants and 75cm between rows resulting in a plant population of 226,666 per hectare.	 Farmers participate in the sowing of Sorghum

IRRIGATION AND MULCHING	Seedlings emerged within 3-4 days after sowing, but due to the intensity of the rain at the time of emergence, seedlings and crops were damaged and only a very few survived, but growth performance was quite poor.	 crop emergence in the field
WEEDING	The field was weeded twice, on April 18th and 20th, 2023, and then again on May 8th.	 Weeding farmer cluster plot
FERTILIZATION	Before sowing, NPK fertilizer was used for a basal application rate of 150 kg/ha.	
PEST MANAGEMENT		
DATA COLLECTION	Colleagues and technicians collected data periodically since the trial's establishment. Parameters such as plant height, panicle length, panicle weight, and fresh biomass yield were measured in the field. Samples were dried in an oven at 70°C for 3 days before being weighed in a desiccator.	 Field data collection by Technicians
HARVESTING OF PEARL MILLET		 Flooded field after crop emergence
HARVESTING OF SORGHUM		

3.2.2. Simulation Modeling Results and Development of Different Scenarios

Following the completion of model calibration using the available data, various production scenarios were investigated. The results of this analysis are summarized in the tables provided below, demonstrating the model's effectiveness in yielding insights into production dynamics (Figure 60). The investigation identified that the primary risk of yield loss due to salinity arises from salt accumulation, particularly associated with non-adaptive irrigation practices or inadequate drainage systems. A key finding of this research is the importance of cultivating salinity-tolerant crops in this region to mitigate potential losses. The introduction of a sensitive sorghum genotype was associated with a decrease in biomass, resulting in a loss of approximately 10 tons per hectare, as detailed in Table 35. This highlights the significance of selecting appropriate crop varieties to address the challenges presented by salinity.

Table 35: yield and biomass estimated using Aquacrop model

Scenario	**Estimated**		**Observed**	
	Biomass	Yield	Biomass	Yield
Sorghum- Sowing during the dry season, with irrigation- fresh water	26.08	4.90		
Sorghum- Sowing during the dry season, with irrigation- saline water (6dS/m)- tolerant crop	26.08	4.90		
Sorghum- Sowing during the dry season, without irrigation tolerant crop	25.45	4.69		

Sorghum- Sowing during the dry season, with irrigation- saline water for 1st year- sensitive crop-loamy sand **soil**	25.61	4.85		
Sorghum- Sowing during the dry season, with irrigation- saline water for 2nd year- sensitive crop-loamy sand soil	20.58	3.8		
Sorghum- Sowing during the dry season, with irrigation- saline water for 2nd year- sensitive crop-loam soil.	17.72	3.25		

Figure 60 presents a comparison of the cumulative crop biomass of sorghum cultivated under various production factors.

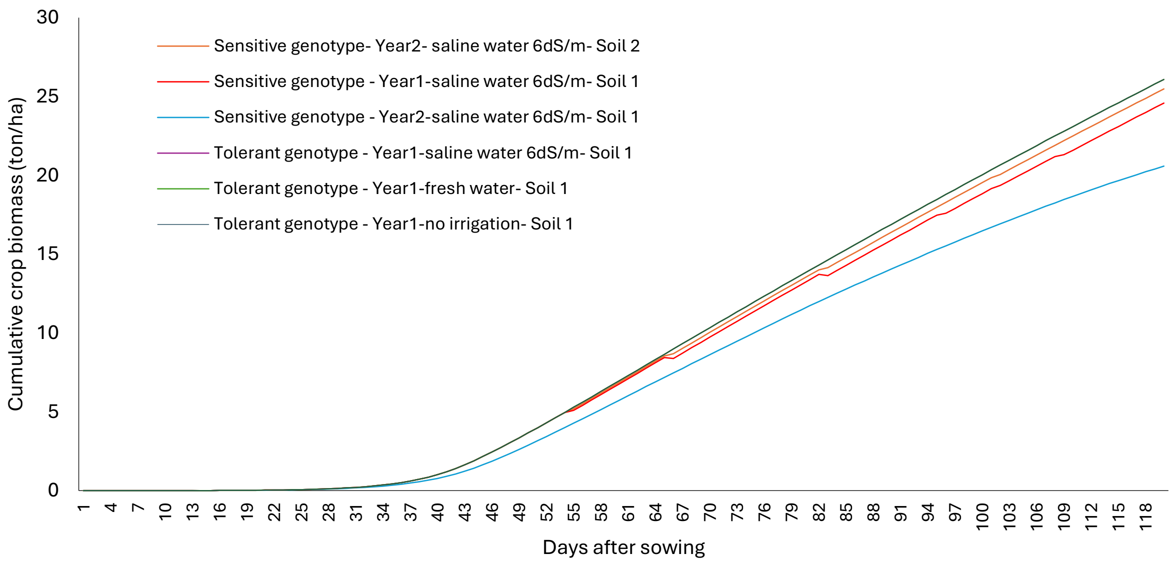


Figure 60: Cumulative crop biomass of sorghum cultivated under different production factors.

3.2.3. Water balance in the soil

Figure 61 displays the soil water content during the sorghum growth cycle in the BPH region with complimentary irrigation. The results confirm that the model's proposed irrigation schedule helps to maintain soil water content between the wilting point and field capacity. This ensures adequate water supply for the sorghum crop without over-irrigation, leading to better crop performance. In the middle of May, the rainy season began, bringing the soil moisture level to saturation at some points during the growth cycle.

Table 36: model output related to crop and water balance and productivity for Sorghum under different production scenarios.

Scenario	Rain	Irri	Ev	Tr	ET0	Infilt	Drain	WPet	Soil ECi	Soil ECf
Sorghum- Sowing during the dry season, with irrigation- fresh water	329.2	97.7	102.7	293.2	404.8	426.7	44.7	1.24	0.1	0.1
Sorghum- Sowing during the dry season, with irrigation- saline water- tolerant crop	329.2	97.7	102.7	293.2	404.8	426.7	44.7	1.24	0.1	1.49
Sorghum- Sowing during the dry season, without irrigation tolerant crop	1245	16	232.8	300.8	513.8	1133.1	602.2	0.92	0.1	0
Sorghum- Sowing during the dry season, with irrigation- saline water for 1st year- sensitive crop-loamy sand **soil**	437	105	105	273.6	390	526.6	150.4	1.28	0.1	1.96
Sorghum- Sowing during the dry season, with irrigation- saline water for 2nd year- sensitive crop-loamy sand soil	437	106	131	217	390.6	527.3	180.3	1.09	1.96	2.26

Sorghum- Sowing during the dry season, with irrigation- saline water for 2nd year- sensitive crop-loam soil.	437	89.4	148	198.4	390	488.7	102.4	0.97	1.96	2.69

Rain: Rainfall; Irri: Water applied by irrigation; Ev: Soil evaporation; Tr: Total transpiration of crop and weeds ET: Evapotranspiration; Infilt: Infiltrated water in soil profile; Drain: Water drained out of the soil profile; WPet: ET Water productivity for yield part (kg yield produced per m3 water evapotranspired); Soil Eci : soil salinity before plantation; Soil ECf: soil salinity after the season; EC Electrical conductivity of the saturated soil-paste extract (ECe in dS/m)

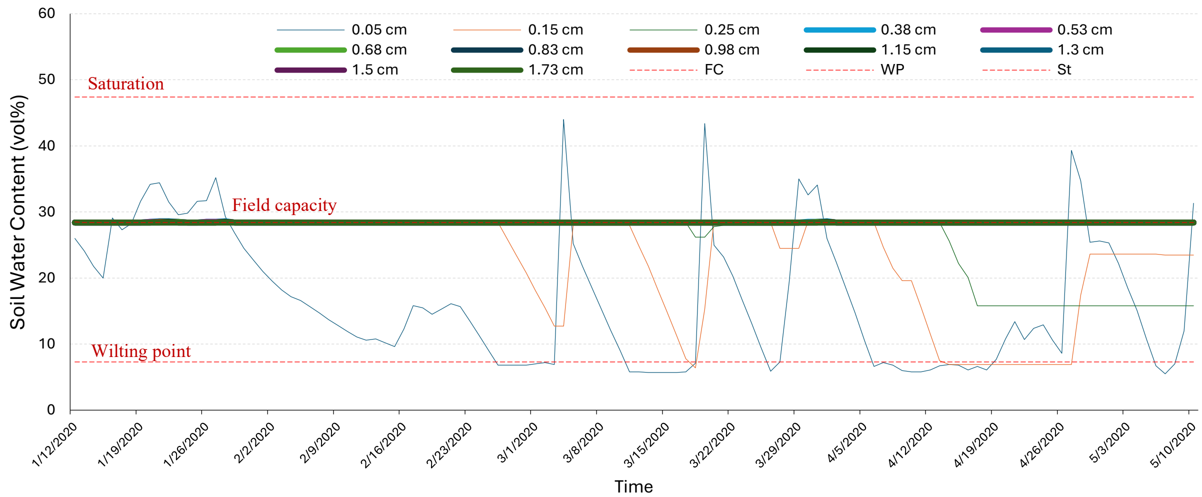


Figure 61: Soil water content in case of complimentary irrigation during the sorghum growth cycle in the Hub- Liberia.

In the absence of irrigation, the soil moisture at a depth of 0 to 30 cm drops below the wilting point at the beginning of the crop's growth cycle. If no irrigation is provided, a significant reduction in crop yield is observed.

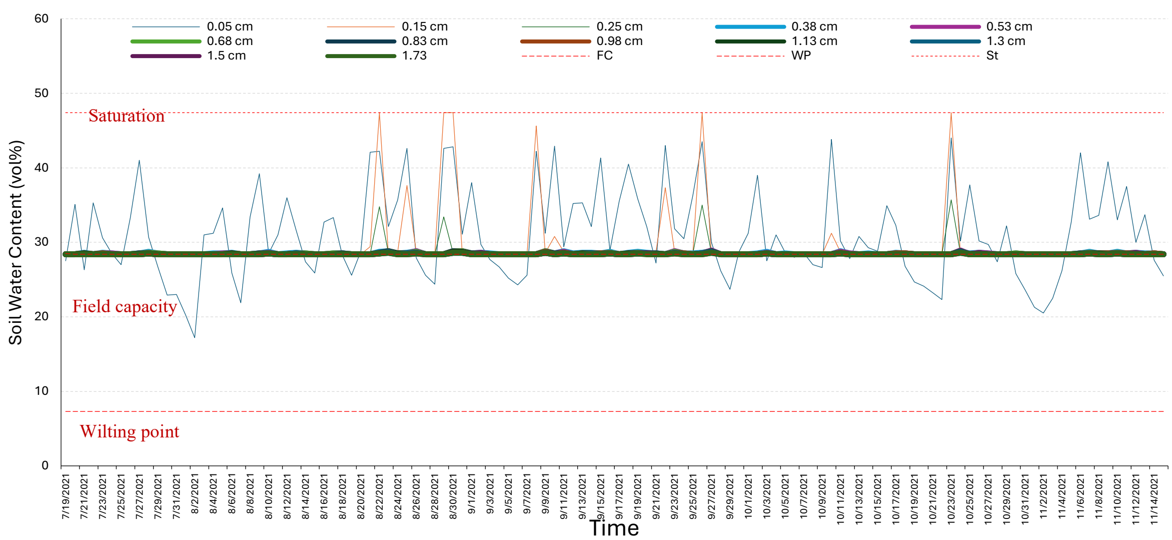


Figure 62: Soil water content in the scenario of the absence of irrigation during the sorghum growth cycle in the Hub- Liberia.

To ensure sufficient water supply for the crops, irrigation was necessary to meet their water requirements prior to the onset of effective rainfall, which typically occurs from May onwards.

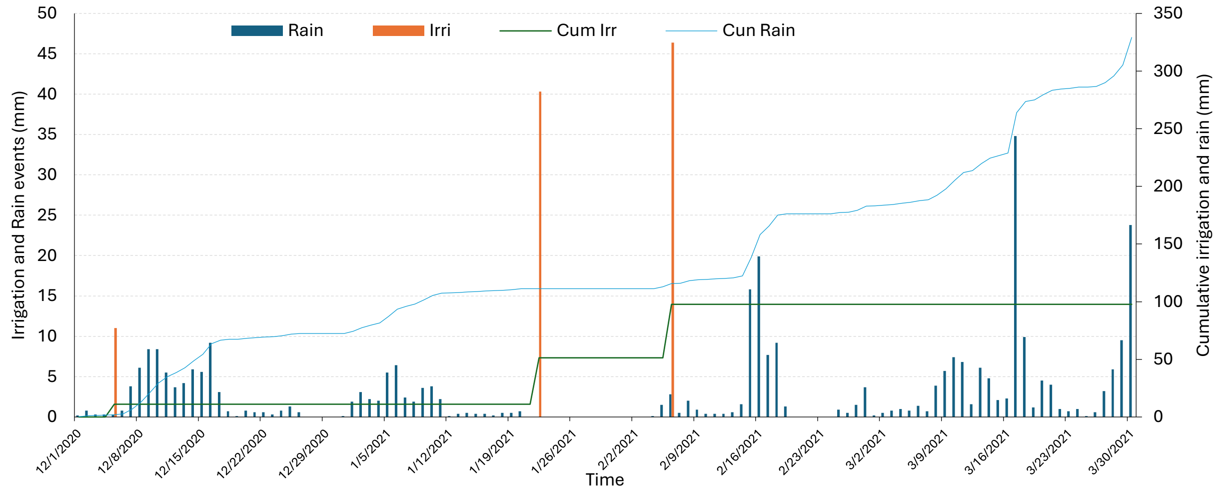


Figure 63: Irrigation and Rain events and their accumulation during the sorghum growth cycle, dry season, in the BPH in the Hub- Liberia.

3.2.4. Salinity build-up risk in case of irrigation with saline water of 6dS/m

The simulation results indicate that certain locations in Liberia do not face the risk of salinity build-up. When 6 ds/m saline water was used for irrigation, the soil salinity increased. However, it decreased after the first rainfall in May, which leached out all the salt accumulated in the soil profile of 1.73 meters.

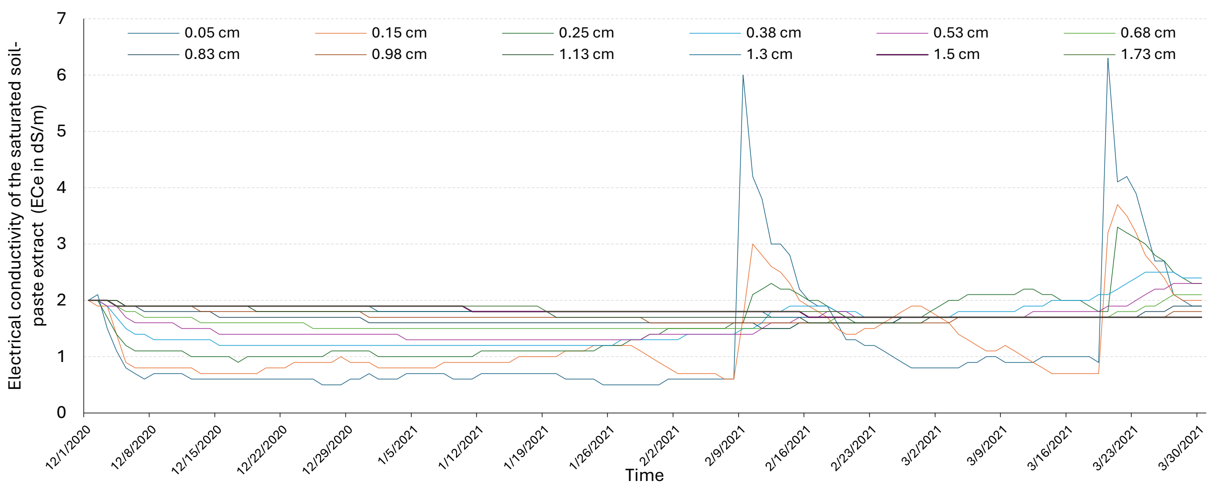


Figure 64: Electrical conductivity of the saturated soil-paste extract (ECe in dS/m) at various depths of the sorghum field irrigated with saline water of 6 dS/m, estimated by the Aquacrop model.

4. Conclusion

In conclusion, the findings from the soil-water-plant modeling study concerning the optimal allocation of irrigation and drainage in Labiria's irrigated regions can be summarized as follows:

- The model can be an effective resource for scientific and technical teams, requiring minimal information regarding weather conditions, crop characteristics, and soil properties to derive essential irrigation management parameters. The comprehensive outputs provided by the model facilitate the evaluation of water requirements and management strategies at the field level, offering crucial support to smallholder farmers.
- Calibration of the model has been completed, leading to the development of various production scenarios that illustrate the effects of salinity on crop yields, particularly arising from inadequate irrigation practices and drainage systems.
- To mitigate yield losses, the use of salinity-tolerant crops is recommended. For instance, a sensitive sorghum genotype demonstrated a biomass loss of approximately 10 tons per hectare due to salinity-related issues.
- The model's irrigation schedule effectively helps maintain soil water content for sorghum, preventing over-irrigation while ensuring an adequate water supply, particularly during the rainy season.
- In the absence of irrigation, soil moisture can fall below the wilting point during the dry season, significantly diminishing yields during the crop's growth phase.
- Some areas in Liberia indicate no risk of salinity accumulation, with soil salinity levels decreasing following rainfall that leaches away the accumulated salts.

Mozambique

1. General information

Mozambique's rich water resources present significant potential for the development of irrigation. Despite 3.3 million hectares of suitable land for irrigation, only 50,000 hectares are currently utilized due to limited water management infrastructure. Notably, 60% of the irrigated land is dedicated to commercial sugarcane production. Major crops in Mozambique include food crops such as maize, sorghum, millet, rice, cassava, vegetables, and cash crops like sesame, cotton, tobacco, pigeon pea, tea, sugar, and cashew. The country faces challenges such as inadequate water management infrastructure and the need for improved irrigation systems. However, Mozambique’s vast water resources and arable land present a great opportunity for agricultural expansion. Addressing these challenges could significantly boost agricultural productivity and reduce reliance on food imports.

The agricultural sector in Mozambique is confronted with noteworthy challenges such as inadequate water management infrastructure, climatic variability, and limited access to modern agricultural technologies, which impede the country's ability to harness its agricultural potential and ensure food security fully. Nevertheless, there are substantial opportunities for growth. Mozambique possesses abundant water resources and fertile land, which, if managed effectively, can significantly enhance agricultural productivity. Ongoing projects aimed at enhancing irrigation systems and supporting smallholder farmers represent pivotal steps toward addressing these challenges. By tackling these issues, Mozambique can augment its agricultural output, diminish its dependence on food imports, and elevate the well-being of its farming communities. Numerous projects in Mozambique are dedicated to enhancing agriculture by providing assistance to smallholder farmers with irrigation, which is essential for fortifying Mozambique's agricultural sector, bolstering food security, and diminishing reliance on food imports.

2. Study site characterization

2.1. Site name

Site name: RESADE-Maputo-Mozambique HUB
The Best Practice Hub (BPH) is located in Moamba, Mozambique.

Best Practice Hub (BPH), Moamba, Mozambique.

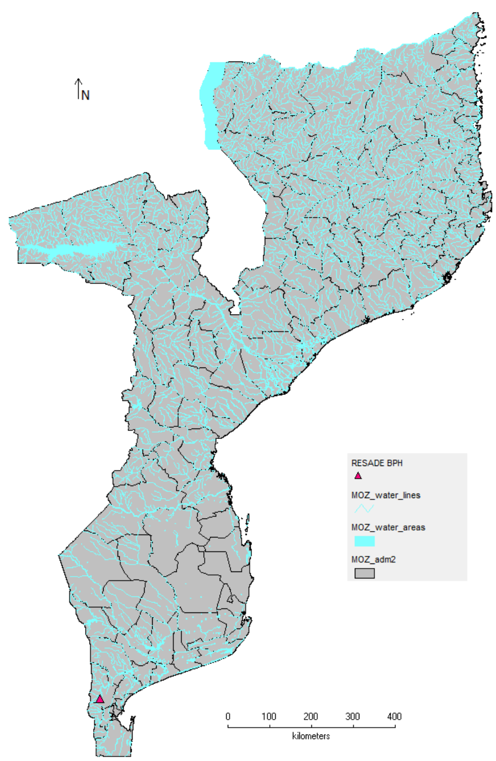


Figure 65: Mozambique map with the geographical distribution of water and rivers and the Best Practice Hub location.
DIVA-GIS software (version 7.5) was used to create the maps.

2.2.Soil characteristics

The data presented in Table 37 pertains to the physical and chemical properties of soil and the soil-water status in the area of Hub, in the region of Moamba, Mozambique. This information has been sourced from the FAO portal and analyzed using the Soil Water Characteristics software to determine the anticipated Soil Water Properties.

Table 37: Physical and Chemical Properties of the Soil of the Hub in the region of Moamba, Mozambique.

Parameters	Topsoil (0-30 cm)	Subsoil (30-60)
Sand Fraction (%)	36	8
Silt Fraction (%)	38	41
Clay Fraction (%)	26	51
USDA Texture Classification	loam	silty clay
Reference Bulk Density (kg/dm3)	1.36	1.2
Bulk Density (kg/dm3)	1.37	1.39
Gravel Content (%)	0	0
Organic Carbon (% weight)	0.87	1.15
pH (H2O)	6.9	6.7
CEC (clay) (cmol/kg)	73	84
CEC (soil) (cmol/kg)	22	46
Base Saturation (%)	96	98
TEB (cmol/kg)	21.1	45.1
Calcium Carbonate (% weight)	1.3	1
Gypsum (% weight)	0.1	0.1
Sodicity (ESP) (%)	2	3
Salinity (ECe) (dS/m)	0.1	0.2

Table 38: Soil-Water Status of the Hub in the region of Moamba, Mozambique.

Parameters	Unit	Topsoil (0-30 cm)	Subsoil (30-60)
Wilting point	% vol	17	29.9
Field capacity	% vol	31.2	42.6
Saturation	% vol	46.5	53.5
Available water	in/ft	1.71	1.53
Salt hydraulic conductivity	in/ha	0.36	0.12
Matric bulk density	Ib/ft3	88.88	76.85

1 in/ft=83.33 millimeter/meter

2.5.Weather condition

Climate data for daily precipitation and maximum and minimum temperature in the region of BPH in Grand Bassa, Liberia, was collected between January 1st, 2013, and December 31st, 2023. This data was obtained from the Worldwide Energy Resource (POWER) Project, which is funded by the National Aeronautics and Space Administration (NASA) Applied Sciences Program. The

POWER website is a dependable source of climate data and can be easily accessed through https://power.larc.nasa.gov/data-access-viewer/.

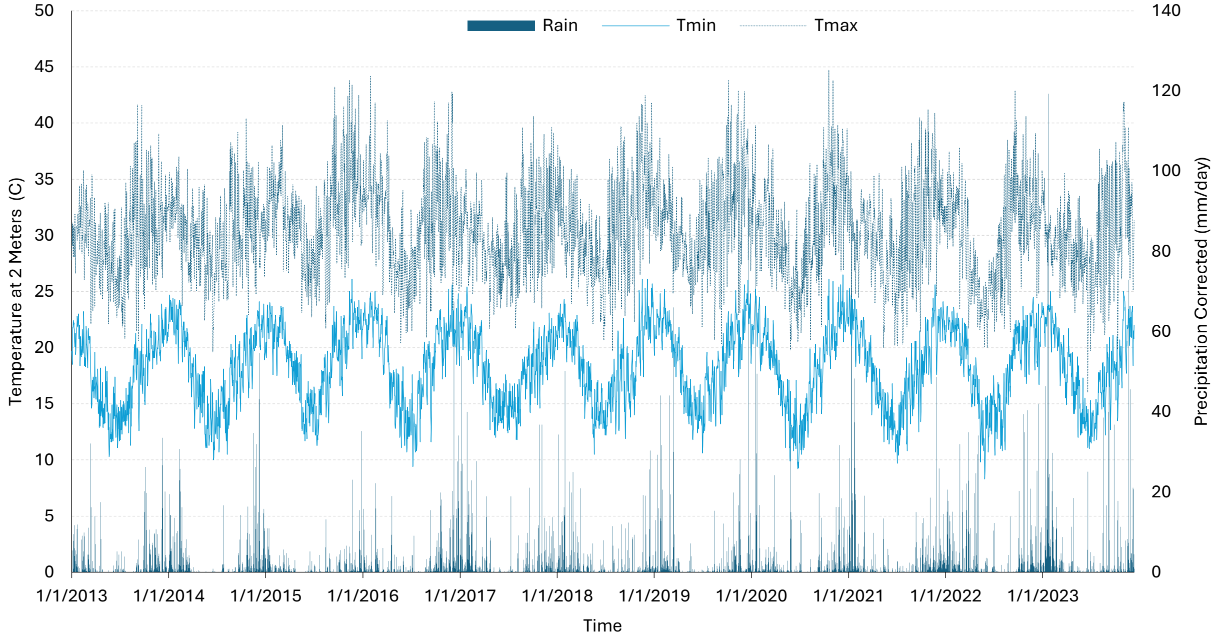


Figure 66: Daily precipitation, maximum and minimum temperature in the region Moamba, Mozambique, from January 1st, 2013, to December 31st, 2023.

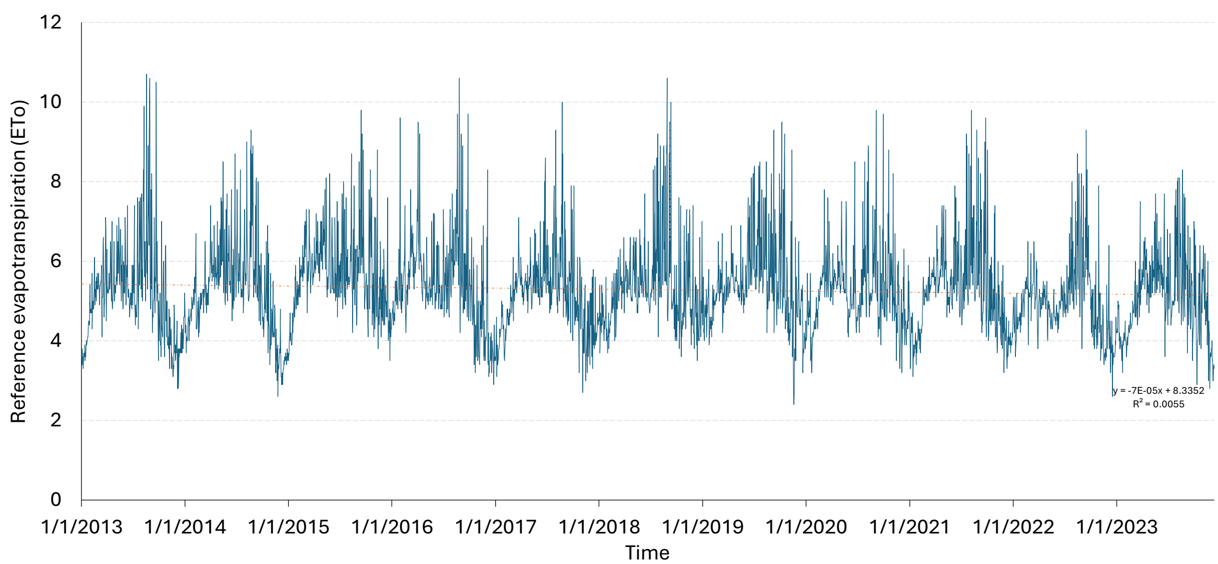


Figure 67: Daily Reference evapotranspiration (ETo) in the region of Moamba, Mozambique, from January 1st, 2013, to December 31st, 2023.

3. Simulation modeling results

AquaCrop is a tool that can be used easily in the RESADE target countries. It only requires a few specific parameters and mostly straightforward input variables that can be determined using simple methods. The inputs consist of weather data, crop and soil characteristics, and a description of field and irrigation management practices that define the environment in which the crop will grow. Soil characteristics are further divided into soil profile and groundwater characteristics.

3.1. Calculation of the reference evapotranspiration (ETo)

AquaCrop includes a calculator that uses weather station data to calculate the reference evapotranspiration (ETo) through the FAO Penman-Monteith equation.

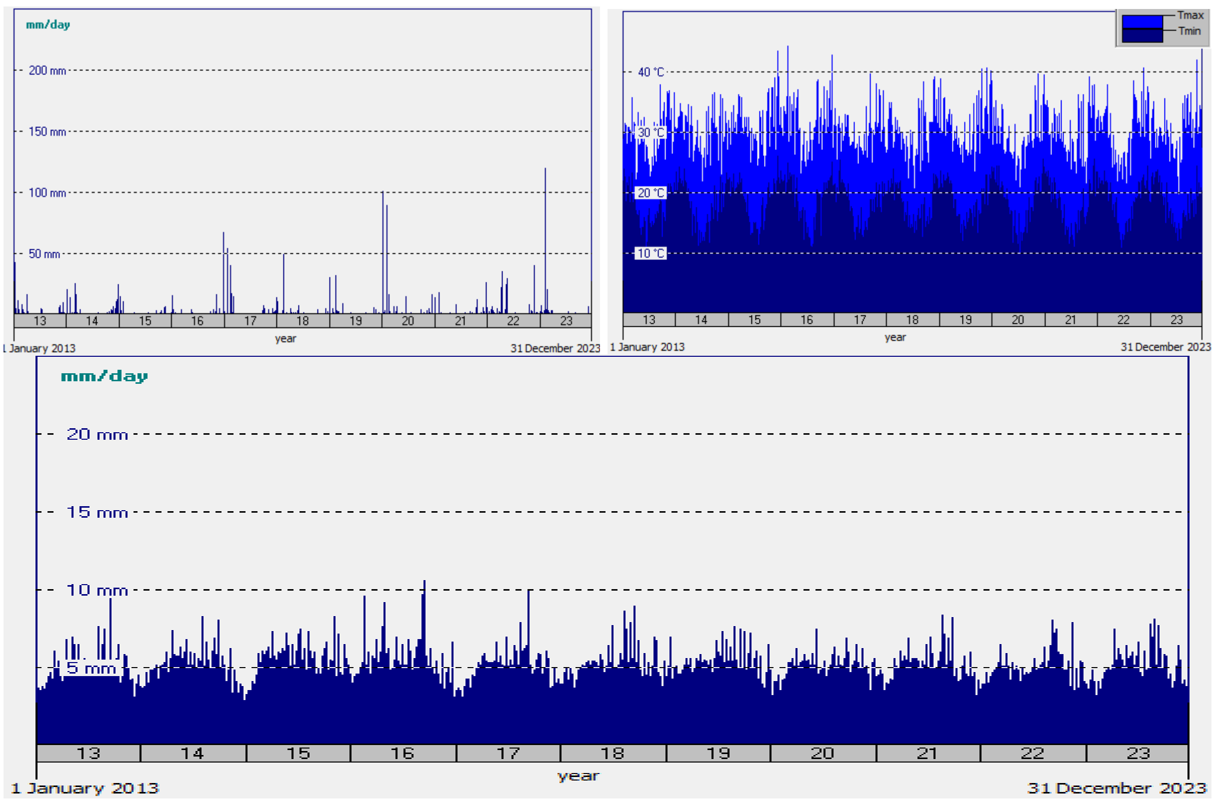


Figure 68: Weather condition (rain and temperature) and the reference evapotranspiration (ETo) estimated by Aquacrop through the FAO Penman-Monteith equation.

3.2. Crop performance: Sorghum.

3.2.1. Crop management

The RESADE-IIMI team has offered valuable insights into crop management, emphasizing key practices crucial for the success of a crop model. These practices encompass a variety of agricultural activities conducted throughout the season, including soil preparation, sowing, crop maintenance, and harvesting, as well as addressing the related challenges.

Table 39: Crop management adopted for the sorghum.

Operation	Dates and Notes	Photos or remarks from the field
LAND PREPARATION	Land preparation was done properly before planting.	 Land preparation and Soil sampling at BPH Moamba, Mozambique.
SOWING	Sorghum the dry season: The field was established on 29 April 2022. A field was established in the dry season on November 17th, 2022. The plant spacing was 50cm between plants and 75cm between rows resulting in a plant population of 226,666 per hectare.	
IRRIGATION AND MULCHING		 Drip and furrow irrigation systems installed at Moamba BPH
WEEDING	The field was weeded properly	 Manually weeded the plot of sorghum.
FERTILIZATION	Recommended fertilizer rate (200 kg/ ha NPK and 150 kg/ha Urea).	
PEST MANAGEMENT		
DATA COLLECTION	Colleagues and technicians have collected data periodically since the trial's establishment	 Field data collection by IIAM team
HARVESTING OF SORGHUM and PEARL MILLET		 Pearl millet during harvesting at the BPH in Mozambique.

3.2.2. Simulation Modeling Results and Development of Different Scenarios

After completing the model calibration with the available data, the model was used to generate various production scenarios, which are summarized in the tables below. The results indicated that, regardless of the sowing time, providing the crop with the appropriate water supply ensures good biomass production and yield.

In the second year of cultivating sensitive crops, a notable yield loss was observed when irrigated with saline water at a concentration of 6 dS/m for 2 years. This finding underscores the critical importance of selecting salt-tolerant crop varieties that can withstand higher salinity levels. Additionally, it emphasizes the need for implementing effective agricultural practices tailored for saline environments; one such practice is installing a reliable drainage system to help manage excess salinity and improve overall crop health.

Table 40: Yield and biomass estimated using Aquacrop model

Scenario	**Estimated**		**Observed**	
	Biomass	Yield	Biomass	Yield
Sorghum- Sowing during the dry season on 29 April, with irrigation- freshwater- tolerant crop	15.64	2.87	16	
Sorghum- Sowing during the dry season on 29 April, with irrigation- saline water (6dS/m)- tolerant crop	15.64	2.87		
Sorghum- Sowing during the season on 17 Nov, with irrigation- freshwater- tolerant crop	15.64	2.87		
Sorghum- Sowing during the dry season on 29 April, with irrigation- saline water for 1st year- sensitive crop	14.97	2.75		
Sorghum- Sowing during the dry season on 29 April, with irrigation- saline water for 2nd year- sensitive crop	6.03	1.16		

The following is a comparison of the cumulative crop biomass of sorghum cultivated under various production factors. The findings indicate that salinity exerts a significant influence on the biomass of the salinity-sensitive genotype.

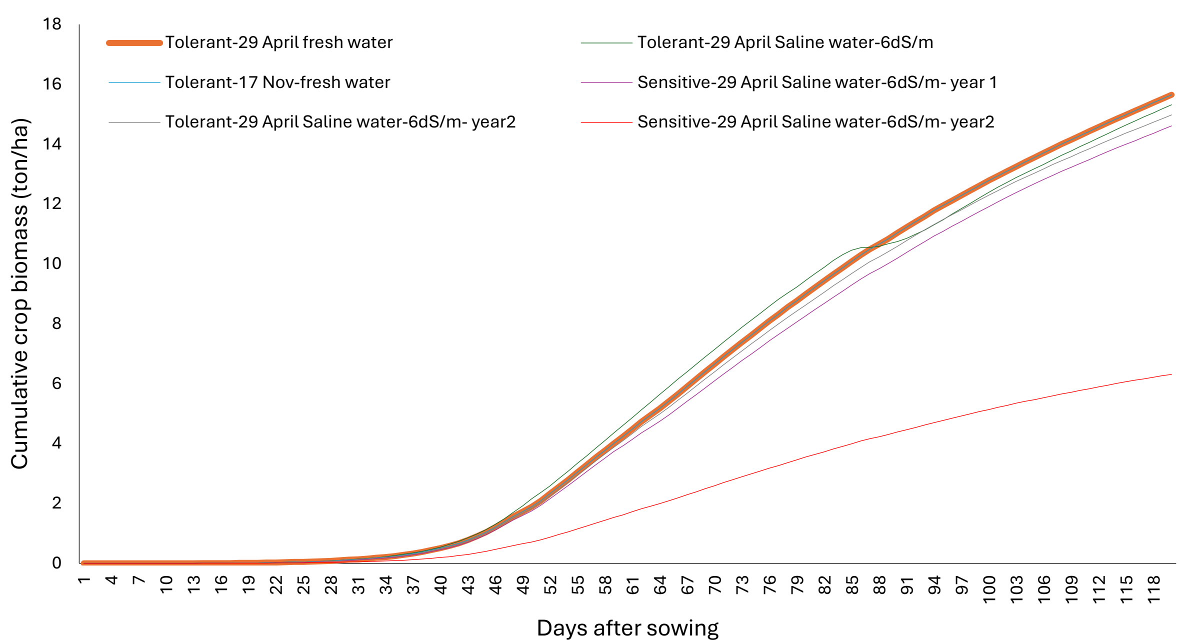


Figure 69: Cumulative crop biomass of sorghum cultivated under different production factors.

3.2.3. Water balance in the soil:

Figure 70 illustrates the soil water content throughout the sorghum growth cycle in the BPH region under a supplementary irrigation regime. The findings confirm that the proposed irrigation schedule effectively maintains soil water content between the wilting point and field capacity (Figure 72). This approach ensures an adequate water supply for the sorghum crop without the risk of over-irrigation, ultimately enhancing crop performance. By mid-May, the onset of the rainy season raised soil moisture levels to saturation at various points during the growth cycle.

When sorghum was planted at different times, specifically on April 29 and November 17, the crops experienced significantly different rainfall levels: 194.3 mm and 909.7 mm, respectively. For the April planting, an additional irrigation of 343 mm was required to meet the crop's water needs (Table 41). Even during the rainy season, where 909 mm of rainfall was recorded, an extra 103 mm of irrigation was still necessary to achieve optimal yields. This requirement is largely due to the irregular distribution of the rainfall.

Table 41: model output related to water balance and productivity for Sorghum under different production scenarios.

Scenario	Rain	Irri	Ev	Tr	ET0	Infilt	Drain	WPet	Soil ECi	Soil ECf
Sorghum- Sowing during the dry season on 29 April, with irrigation- freshwater- tolerant crop	194.3	284	181.6	273.1	601.1	459.1	51.4	0.63	0.1	0.1
Sorghum- Sowing during the dry season on 29 April, with irrigation- saline water (6dS/m)- tolerant crop	194.3	284	181.6	273.1	601.1	459.1	51.4	0.63	0.1	4.13
Sorghum- Sowing during the season on 17 Nov, with irrigation- freshwater- tolerant crop	909.7	103	181.6	273.1	497	794.3	342.9	0.63	0.1	0.1
Sorghum- Sowing during the dry season on 29 April, with irrigation- saline water for 1st year- sensitive crop	194.3	343	237	210	497	794.3	342.9	0.6	0.1	4.13
Sorghum- Sowing during the dry season on 29 April, with irrigation- saline water for 2nd year- sensitive crop	194.3	181	228	90.8	607	354	59.6	0.3	4.13	5.11

Rain: Rainfall; Irri: Water applied by irrigation; Ev: Soil evaporation; Tr: Total transpiration of crop and weeds ET: Evapotranspiration; Infilt: Infiltrated water in soil profile; Drain: Water drained out of the soil profile; WPet: ET Water productivity for yield part (kg yield produced per m3 water evapotranspired); Soil Eci : soil salinity before plantation; Soil ECf: soil salinity after the season; EC Electrical conductivity of the saturated soil-paste extract (ECe in dS/m)

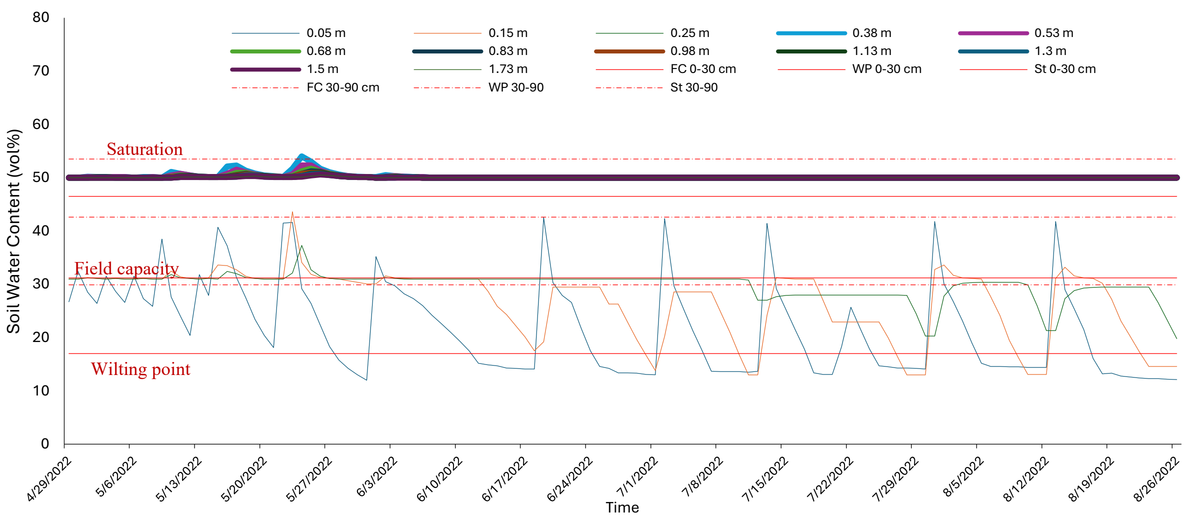


Figure 70: Soil water content in case of complimentary irrigation during the sorghum growth cycle in the Hub, Mozambique, during the dry season.

In the absence of irrigation, the soil moisture at a depth of 0 to 30 cm drops below the wilting point at the beginning of the crop's growth cycle. If no irrigation is provided, a significant reduction in crop yield is observed.

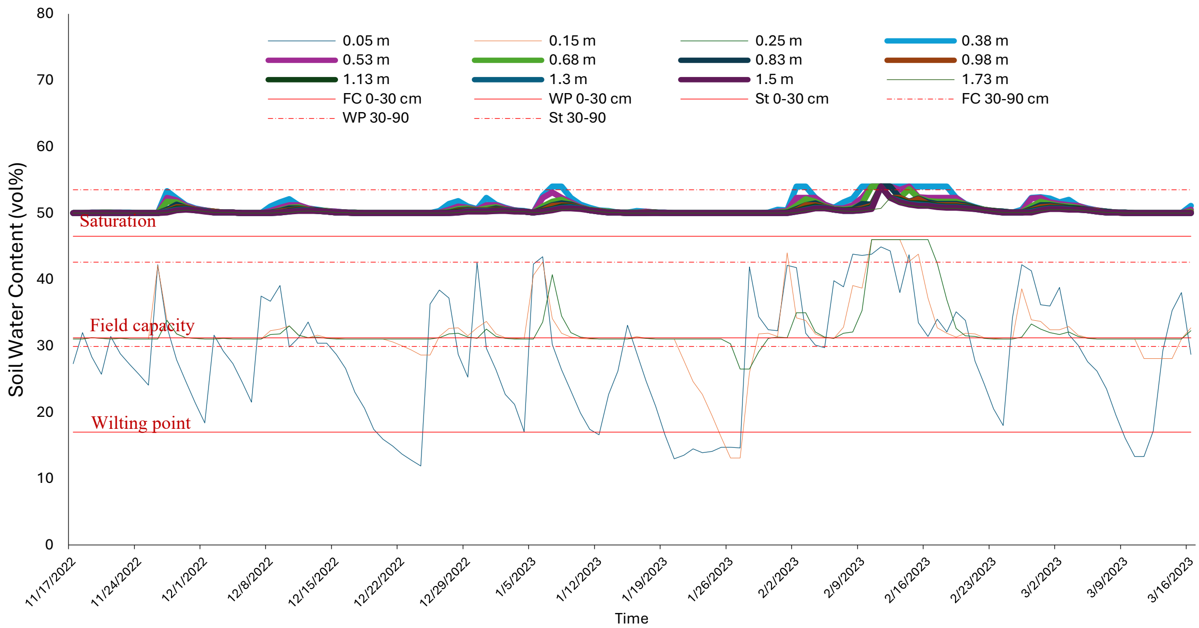


Figure 71: Soil water content in the scenario of absence of irrigation during the sorghum growth cycle in the Hub- Mozambique during the dry season.

To ensure sufficient water supply for the crops, irrigation was necessary to meet their water requirements before effective rainfall, which typically occurs from May onwards.

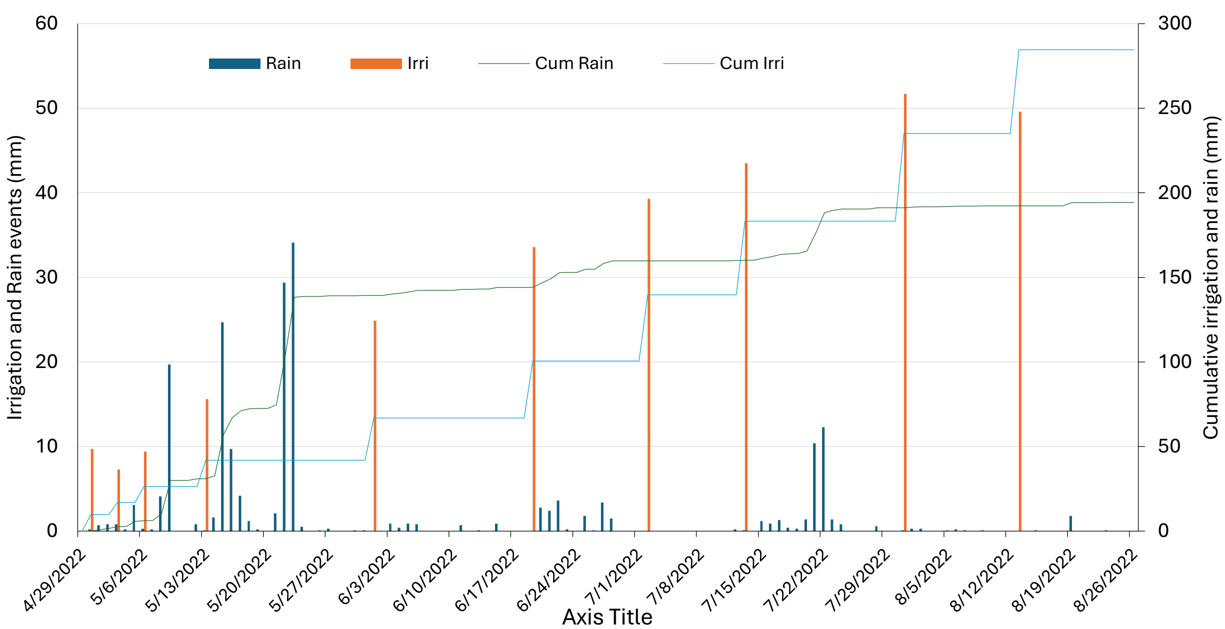


Figure 72: Irrigation and Rain events and their accumulation during the sorghum growth cycle, dry season, in the BPH in the Hub- Mozambique during the dry season.

3.2.4. Salinity build-up risk in case of irrigation with saline water of 6dS/m

The simulation results suggest that the BPH location in Mozambique may face a risk of salinity accumulation. When irrigated with saline water at a concentration of 6 ds/m, the soil salinity levels rose. Therefore, it is crucial to establish an effective management system prior to using saline water. This system should include a suitable drainage solution and the incorporation of a leaching fraction into the irrigation requirements, particularly since the soil demonstrates good drainage capabilities, as evidenced by the accompanying table showing conditions when water exceeds crop needs (Table 73). Moreover, it is always recommended to utilize a salt-tolerant genotype.

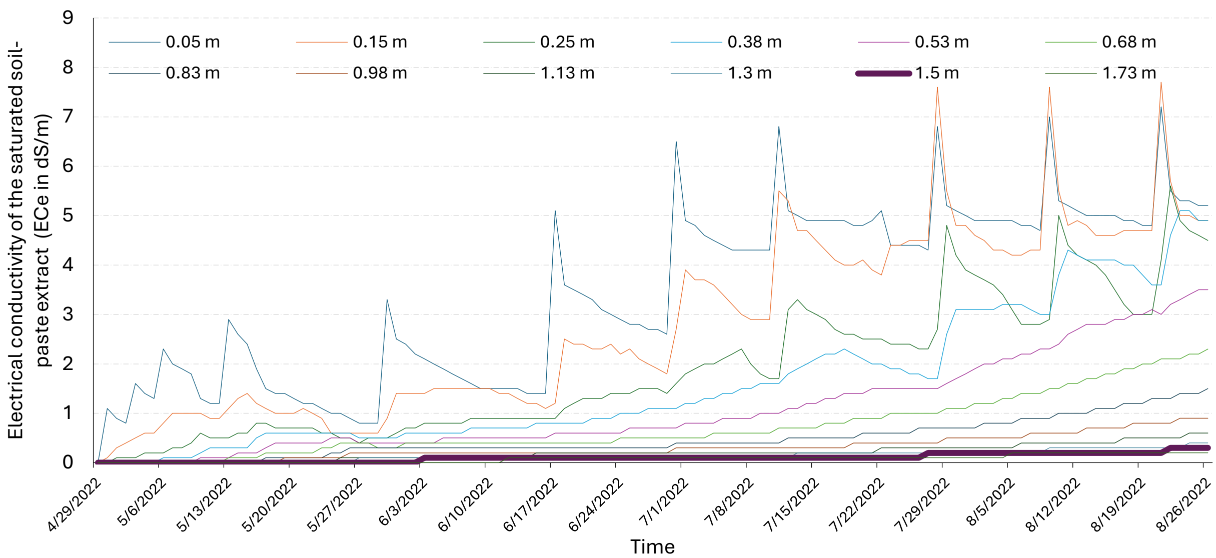


Figure 73: Electrical conductivity of the saturated soil-paste extract (ECe in dS/m) at various depths of the sorghum field irrigated with saline water of 6 dS/m, estimated by the Aquacrop model.

4. Conclusion

In conclusion, the findings from the soil-water-plant modeling study regarding the irrigation and drainage in Mozambique's irrigated regions can be summarized as follows:

- Sorghum sown on April 29 received 194.3 mm of rainfall and required an additional 343 mm of irrigation. Conversely, sorghum planted on November 17 received 909.7 mm of rainfall but necessitated an extra 103 mm of irrigation to achieve optimal yields, primarily due to irregular rainfall distribution.
- The results indicated that irrespective of planting time, ensuring the crop receives an adequate water supply is crucial for achieving good biomass production and yield.
- In the second year of cultivating sensitive crops, a significant yield loss was noted when irrigated with saline water at a concentration of 6 dS/m over a two-year period. This finding highlights the critical importance of selecting salt-tolerant crop varieties that can endure higher salinity levels. Furthermore, it underscores the necessity of implementing effective agricultural practices tailored to saline environments; one such practice is installing reliable drainage systems to manage excess salinity and enhance overall crop health.
- The results of the soil water content throughout the sorghum growth cycle in the BPH region under a supplementary irrigation regime confirmed that the proposed irrigation schedule effectively maintains soil water content between the wilting point and field capacity. This approach ensures an adequate water supply for the sorghum crop while mitigating the risk of over-irrigation, thereby enhancing crop performance. By mid-May, the onset of the rainy season elevated soil moisture levels to saturation at various stages of the growth cycle.
- In the absence of irrigation during the dry period, soil moisture at a depth of 0 to 30 cm drops below the wilting point at the onset of the crop's growth cycle. If irrigation is not provided, a significant reduction in crop yield is observed.
- To guarantee sufficient water supply for the crops, irrigation is essential to meet their water requirements prior to the effective onset of rainfall, which typically occurs from May onward.
- The simulation results indicate that the BPH location in Mozambique is at risk of salinity accumulation when irrigated with saline water at a concentration of 6 ds/m. To manage this risk effectively, it is important to establish a management system that includes suitable drainage and a leaching fraction in irrigation. The soil shows good drainage capabilities, and salt-tolerant genotypes are also recommended.

Botswana

1. General information

Botswana is a landlocked country with limited surface water, relying primarily on groundwater, which constitutes about 65% of its water supply. The country has four main river basins shared with neighboring nations, and rural areas depend heavily on groundwater for agriculture, including arable and livestock farming. The largest of the eight dams in the country is Dikgatlhong, with a capacity of 400 million cubic meters. Botswana shares all its rivers, like the Okavango, Zambezi, Orange-Senqu, and Shashe-Limpopo, with neighboring countries. Because Botswana has flat land, it has one of the lowest water storage capacities in the region.

The agricultural sector faces challenges due to harsh climatic conditions and unreliable rainfall, with irrigation development still in its early stages. Only 1,200 hectares are irrigated out of an estimated 200,000 hectares planted annually. Water scarcity and competition with other sectors limit irrigation, mostly supporting small-scale farmers and high-value crops. The government manages small-scale irrigation schemes, taking responsibility for infrastructure maintenance and water supply. Climate change further exacerbates water resource challenges. The country faces serious water scarcity caused by low rainfall and semi-arid conditions, which limit water availability. This scarcity greatly affects agriculture, a key sector for rural communities. Rain-fed farming, which is common in Botswana, struggles due to low rain and high evaporation. For example, during the 2018-2019 drought, two-thirds of the crops failed. The cattle sector also suffers, with around 40,000 cattle dying in Ngamiland, a major beef region, during that same drought. Over 10% of the population experiences chronic food insecurity because of these drought-related effects, and about 70% of rural households depend on agriculture for their livelihoods.

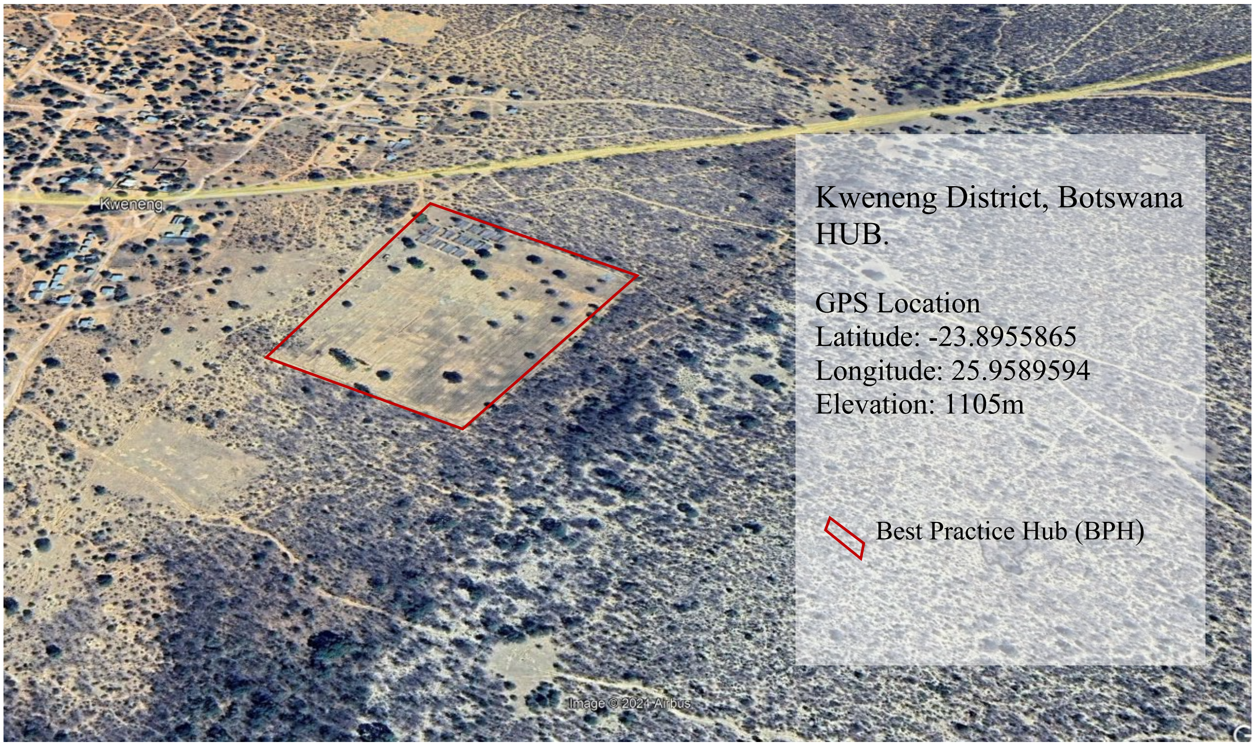
Since the 1950s, Botswana has been vulnerable to multi-year droughts. These droughts reduce food and crop production, affect urban water supplies, and harm rural economies. To address these challenges, Botswana needs better water management practices and more investment in infrastructure to improve water storage and distribution.

2. Study site characterization

2.1. Site name

Site name: RESADE-Maputo-Mozambique HUB

Location: The Best Practice Hub (BPH) is located in Kweneng District, Botswana.



Best Practice Hub (BPH) in Kweneng District, Botswana.

Figure 74: Botswana map with the geographical distribution of water and rivers and the Best Practice Hub location.
DIVA-GIS software (version 7.5) was used to create the maps.

2.2.Soil characteristics

The data presented in Table 42 pertains to the physical and chemical properties of soil and the soil-water status in the area of Hub in Kweneng District, Botswana. This information has been sourced from the FAO portal and analyzed using the Soil Water Characteristics software to determine the anticipated Soil Water Properties.

Table 42: Physical and Chemical Properties of the Soil of the Hub in Kweneng District, Botswana.

Parameters	Topsoil (0-30 cm)	Subsoil (30-60)
Sand Fraction (%)	79	66
Silt Fraction (%)	8	10
Clay Fraction (%)	13	24
USDA Texture Classification	sandy loam	sandy clay loam
Reference Bulk Density (kg/dm3)	1.54	1.43
Bulk Density (kg/dm3)	1.47	1.43
Gravel Content (%)	1	1
Organic Carbon (% weight)	0.18	0.21
pH (H2O)	6.5	6.1
CEC (clay) (cmol/kg)	16	18
CEC (soil) (cmol/kg)	5	5
Base Saturation (%)	80	78
TEB (cmol/kg)	4	3.9
Calcium Carbonate (% weight)	0.8	0.3
Gypsum (% weight)	0.1	0
Sodicity (ESP) (%)	2	2
Salinity (ECe) (dS/m)	0.1	0

Table 43: Soil-Water Status of the Hub in Kweneng District, Botswana.

Parameters	Unit	Topsoil (0-30 cm)	Subsoil (30-60)
Wilting point	% vol	9.7	16.0
Field capacity	% vol	16.5	25.1
Saturation	% vol	43.5	42.8
Available water	in/ft	0.81	1.09
Salt hydraulic conductivity	in/ha	1.85	0.51
Matric bulk density	Ib/ft3	93	94.61

1 in/ft=83.33 millimeter/meter

2.3.Weather condition

Climate data for daily precipitation and maximum and minimum temperature in the region of BPH in the region Kweneng District, Botswana, was collected between January 1st, 2013, and December 31st, 2023. This data was obtained from the Worldwide Energy Resource (POWER) Project, which is funded by the National Aeronautics and Space Administration (NASA) Applied

Sciences Program. The POWER website is a dependable source of climate data and can be easily accessed through https://power.larc.nasa.gov/data-access-viewer/.

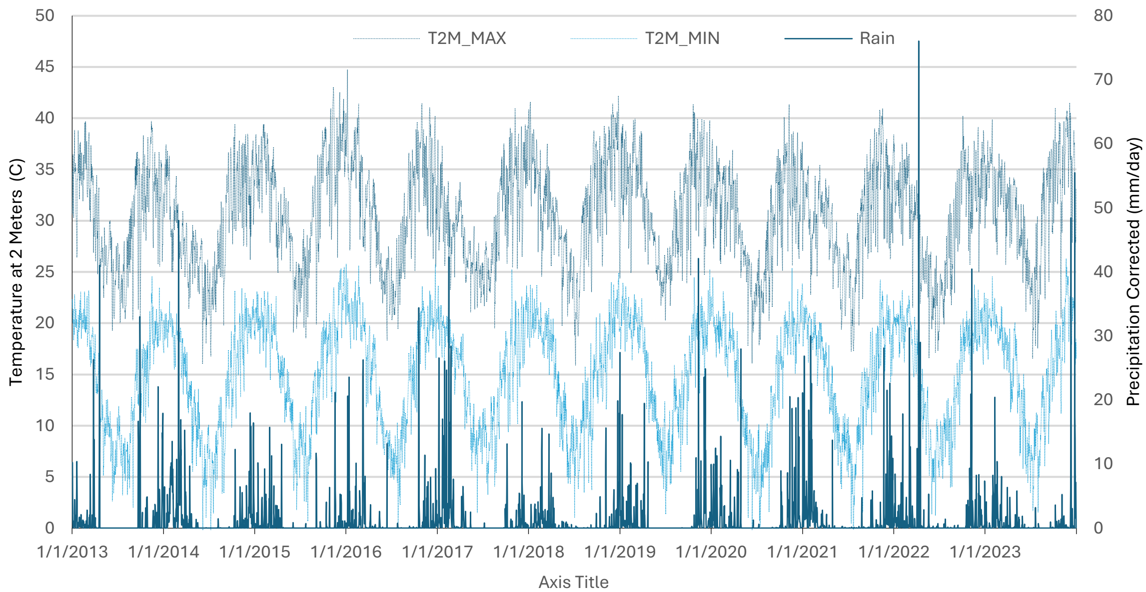


Figure 75: Daily precipitation, maximum and minimum temperature in Kweneng District, Botswana, from January 1st, 2013, to December 31st, 2023.

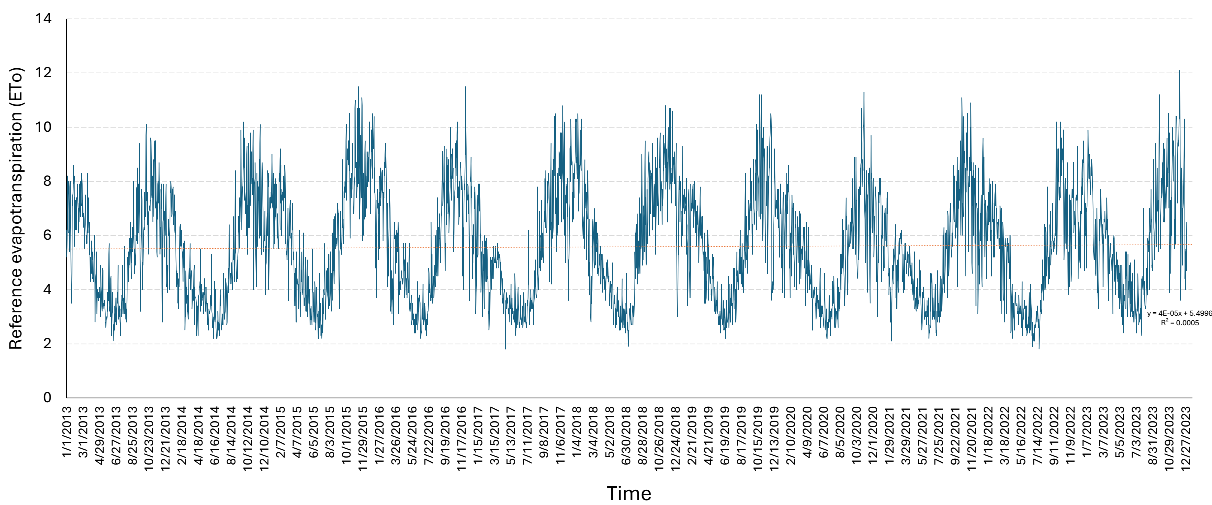


Figure 76: Daily Reference evapotranspiration (ETo) in the region Kweneng District, Botswana, from January 1st, 2013, to December 31st, 2023.

3. Simulation modeling results

AquaCrop is an easy-to-use tool for the RESADE target countries. It needs only a few specific parameters and mostly simple input variables that can be found using straightforward methods. The inputs include weather data, crop and soil features, and details about field and irrigation practices that affect how the crop will grow. Soil features are divided into two categories: soil profile and groundwater characteristics.

3.1.Calculation of the reference evapotranspiration (ETo)

AquaCrop includes a calculator that uses weather station data to calculate the reference evapotranspiration (ETo) through the FAO Penman-Monteith equation.

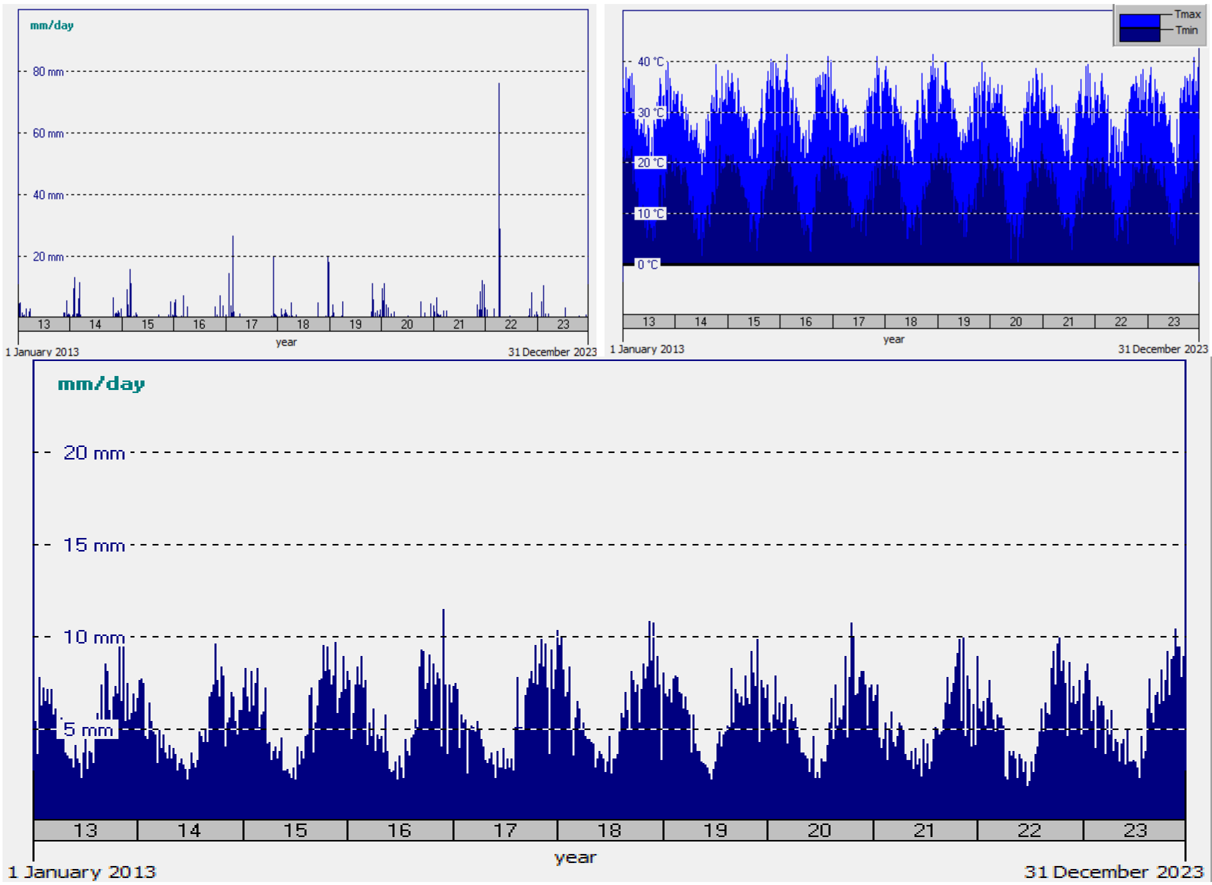


Figure 77: Weather condition (rain and temperature) and the reference evapotranspiration (ETo) estimated by Aquacrop through the FAO Penman-Monteith equation.

3.2.Crop performance: Sorghum.

3.2.1. Crop management:

The RESADE-NARDI team has provided valuable insights into crop management, highlighting essential practices for a crop model's success. These practices cover a range of agricultural activities carried out throughout the season, such as seedbed preparation, seed sowing, crop maintenance, harvesting, and all the associated problems.

Table 44: Crop management adopted for the sorghum.

Operation	Dates and Notes	Photos or remarks from the field
LAND PREPARATION	Land preparation was done properly before planting.	

		Land preparation at the BPH in Kweneng, Botswana.e.
SOWING	Sorghum Planting was done on 22 December 2022. The plant spacing was 50cm between plants and 75cm between rows resulting in a plant population of 226,666 per hectare.	 Trial establishment at the BPH in Kweneng, Botswana.
IRRIGATION AND MULCHING	--	Drip and furrow irrigation systems installed at Moamba BPH
WEEDING	The field was weeded properly.	
FERTILIZATION	Recommended fertilizer rate (200 kg/ ha NPK and 150 kg/ha Urea).	
PEST MANAGEMENT	--	
DATA COLLECTION	--	
HARVESTING OF SORGHUM	--	
THE DRYING PROCESSING	--	

3.2.2. Simulation Modeling Results and Development of Different Scenarios

Upon completing model calibration using the available data, the model was utilized to derive various production scenarios, which have been succinctly presented in Table 45. The results are a testament to the effectiveness of the model and its ability to produce valuable insights into the production process.

The simulation results demonstrate that using freshwater significantly boosts biomass production and overall yield. Notably, employing a tolerant genotype was shown to maintain comparable yields even when irrigated with saline water at a concentration of 6 dS/m. However, an unintended consequence of shifting the sowing date from December 22 to April 22 led to a substantial yield reduction of 30%. This highlights the critical role of timing in crop cultivation to mitigate temperature-related stress that can adversely affect performance.

Additionally, the cultivation of sensitive genotypes irrigated with saline water over several seasons resulted in a drastic decline in yield (Table 45). If this practice continues, projections indicate that yield could ultimately approach zero. These findings emphasize the essential need for selecting tolerant genotypes and implementing effective drainage systems. Adequate drainage is vital for leaching excess salts from the root zone, particularly when utilizing saline water sources.

Table 45: Yield and biomass estimated using Aquacrop model

Scenario	**Estimated**		**Observed**	
	Biomass	Yield	Biomass	Yield
Sorghum- Sowing on 22 Dec, with irrigation- freshwater- tolerant crop	16.33	3.00	--	--
Sorghum- Sowing 22 Dec, with irrigation- saline water (6dS/m)- tolerant crop	16.33	3.00	--	--
Sorghum- Sowing during the season on 22 April, with irrigation- freshwater- tolerant crop	11	2.04	--	--
Sorghum- Sowing 22 Dec, with irrigation- saline water for 1st year- sensitive crop	14.81	2.72	--	--
Sorghum- Sowing 22 Dec, with irrigation- saline water for 2nd year- sensitive crop	2.1	0.38	--	--

This analysis offers a comprehensive comparison of the cumulative crop biomass of sorghum grown under different production conditions. The findings reveal that salinity levels significantly adversely impact biomass yield, especially when sensitive sorghum genotypes are cultivated over multiple years without effective strategies to counteract salinity's effects. Over time, the accumulation of salts in the soil can result in harmful physiological consequences for the plants, diminishing their growth potential and overall biomass production. Consequently, it is essential to implement preventive measures to manage salinity effectively, promoting more resilient genotypes and enhancing sustainable crop yields.

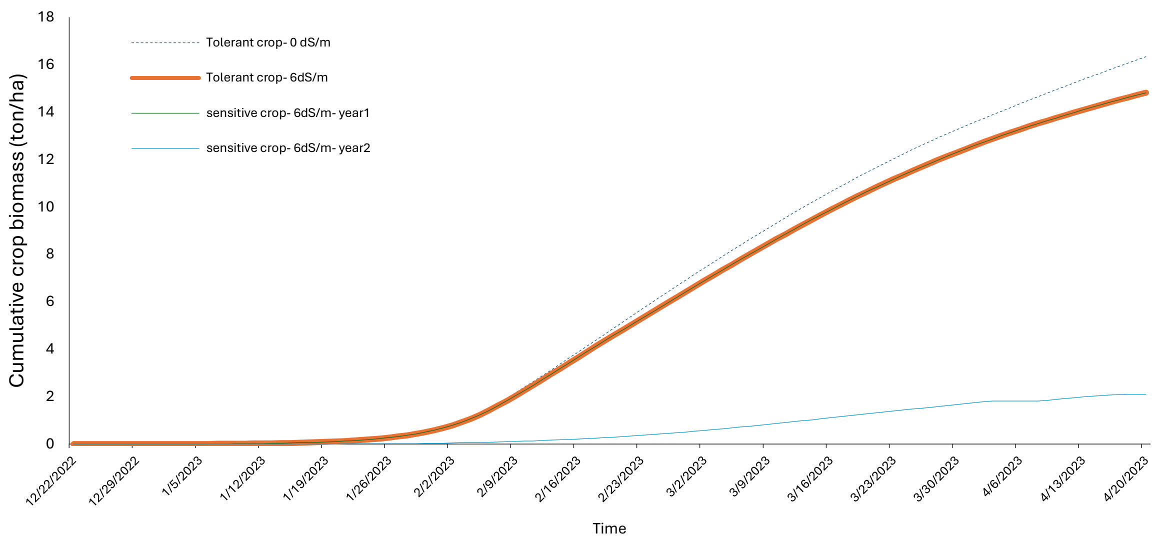


Figure 78: Cumulative crop biomass of sorghum cultivated under different production factors.

3.2.3. Water balance in the soil

The output regarding the water balance and productivity of sorghum across different production scenarios is thoroughly outlined in Table 46. The results indicate that to meet the water requirements of sorghum planted on December 22, a total irrigation volume of 343 millimeters is essential. This finding highlights the substantial influence of climatic conditions in Botswana, where high levels of evapotranspiration are prevalent due to the arid environment. As such, irrigation becomes a critical practice to ensure optimal yields for the sorghum crop.

Furthermore, it is crucial to utilize sorghum genotypes that exhibit tolerance to water stress. Employing these drought-resistant varieties not only improves water productivity but also significantly contributes to maximizing overall crop yield under diverse environmental conditions. This strategy is especially important for farmers aiming to enhance productivity in resource-limited settings, ensuring they obtain the best possible results from their sorghum cultivation efforts.

Table 46: Model output related to water balance and productivity for Sorghum under different production scenarios.

Scenario	Rain	Irri	Ev	Tr	ET0	Infilt	Drain	WPet	Soil ECi	Soil ECf
Sorghum- Sowing on 22 Dec, with irrigation- freshwater- tolerant crop	170	343.3	186.5	313.7	750.3	515.7	30.2	0.60	0.1	0.1
Sorghum- Sowing 22 Dec, with irrigation- saline water (6dS/m)- tolerant crop	170	343.3	186.5	313.7	750.3	515.7	30.2	0.60	0.1	0.1
Sorghum- Sowing during the season on 22 April, with irrigation- freshwater- tolerant crop	15.4	164.1	623	135.1	397.3	179.5	3.9	1.04	0.1	0.1

Sorghum- Sowing 22 Dec, with irrigation-saline water for 1st year- sensitive crop	170	325.5	208.3	277	750	488.2	25	0.56	0.1	4.72
Sorghum- Sowing 22 Dec, with irrigation-saline water for 2nd year- sensitive crop	133.6	211.1	316.6	130	750	383.7	47.1	0.11	4.73	5.51

Rain: Rainfall; Irri: Water applied by irrigation; Ev: Soil evaporation; Tr: Total transpiration of crop and weeds ET: Evapotranspiration; Infilt: Infiltrated water in soil profile; Drain: Water drained out of the soil profile; WPet: ET Water productivity for yield part (kg yield produced per m3 water evapotranspired); Soil Eci : soil salinity before plantation; Soil ECf: soil salinity after the season; EC Electrical conductivity of the saturated soil-paste extract (ECe in dS/m)

The proposed irrigation schedule (Figure 80) is designed to maintain the soil water content within the appropriate range, specifically between the wilting point and the field capacity (Figure 79). This approach is intended to facilitate supplemental irrigation during the growth cycle of sorghum in the Hub, Kweneng District, Botswana, throughout the dry season.

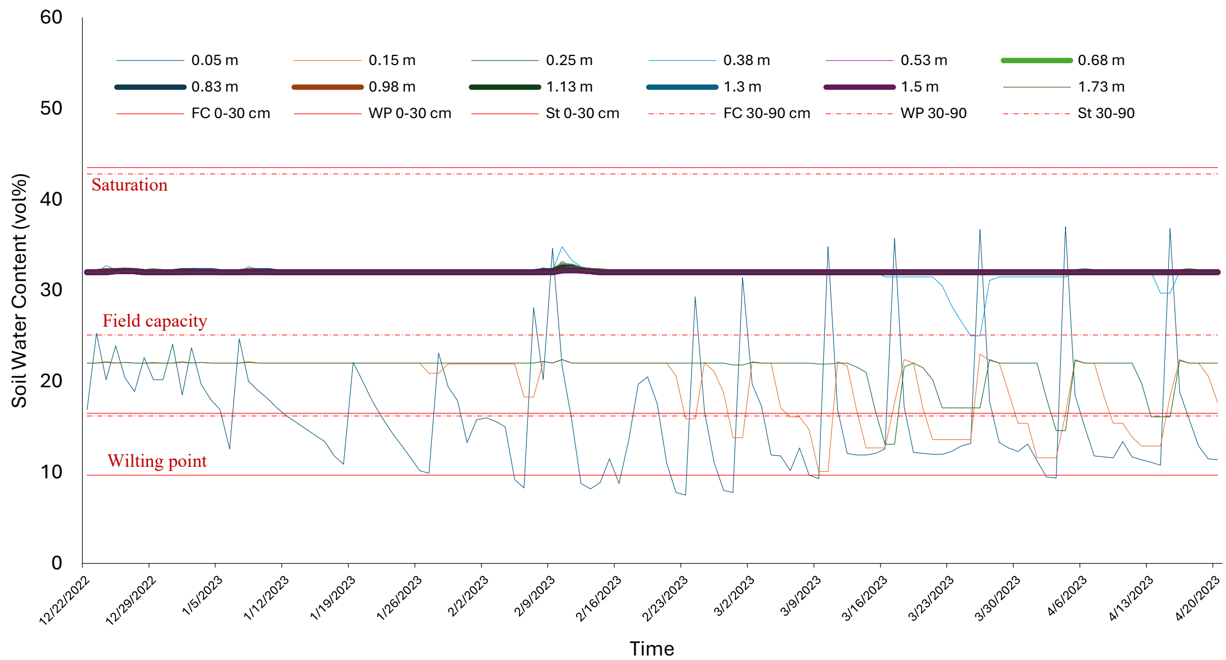


Figure 79: Soil water content in case of complimentary irrigation during the sorghum growth cycle in the Hub, Kweneng District, Botswana, during the dry season.

In order to guarantee an adequate supply of water for the crops, implementing an effective irrigation system became essential. This system was designed to meet the specific water needs of the plants throughout their growing cycles, ensuring they received the necessary moisture for optimal growth and productivity. By utilizing various irrigation techniques, such as drip or sprinkler systems, we aimed to maintain soil moisture levels and support the health and vitality of the crops, particularly during dry periods or when rainfall was insufficient.

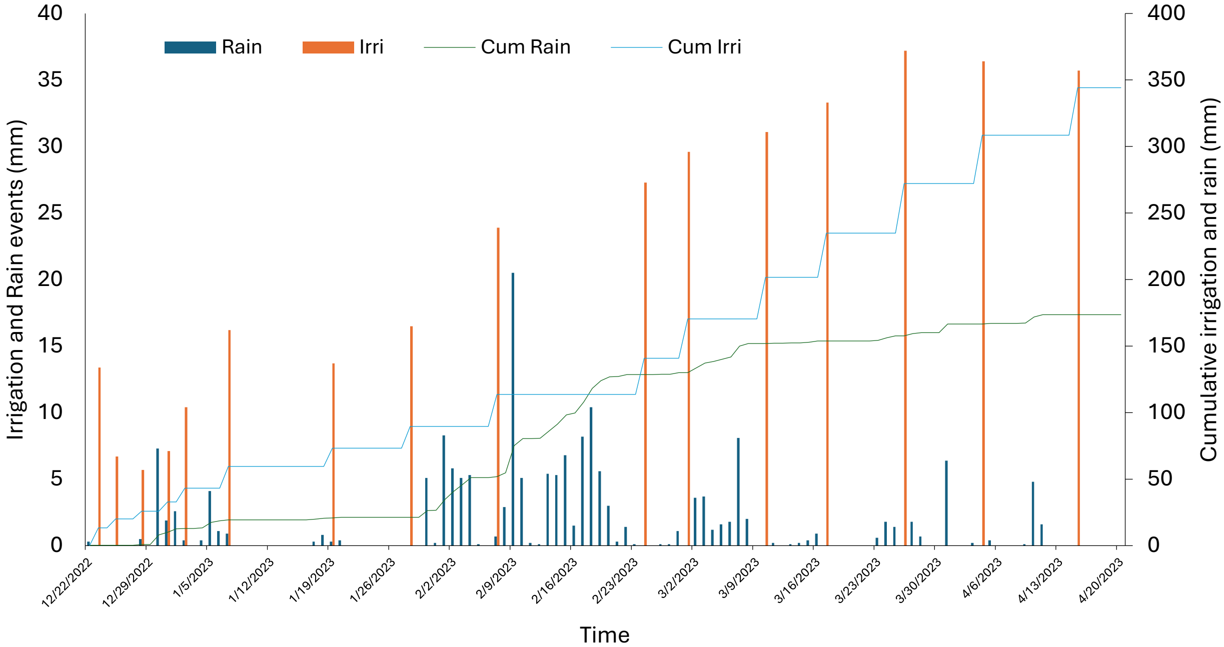


Figure 80: Irrigation and Rain events and their accumulation during the sorghum growth cycle, dry season, in the BPH in the Hub-Kweneng District, Botswana during the dry season.

3.2.4. Salinity build-up risk in case of irrigation with saline water of 6dS/m

The results of the simulation indicate that the BPH location in Botswana faces a potential risk of salinity accumulation. When irrigated with saline water at a concentration of 6 ds/m, the soil salinity levels exhibited an increase. Therefore, it is imperative to establish an effective management system before the utilization of saline water. This management system should incorporate an appropriate drainage solution and include a leaching fraction within the irrigation requirements. Furthermore, it is advisable to employ a salt-tolerant genotype.

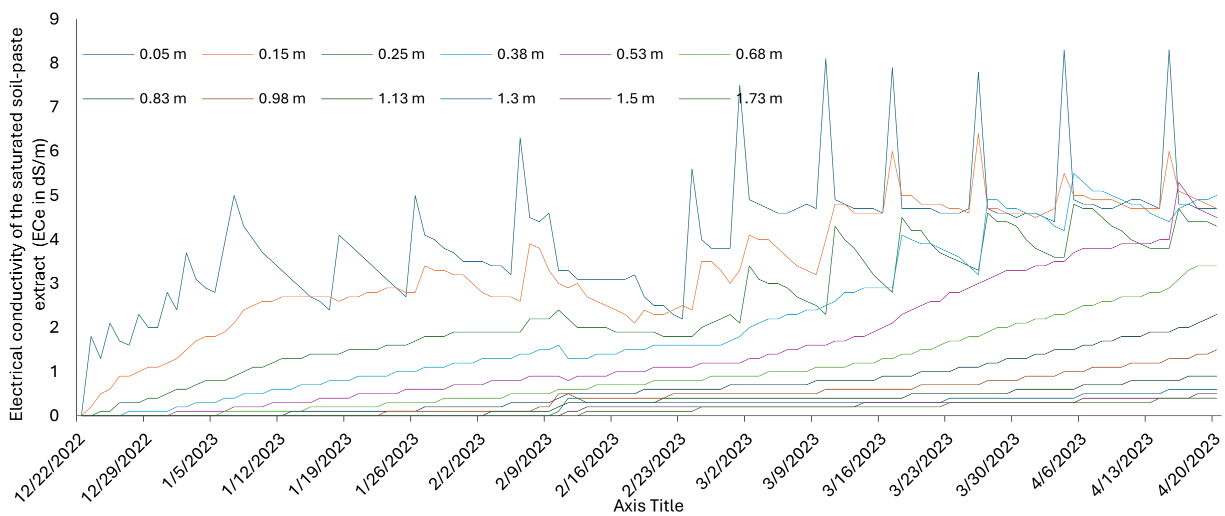


Figure 81: Electrical conductivity of the saturated soil-paste extract (ECe in dS/m) at various depths of the sorghum field irrigated with saline water of 6 dS/m, estimated by the Aquacrop model.

4. Conclusion

In conclusion, the findings from the soil-water-plant modeling study concerning irrigation and drainage in Botswana's irrigated regions can be summarized as follows:

- The soil-water-plant modeling study effectively identified optimal irrigation and drainage practices for crop production in Botswana. Model calibration facilitated the development of various production scenarios, demonstrating the model's reliability.
- The application of freshwater significantly boosts biomass production, whereas salt-tolerant genotypes were able to sustain yields even with saline water (6 dS/m). However, delaying the sowing date from December 22 to April 22 resulted in a 30% reduction in yield, highlighting the critical importance of timely planting.
- Sensitive genotypes irrigated with saline water over multiple seasons experienced severe yield declines, which could approach zero if current practices persist. This underscores the necessity of selecting tolerant genotypes and implementing effective drainage strategies.
- Salinity has a detrimental impact on the cumulative biomass yield of sorghum, particularly for sensitive genotypes over time. Therefore, prudent management strategies are essential to mitigate salinity and enhance resilience in crop production.
- To adequately meet the water demands for sorghum planted on December 22 in Botswana, a total irrigation volume of 343 millimeters is required due to the high rates of evapotranspiration in the arid climate.
- The adoption of drought-resistant sorghum genotypes can significantly enhance water productivity and crop yields, especially in resource-limited settings.
- An effective irrigation schedule is designed to maintain soil moisture levels between the wilting point and field capacity, allowing for supplemental irrigation during dry periods.
- A reliable irrigation system is crucial for providing adequate moisture to support optimal crop growth, utilizing advanced techniques such as drip or sprinkler systems.
- There is a potential risk of salinity accumulation at the BPH location when employing saline water for irrigation. Developing a robust management system, including appropriate drainage solutions and a leaching fraction, is necessary prior to saline water usage, alongside the selection of salt-tolerant genotypes.

Key findings and recommendations

Sierra Leone

The key points and findings from the soil-water-plant modeling study conducted in the irrigated regions of Sierra Leone are as follows:

1. Improved Crop Management: This approach enhances the efficiency of crop growth, prioritizing profitability, sustainability, and environmental conservation.
2. Weed and Soil Fertility Issues: The prevalence of weed infestation and inadequate soil fertility due to insufficient fertilization are significant contributors to yield loss, with weeds potentially reducing biomass by approximately 4 tonnes per hectare.
3. Impact of Saline Water: The use of saline water (with a salinity level of 6 dS/m) may reduce potential yield by as much as 20 tonnes per hectare from a maximum yield of 27 tonnes per hectare.
4. Soil Quality: Soil quality is identified as a critical factor influencing yield losses, with salinity further impacting agricultural productivity.
5. Enhancing Soil Fertility: Improving soil fertility is essential for augmenting crop water productivity and enhancing yield and profitability from underutilized water resources.
6. Supplementary Irrigation: This practice is necessary during the dry season to enhance yield and water productivity, with sorghum crops requiring approximately 200 mm of irrigation.
7. Timely Irrigation: Adequate irrigation before the onset of significant rainfall in May is vital for maintaining crop health throughout the dry months.
8. Rice Yields: The soil fertility enhancement remains crucial, notwithstanding salinity challenges, with potential rice production estimated at 2.3 tonnes per hectare on affected lands.
9. Salinity Accumulation: Certain regions exhibit resilience to salinity accumulation, where high rainfall effectively leaches accumulated salts away.
10. Rainy Season Irrigation: Rice generally does not necessitate additional irrigation owing to sufficient natural rainfall, which averages 1567.1 mm during the growing season.
11. Benefits of Supplementary Irrigation: This method may significantly enhance rice yields during critical growth phases.
12. Risks Associated with Saline Water: Irrigation with saline water does not pose substantial risks to soil health, given the region's specific soil types and average annual rainfall.
13. Traditional Irrigation Methods: Permanent flood irrigation necessitates considerable water (6240 mm) for optimal crop growth; however, the use of saline water may exacerbate soil salinity, thereby threatening future yields.

These findings underscore the necessity for tailored irrigation and drainage practices to optimize agricultural production in Sierra Leone.

The Gambia

Key Points and Findings from the Soil-Water-Plant Modeling Study in The Gambia's Irrigated Regions:

1. Sorghum Yield: Utilizing freshwater irrigation maximizes sorghum yield, whereas the use of saline water leads to significant declines in yield over time due to salt accumulation, particularly when proper drainage is lacking.
2. Irrigation Needs: During dry seasons, approximately 800 mm of irrigation water is required. The presence of saline water diminishes transpiration, which necessitates a leaching fraction to remove the accumulated salts effectively.
3. Drainage System: The model indicates zero water drainage, resulting in a toxic salt buildup in the root zone. This underscores the urgent need for an effective drainage system for saline water.
4. Salinity Management: Without adequate drainage, salinity levels will rise, posing risks to plant health. This highlights the critical importance of managing irrigation practices when using saline water.
5. Irrigation Scheduling: Effective scheduling is essential for maintaining optimal soil moisture levels, ultimately enhancing crop growth and yield potential.
6. Rice Yields: Freshwater is crucial for achieving optimal rice yields; however, satisfactory yields can be attained with moderately saline water (2 dS/m) when best agricultural practices are implemented.
7. Supplemental Irrigation: During the rainy season, which receives 656 mm of precipitation, supplemental irrigation may be required during critical growth phases due to irregular rainfall patterns.
8. Timely Irrigation: Timely irrigation helps prevent soil moisture from reaching wilting points, which is vital for crop performance. Additionally, precise fertilization can enhance water productivity.
9. Water Budget: A thorough understanding of water dynamics in plant rooting zones is essential, and effective management of both rainfall and irrigation is necessary to maintain a favorable water balance during rice growth.
10. Leaching Fraction: Maintaining acceptable soil salinity levels is possible through the use of a leaching fraction, contributing to healthier soil conditions and sustainable rice production in saline environments.

These findings stress the importance of tailored irrigation and drainage practices to optimize crop production in The Gambia.

Togo

The soil-water-plant modeling study conducted in the irrigated regions of Togo presents several critical insights and conclusions:

1. Supplementary Irrigation: The application of supplementary irrigation during the dry season is essential for sustaining optimal sorghum productivity. Weed infestations have the potential to diminish yields by as much as 50%, particularly under conditions of low soil fertility, thereby highlighting the necessity for effective weed management and enhanced soil management practices.
2. Soil Fertility: The study underscores the detrimental effects of low soil fertility on the biomass accumulation of sorghum, reinforcing the vital importance of maintaining favorable soil conditions.
3. Irrigation Volume: An irrigation volume ranging from 200 to 250 mm is imperative for the adequate growth of sorghum, with notable differences established between scenarios of irrigation and non-irrigation.
4. Rainfall and Irrigation: In the locality of Atti-Apedokoe, a total rainfall of 360 mm is supplemented by an additional requirement of 260 mm of irrigation water for optimal development of sorghum during critical growth phases.
5. Salinity Risk: There exists a significant risk of soil salinity accumulation resulting from the utilization of saline water (6 dS/m) in clay loam soils, especially in the absence of appropriate drainage and leaching strategies, which compromises soil health and agricultural sustainability.
6. Freshwater Irrigation: The combination of freshwater irrigation with optimal fertilization proves effective for achieving high yield levels and enhanced water productivity. In contrast, continuous flooding with saline water significantly impairs yields, underscoring the critical importance of water quality.
7. Soil Moisture Maintenance: An irrigation volume of 213 mm, supplemented by an additional 352 mm from rainfall, is essential for maintaining soil moisture at field capacity. Continuous flooding necessitates considerably higher water volumes, which indicates greater management challenges.
8. Water Budget: Monitoring the water budget, which tracks soil moisture dynamics, is crucial for plant uptake and transpiration processes, with potential yields estimated between 2.5 and 3.5 tonnes per hectare, contingent upon an adequate water supply.
9. Salinity Management: The risk of sodium accumulation from the use of saline water, particularly in clay loam soils, poses a threat to soil quality and crop yields. The implementation of effective leaching methods and drainage systems is necessary to mitigate salinity risks and to promote sustainable farming practices.

These findings highlight the importance of implementing tailored irrigation and drainage practices to optimize crop production in the context of Togo.

Liberia

The key points and findings from the soil-water-plant modeling study conducted in Liberia's irrigated regions:

1. Model Utility: The model serves as a valuable tool for scientific and technical teams, requiring minimal data to derive essential irrigation management parameters, thereby supporting smallholder farmers effectively.
2. Calibration and Scenarios: The calibration of the model has generated various production scenarios that illustrate the effects of salinity on crop yields resulting from inadequate irrigation and drainage.
3. Salinity-Tolerant Crops: The use of salinity-tolerant crops is advised to mitigate yield losses, as sensitive sorghum genotypes demonstrated significant biomass loss due to salinity.
4. Effective Irrigation Schedule: The model's irrigation schedule is crucial in maintaining soil water content, preventing over-irrigation, and ensuring an adequate water supply, particularly during the dry season.
5. Dry Season Challenges: Without irrigation, soil moisture may fall below the wilting point during the dry season, leading to significant yield reductions.
6. Salinity Risk: Certain areas in Liberia exhibit no risk of salinity accumulation, as rainfall effectively helps to leach away salts.

These findings highlight the necessity of tailored irrigation and drainage practices to optimize crop production in Liberia.

Mozambique

This summary highlights the key findings and recommendations for improving irrigation and drainage practices in Mozambique's irrigated regions based on the soil-water-plant modeling study.

1. Water Requirements: Sorghum sown on April 29 required 194.3 mm of rainfall in addition to 343 mm of irrigation. In contrast, sorghum planted on November 17 received 909.7 mm of rainfall but still needed an extra 103 mm of irrigation due to uneven rainfall distribution.
2. Importance of Adequate Water Supply: Regardless of the planting schedule, ensuring an adequate water supply is essential for optimal biomass production and yield.
3. Impact of Saline Water: Crops sensitive to saline water (6 dS/m) irrigated over two years experienced substantial yield losses, underscoring the need for salt-tolerant varieties and effective agricultural practices, such as reliable drainage systems.
4. Soil Water Content Management: The proposed irrigation schedule effectively maintained soil water content within the range between the wilting point and field capacity, ensuring sufficient water supply and enhancing crop performance. Additionally, the rainy contributed to increased soil moisture levels.

5. Dry Period Challenges: Without irrigation during the dry season, soil moisture at a depth of 0-30 cm can fall below the wilting point, resulting in significant yield reductions if irrigation is not provided.
6. Pre-Rainfall Irrigation: Irrigation is crucial to fulfill crop water requirements before the effective onset of rainfall.
7. Salinity Risk Management: The BPH location in Mozambique may face risks associated with salinity accumulation from saline water irrigation. Effective management strategies, including appropriate drainage and a leaching fraction, are vital. Fortunately, the soil demonstrates good drainage capabilities, and the use of salt-tolerant genotypes is recommended.

Botswana

This summary presents key findings and recommendations to improve irrigation and drainage practices in Botswana's irrigated regions based on the Soil-Water-Plant Modelling Study.

1. Optimal Practices Identified: The study successfully pinpointed the best irrigation practices for crop production, demonstrating the model's reliability across various scenarios.
2. Freshwater vs. Saline Water: The use of freshwater significantly enhances biomass production. Although salt-tolerant genotypes can sustain yields with saline water (6 dS/m), delaying planting from December 22 to April 22 can lead to a 30% reduction in yield.
3. Impact of Saline Water: Sensitive genotypes subjected to saline water irrigation over multiple seasons may experience severe declines in yield, potentially reaching zero. This underscores the necessity for tolerant genotypes and effective drainage solutions.
4. Salinity Effects: Salinity adversely affects sorghum biomass yield, particularly for sensitive genotypes over time, highlighting the need for careful management strategies.
5. Water Requirements: Sorghum planted on December 22 requires 343 mm of irrigation owing to high evapotranspiration rates in Botswana's arid climate.
6. Drought-Resistant Genotypes: Adopting drought-resistant sorghum genotypes can enhance water productivity and improve crop yields in resource-constrained environments.
7. Irrigation Schedule: Implementing effective irrigation schedules is essential to maintain soil moisture levels between the wilting point and field capacity, alongside supplemental irrigation during dry spells.
8. Reliable Irrigation Systems: Advanced irrigation systems, such as drip or sprinkler systems, are vital for providing adequate moisture necessary for optimal crop growth.
9. Salinity Management: There exists a risk of salinity accumulation when utilizing saline water for irrigation. Therefore, effective management, encompassing drainage solutions and selecting salt-tolerant genotypes, is crucial.