

Modeling and Optimization of Solar Photovoltaic Pumping in Chad: The Case of Maralfalfa (*Pennisetum purpureum*) Irrigation across Climatic Zones

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Abstract

Chad is located between 7° and 24° North latitude and 13° and 24° longitude. It comprises three main climatic zones: the Saharan zone in the north (precipitation: 50 - 200 mm), the Sahelian zone in the center (precipitation: 300 - 800 mm), and the Sudanian zone in the south (precipitation: 900 - 1200 mm). Actual data for the study area, covering a 32-year period from January 1, 1991, to December 31, 2022, were collected from Chad's National Meteorological Agency facilities and processed using CROPWAT software. Although the software did not initially include the forage crop Maralfalfa (*Pennisetum purpureum*), it was subsequently configured to recognize and account for this plant. The research aims to replace the solar radiation component (G) of the Penman-Monteith model (FAO 1975) with radiation estimates derived from Hussein's solar radiation estimation model (G_h) in order to evaluate the influence of relative humidity and temperature on system efficiency. The proposed methodology relies on using this evapotranspiration model within CROPWAT. The software calculates crop water requirements and irrigation volumes based on FAO irrigation and drainage manuals and schedules tailored to various cultivation practices; it also enables the assessment of the impact of water deficit on crops and the efficiency of different irrigation methods. The study focuses on a one-hectare plot cultivated with 30% potatoes and tomatoes and 70% Maralfalfa. The selected planting date is January 1, 2022, and the harvest date is December

31, 2022, spanning a 365-day period. The crop coefficient (K_c) is 0.4 during the initial stage, which lasts 30 days. The critical soil moisture threshold is set at 0.65, with a yield factor of 0.5. The growth phase lasts 60 days, with a yield response factor of 0.75. The mid-season period extends over 180 days with a yield response factor of 1.20, while the late-season period lasts 95 days, with a crop coefficient of 0.75 and a yield response factor of 0.10. The initial root depth is 0.25 meters, the maximum depth is 1.50 meters, and the plant reaches a height of 3 meters across Chad's various climatic zones. Our simulations reveal that each climatic zone requires a tailored solution. This solar photovoltaic pumping system, based on the specific PS2-4000 C-SJ8-15 pump model, demonstrates its ability to adapt effectively to Chad's climatic conditions. By analyzing the solar array—comprising SL250CE-36P polycrystalline modules—and adjusting storage tank sizes for each zone, the system aims to supply 7.5 mm of water per day to a field planted with 70% Maralfalfa and 30% tomatoes and potatoes. Thus, in the Saharan zone, the pump meets high water demands thanks to a higher power output of 4.5 kW and a high-performance system; meanwhile, in the Sahelian and Sudanian zones, technical choices—specifically regarding the number of panels and storage tank volume—make it possible to reduce energy requirements while maintaining flow rates. This study demonstrates that a properly sized pump can provide a solution that is sustainable, cost-effective, and resilient to climate variability. Overall, this work presents a decision-support tool for solar photovoltaic irrigation, specifically for cultivating Maralfalfa fodder across Chad's various climatic zones.

Keywords

Solar Photovoltaic Pumping, Irrigation, Forage Crops, Maralfalfa, Modeling, Water Requirements, Different Climatic Zones of Chad

1. Introduction

1.1. Context and Rationale for the Study

Livestock farming, like agriculture, depends on water availability. In Chad, water-related challenges are mounting year by year. This is a critical issue in a difficult context marked by limited water resources [1]. Indeed, reliance on fossil fuels, often an unreliable method for water supply, presents significant limitations regarding availability, sustainability, and efficiency [2]. This is particularly evident given a climate increasingly characterized by high variability and extreme conditions, a situation that makes the issue of irrigation even more complex and challenging [3]. Adopting innovative technologies, such as solar photovoltaic irrigation, could radically transform Chad's agricultural landscape. This method efficiently powers irrigation systems without relying on fossil fuels. It harnesses the country's abundant sunshine, which ranges from 2850 hours annually in the south to 3750 hours in the north. Available solar radiation averages between 4.5 and 6.5 kWh/m²/day [4]. From an economic perspective, empowering farmers through sus-

tainable irrigation systems could also stimulate job creation and foster crop diversification, thereby enhancing community resilience in the face of economic and environmental crises [5]. Furthermore, irrigation systems designed to align with local watercourse configurations improve water resource conservation. These networks protect Chad's groundwater reserves estimated at 20 billion cubic meters and spanning 75% of the territory, as well as its 19 million hectares of arable land (of which 5.6 million are irrigable but only 10% currently cultivated) [6]. In doing so, they prevent the overexploitation of aquifers. An integrated approach that accounts for the ecological specificities of each region, combined with training and awareness programs for farmers on modern irrigation techniques, could indeed bolster food security and foster sustainable economic development [7]. It is therefore essential to mobilize public policy in support of these innovative initiatives, as the future of agriculture in Chad hinges on rapid, effective adaptation to changing climatic conditions [8]. This research delivers tangible, concrete benefits to the local population, ensuring a better future for communities affected by the water crisis [9].

1.2. Irrigation Worldwide

Controlled irrigation has for centuries served as a fundamental bulwark against undernourishment and a pillar of food security for populations. Today, in the face of climate imperatives, drip irrigation represents the culmination of an essential technological evolution that balances the optimization of agricultural yields with resource conservation. By precisely targeting water and nutrient delivery, this method offers a concrete response to the threats of water scarcity and environmental pollution. Although not universally applicable to every type of crop, its widespread adoption remains a key strategic lever for rationalizing the use of water and fertilizers [10].

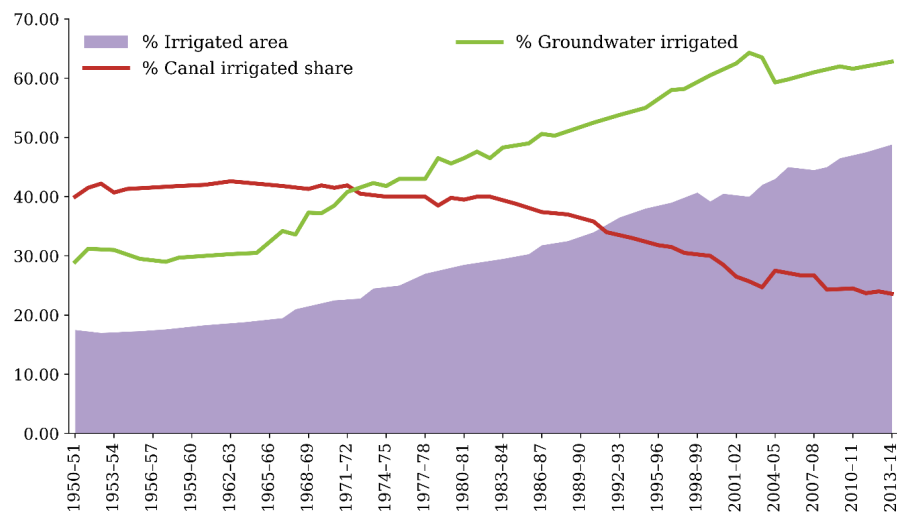


Figure 1. Irrigation trends since 1950-1951 [11].

Figure 1 shows the evolution over time from 1950 to 2013 of three irrigation-

related indicators: the share of land irrigated via surface methods (purple curve), the share irrigated by canals (red curve), and the share irrigated using groundwater (green curve). Overall, irrigated land area shows a steady increase over the period, rising from approximately 15% - 20% at the start to nearly 50% by the end. Concurrently, the share of canal-based irrigation remained relatively stable until the late 1960s before gradually declining after 1970, whereas the share relying on groundwater showed an upward trend, particularly from 1970 onwards, reaching levels comparable to or higher than the other methods by the end of the period. Overall, **Figure 1** thus suggests a shift in irrigation methods toward groundwater resources, alongside an expansion of irrigated land over time.

1.3. Irrigating Forage Crops in Africa

Sorghum is a forage crop that has long been cultivated in sub-Saharan Africa, typically during the rainy season, meaning it relies on rainfall. However, climate change is making this production increasingly vulnerable: rainfall patterns are becoming erratic, and crop yields are at risk of decline. Against this backdrop, the idea of growing forage crops during the dry season using irrigation makes perfect sense. The goal is simple: to help farmers better withstand climate shocks by ensuring more stable production. A field trial was therefore conducted at a technology and innovation park located at the ITRAD headquarters, using the Maralfalfa forage crop.

Before and during cultivation, researchers assessed soil fertility and applied Integrated Soil Fertility Management (ISFM) techniques. Ultimately, the study aims to demonstrate that farmers can boost their resilience by growing rain-fed varieties under irrigation during the dry season. The results are encouraging: analysis of variance shows that, under these conditions, the yield of Maralfalfa, normally a rain-fed crop, nearly tripled, rising from 2 t/ha/year to 15 t/ha/year. The study also highlights a crucial point: access to water is key to securing production and enhancing farm resilience. Finally, growing sorghum under irrigation represents a promising innovation, as agricultural water infrastructure is often reserved for rice or vegetable farming. Diversifying crops allows for better utilization of these resources and strengthens food security [12].

1.4. Irrigation in Chad

Forage cultivation still plays a very marginal role in rural Chad. Animal nutrition relies largely on natural resources such as fallow land, grasslands, and forest areas supplemented by cereal crop residues. However, life is becoming increasingly difficult for pastoral communities: climate change and land-use pressure are steadily eroding their access to grazing grounds. In this context, producing forage crops is becoming essential to help livestock farmers get through the critical months of the year. The timing is particularly favorable for developing this sector, especially given the availability of storage and transport solutions. Unfortunately, concrete projects that deliver tangible results have yet to materialize [13].

1.5. Problem Statement

Although modeling for pumping systems exists, several factors can significantly affect system performance, thereby reducing reliability. The system depends on soil parameters, climatic variations, and evapotranspiration. While evapotranspiration determines crop water requirements and soil type dictates the irrigation technique, what influence do relative humidity and temperature have on system efficiency?

1.6. Central Research Question

What are the possibilities for adapting and optimizing solar photovoltaic pumping systems to address climatic variations affecting Maralfalfa forage crops within the Chadian climate context?

1.7. Secondary Research Questions

To design and model a solar photovoltaic pumping system adapted to the various climatic zones of Chad in order to optimize the irrigation of forage crops—specifically Maralfalfa—while accounting for climatic variations.

1.8. Research Objectives

a) General Objective

To identify a solar photovoltaic pumping system model for Maralfalfa irrigation that incorporates relative humidity and temperature, thereby improving the production of this forage crop across different cultivation zones.

b) Specific Objectives

To contribute to the modeling of the solar photovoltaic irrigation system by replacing the solar radiation parameter in the Penman-Monteith (FAO, 1975) evapotranspiration model (used in CROPWAT simulation software) with the G_h value from Hussein's meteorological solar radiation estimation model, in order to assess the impact of relative humidity and temperature on the system. The study focuses on a 1-hectare field comprising 30% potatoes and tomatoes and 70% Maralfalfa.

c) Research Hypotheses

The Penman-Monteith model (FAO 1975) enables the modeling of the photovoltaic irrigation system across various study areas.

1.9. General Methodology

Section 2 provides a continental overview and outlines general irrigation prospects before focusing on the specific context of Chad. Section 3 describes the study area in terms of its geography and climate, covers data processing, and details the algorithmic methodological approach of the Penman-Monteith evapotranspiration model (FAO, 1975). Section 4 presents a detailed statistical analysis of climatological, soil, and crop-related data, as well as crop and irrigation water requirements based on evapotranspiration and the evolution of soil water retention over the days following planting.

2. Previous Work

Studies on solar photovoltaic pumping highlight the technical and economic viability of these systems, particularly in arid and rural areas. Research by [14] and [15] underscores the importance of renewable energy sources (solar and wind) for water pumping, especially in regions such as Cameroon and Burkina Faso. However, these studies are often limited to specific geographic areas and fail to account for long-term climatic variations or maintenance costs, as noted in [16]. Research on system optimization, such as that by [17], demonstrates that techniques like MPPT (Maximum Power Point Tracking) and sizing tools can enhance pumping system efficiency. Nevertheless, these studies often lack large-scale experimental validation, which limits their practical applicability.

Work regarding socio-economic and environmental impacts, such as that by [18] and [19], reveals that solar pumping can bolster traditional systems but presents sustainability challenges, particularly concerning water resource management [20]. These studies are frequently qualitative and lack the quantitative data needed to substantiate their conclusions. [21] shows that the performance gap between the most and least efficient systems stems from the choice of pump and the irrigation method. However, these studies do not account for climatic variations, and a common limitation is the lack of practical field applications.

Although solar photovoltaic pumping systems show promise, their large-scale adoption requires further in-depth study regarding long-term costs, environmental impacts, and adaptability to climatic variations. This is why we have focused on modeling solar photovoltaic pumping systems for irrigation across Chad's various climatic zones, specifically for the cultivation of Maralfalfa fodder crops.

3. Materials and Methods

3.1. Description of the Study Area

Chad is characterized by a tropical semi-arid climate. It is subdivided into three climatic zones: the Saharan zone in the north, with rainfall between 50 and 200 mm; the Sahelian zone in the center, with rainfall of 300 to 800 mm; and the Sudanian zone, characterized by rainfall ranging from 900 to 1200 mm (see **Figure 2**). In the Saharan zone, the rainy season lasts no more than two months; in the Sahel, it lasts three to four months; and in the Sudanian zone, it lasts five to six months. It is a landlocked country. It shares borders with Libya to the north, Sudan to the east, the Central African Republic to the south, and Cameroon, Niger, and Nigeria to the west, the latter three being the countries with which it shares Lake Chad. The nearest port, Douala in Cameroon, is located 1700 km from the capital, N'Djamena. The Chadian population was estimated at 11.5 million inhabitants in 2011 (representing 27.2% of the population of the CEMAC zone). The population is relatively young, and a large majority lives in rural areas. Although the trend is downward, the average annual population growth rate is 2.6%. At this rate, the population would double before the year 2040. Chad is an agro-pastoral country. Since the onset of oil production, the Chadian economy has relied primarily on export revenues. The country

also possesses immense tourism potential [22].

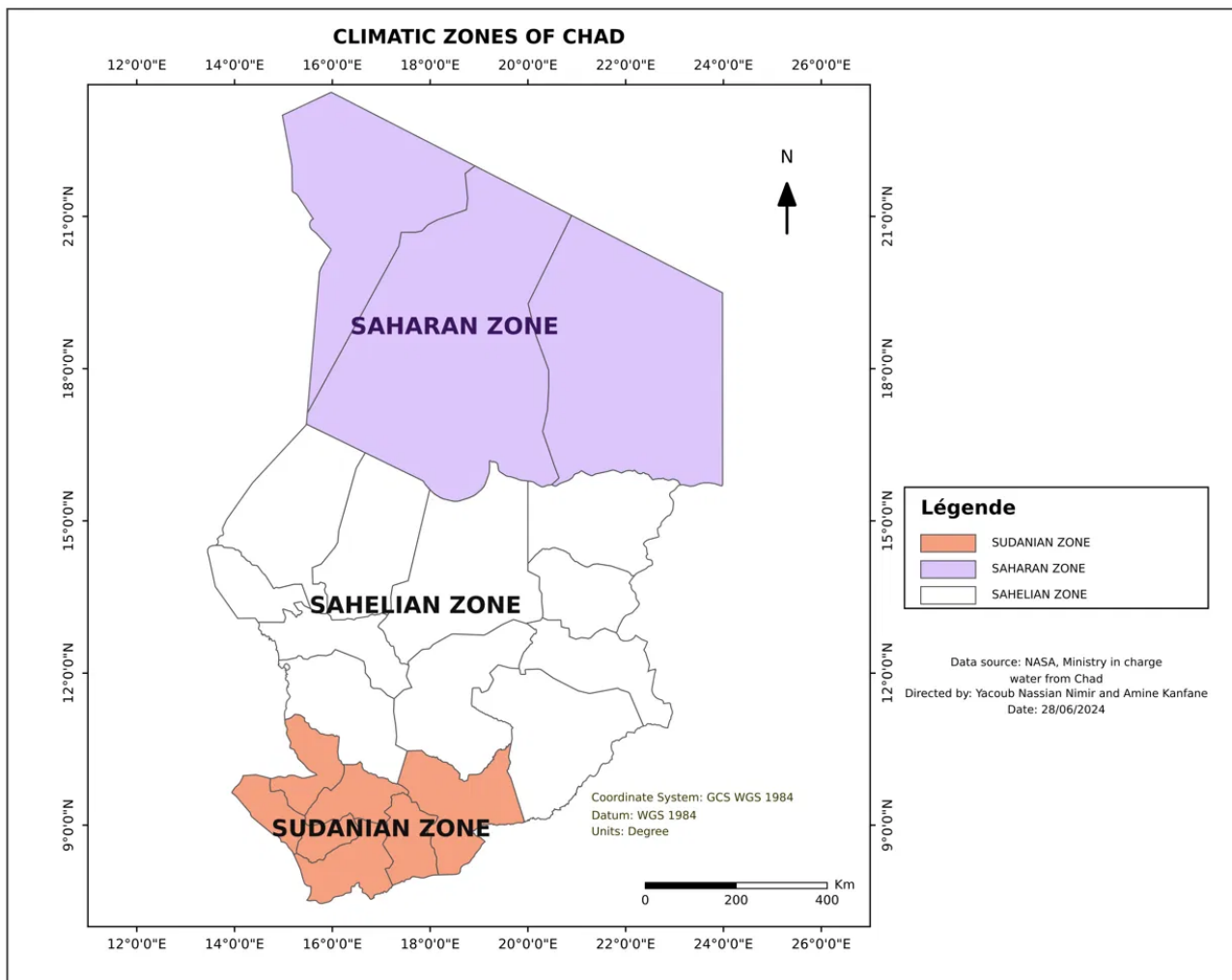


Figure 2. Map of the different climatic zones of Chad (Source: Ministry in charge of Water, Chad).

Figure 2 shows the different climatic zones of Chad: the Saharan zone in the north, the Sahelian zone in the center, and the Sudanian zone in the south.

3.2. Data Collection

Chad's National Meteorology and Aviation Agency (ANAM) facilitated data collection across the country's distinct climatic zones: the Saharan zone in the north, the Sahelian zone in the center, and the Sudanian zone in the south. The data cover a 32-year period from January 1, 1991, to December 31, 2022, to ensure robust analysis and statistical validity. The choice of study period adheres to strict methodological and scientific criteria aligned with World Meteorological Organization (WMO) recommendations. This 32-year timeframe aligns with the definition of a standard climatological normal, which is necessary to smooth out inter-annual variability and capture robust long-term climate change signals in Chad. This temporal scope is justified by a dual dynamic: climatic and technical. From a climatic or environmen-

tal perspective, it encompasses the decades following the major droughts of the 1970s and 1980s, a pivotal era marked by shifts in precipitation patterns and global warming across sub-Saharan Africa. Methodologically, this period coincides with the use of modern observation tools by ANAM. It thus represents the best possible compromise between the continuity of ground-based station readings and the increasing reliability of space-based remote sensing data. This approach enables the use of standard models and software such as CROPWAT and CLIMWAT to accurately estimate evapotranspiration using the Penman-Monteith method (FAO-75), thereby ensuring a reliable assessment of crop water requirements in the context of food security and water resource sustainability challenges.

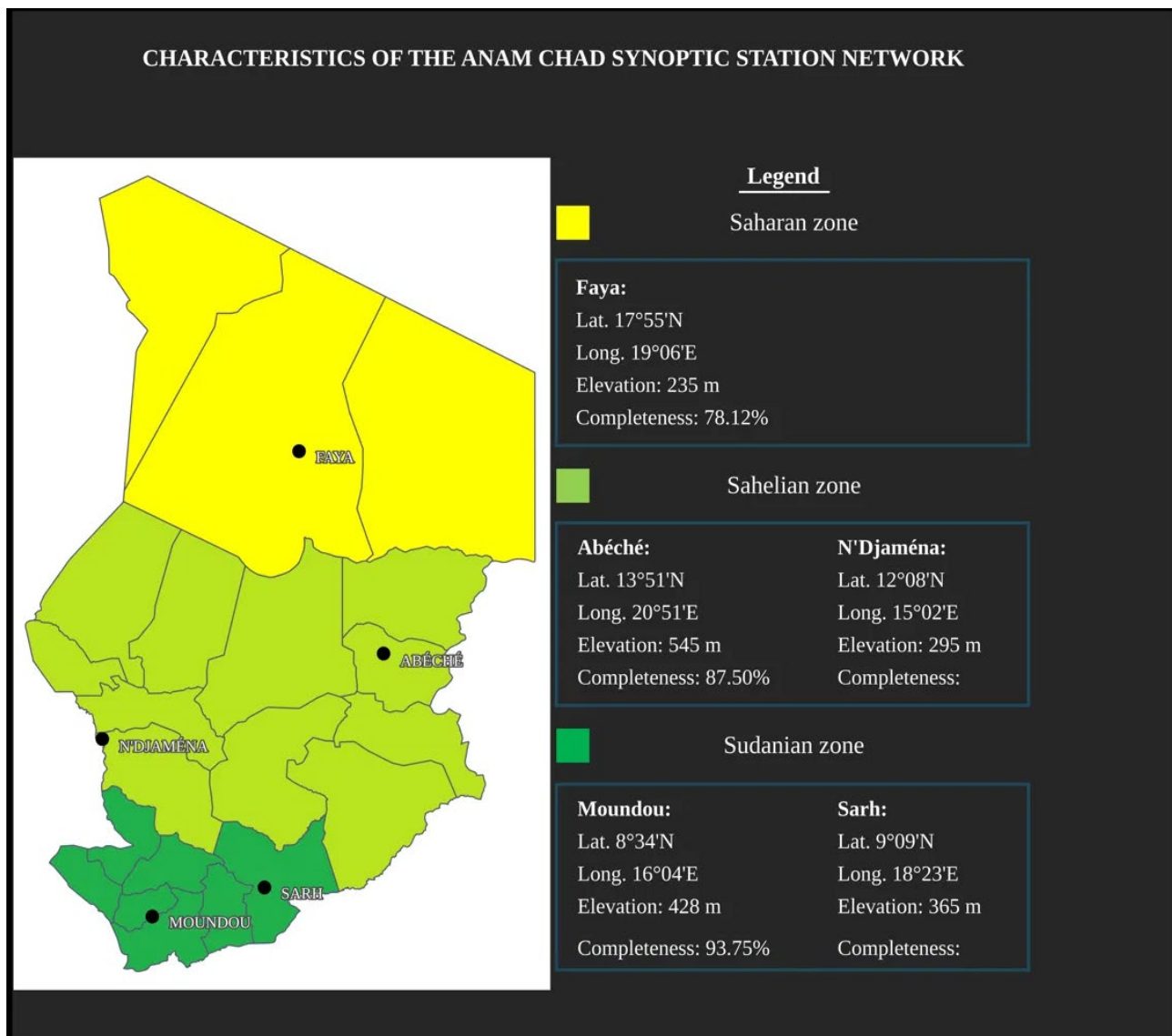


Figure 3. Map showing the locations of weather stations and the various climate zones of Chad (Source: National Meteorology Agency (ANAM) of Chad).

Figure 3 shows a map of Chad depicting the locations and elevations of weather stations across the various climatic zones.

- **Data Continuity and Quality Control**

Processing the raw climate databases from ANAM Chad involved a strict quality control and homogenization protocol comprising four successive steps:

- 1) Calculation of Data Completeness Rates by Station and Variable**

A systematic assessment of record availability was conducted for the 1991 - 2022 period. This analysis was applied separately to primary variables (temperature T_{min} and T_{max} and precipitation) and secondary variables (wind speed, relative humidity, and sunshine duration), making it possible to quantify the overall completeness for each station, ranging from 78.12% at Faya to 96.87% at N'Djamena.

- 2) Detection of Breaks and Technical Anomalies**

Periods of chronological discontinuity (instrument failures, prolonged transmission interruptions, or logistical isolation) were mapped. The major breaks identified occurred primarily in the mid-1990s and early 2000s at the Abéché and Moundou stations, whereas the Faya station shows chronic data gaps regarding humidity and sunshine sensors.

- 3) Imputation and Gap-Filling Protocol**

To address raw data incompleteness and stabilize time series, correction procedures combining remote sensing data and global reanalysis products were applied:

- Thermal and energy variables (T_{min} , T_{max} , relative humidity, and wind speed) were corrected and supplemented by extracting corresponding grid cells from the ECMWF's ERA5 global reanalysis model.
- Missing precipitation data were filled using the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) high-resolution spatiotemporal grids—a hybrid product combining satellite imagery with ground-based station observations.

- 4) Creation of a Modeling-Ready Dataset**

Integrating these spatiotemporal imputation techniques made it possible to artificially bring the practical data completeness rate of the series to 100%. The resulting homogenized and validated monthly datasets provide a robust statistical foundation for calculating multi-year averages and driving climate and agricultural models.

Figure 4 illustrates the seasonal rhythm in Chad, characterized by a distinct transition between heat and rainfall throughout the year. The year is marked by two clearly defined heatwaves: an initial, stifling spring surge in April and May with temperatures exceeding 40°C followed by a second, more moderate rise to 36°C in October. Between these two peaks, the African monsoon arrives, building from July to reach its height in August. Naturally, this rainy season brings heavy, cloudy skies that cause sunshine levels to drop to a low of 6.2 hours per day in August, a stark contrast to the clear skies of the winter months. Regarding wind conditions, the atmosphere is particularly turbulent in March (4 m/s) before calming during the rainy season to reach a minimum of 2.2 m/s in September, marking a lull before the return of dry continental winds at the end of the year.

Evolution of multi year monthly climate averages (1991-2022) Reference Station ANAM Chad Network

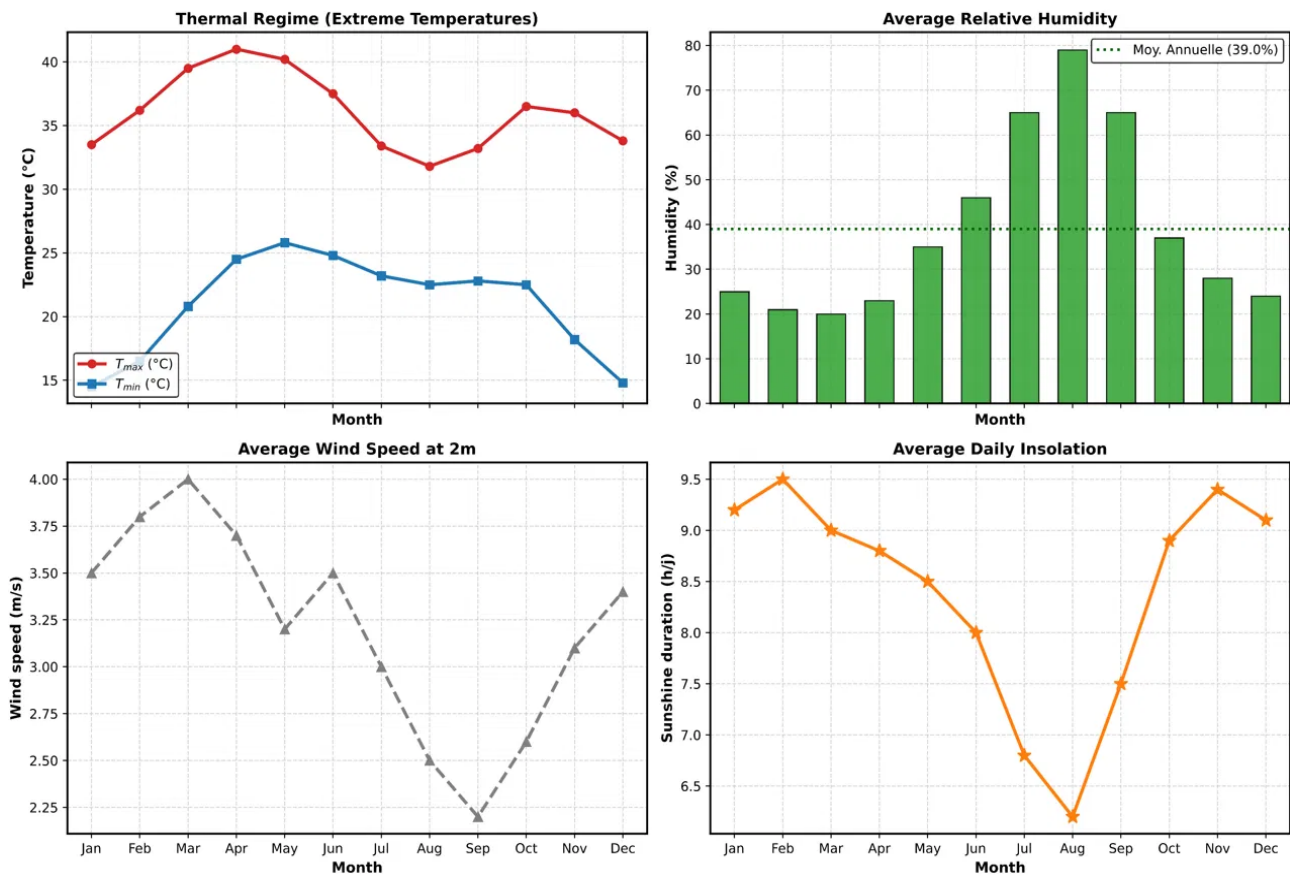


Figure 4. Evolution of multi-year monthly climate averages (1991-2022) reference station ANAM Chad network.

3.3. Data Processing

The CROPWAT model estimates water requirements based on the crop species and local climatic and environmental conditions. It is used by farmers and planners to better manage water resources. Developed in 1975 by the FAO (Food and Agriculture Organization of the United Nations) and based on water balance calculations, it serves as a tool to support crop irrigation and the development of water supply schedules. The model calculates reference evapotranspiration using the modified Penman-Monteith equation and meteorological data. It also enables the creation of irrigation schedules and the assessment of the impact of water deficits on crops, as well as the efficiency of various irrigation practices [23].

To accurately assess the impact of modeling on crop water requirements, the methodology was applied to Chad's various climatic zones using data from five stations of the National Meteorological Agency (ANAM) of Chad. The representative sample included the Faya station for the Saharan zone, the Abéché and N'Djamena stations for the Sahelian zone, and the Moundou and Sarh stations for the Sudanian zone. Global radiation (G_h) was calculated on a monthly basis for each station using Hussein's Meteorological Model for Solar Radiation Estimation (MMER). The resulting values were converted into MJ/m²/day to comply with the strict input for-

mat required by the CROPWAT 8.0 software. Within the software interface, this data was entered into the “Climate/Eto data” module by directly populating the “Rad (MJ/m²/day)” field in the custom climate table. This method of directly inputting global radiation calculated via Hussein’s model overrides the use of CROPWAT/CLIMWAT’s internal estimation formulas, which typically rely solely on sunshine hours. To rigorously isolate the radiation effect specific to each local context, the other climatic input variables required to calculate reference evapotranspiration (ET_0) using the Penman-Monteith equation (FAO-75) were extracted from the CLIMWAT database for the corresponding stations. These variables include minimum and maximum temperatures (T_{min} and T_{max}), relative humidity (H_a), wind speed (v), and sunshine duration (DI). Thanks to this substitution mechanism, any variation observed in net radiation (Rn), reference evapotranspiration (ET_0), and consequently crop water requirements (ET_c) stems exclusively from replacing theoretical radiation with the radiation calculated using the Hussein model, thereby faithfully reflecting the specific global radiation characteristics of the three different zones of Chad.

3.3.1. Input Data

This model requires climatic data (precipitation in mm, minimum and maximum temperatures in °C, relative humidity in %, wind speed in m/s, and sunshine duration in hours), crop data (sowing and harvest dates, phenological stages, rooting depth, crop coefficient K_c , crop height, and crop cycle), and soil data (physical properties). These parameters can be obtained through experimental work [24]. In this study, they are from Chad’s National Agency for Meteorology and Aviation (ANAM).

a. Hussein’s Meteorological Method for Solar Radiation Estimation (MMER).

Hussain’s model is based on [25]. Thus, this expression allows for the examination of global irradiation as a function of monthly daily averages of absolute humidity and sunshine duration. The expression is given as follows:

$$G_H = G_{H_0} \left(0.394 - 0.364 \left(\frac{DI}{T_M} \right) - 0.0035 H_A \right) \quad (1)$$

DI : daily monthly averages of sunshine duration;

G_{H_0} : irradiation calculated on a horizontal plane;

T_m : astronomical day length;

H_A : absolute humidity.

b. Penman-Monteith (FAO 1975)

This is the best-known and most widely used formula; it is recommended by the FAO. It was developed for a reference crop 0.2 m in height, with a resistance of 70 s/m and an albedo of 0.23 [26].

- The Penman-Monteith (FAO 1975) model is presented as follows:

$$ET_o = \frac{0.4\Delta(Rn - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (2)$$

ET_o : reference evapotranspiration (mm/day);

R_n : net radiation (MJ/m²/day);

G : soil heat flux (MJ/m²/day);

$(e_s - e_a)$: represents the air vapor pressure deficit (kPa);

e_s : saturation vapor pressure of the air (kPa);

e_a : actual vapor pressure of the air (kPa);

Δ : slope of the saturation vapor pressure curve at the temperature (kPa/°C);

γ : psychrometric constant (kPa/°C);

U_2 : mean daily wind speed measured at 2 meters (m/s).

- Crop evapotranspiration is calculated as follows:

$$ETc = KC ET_o \quad (3)$$

ETc : crop evapotranspiration;

Kc : crop coefficient.

- Crop water requirements are calculated as follows:

$$CWR = KC ET_o - Peff \quad (4)$$

$Peff$: effective rainfall;

CWR : crop water requirement.

The modeling is structured as follows:

- **Modelling**

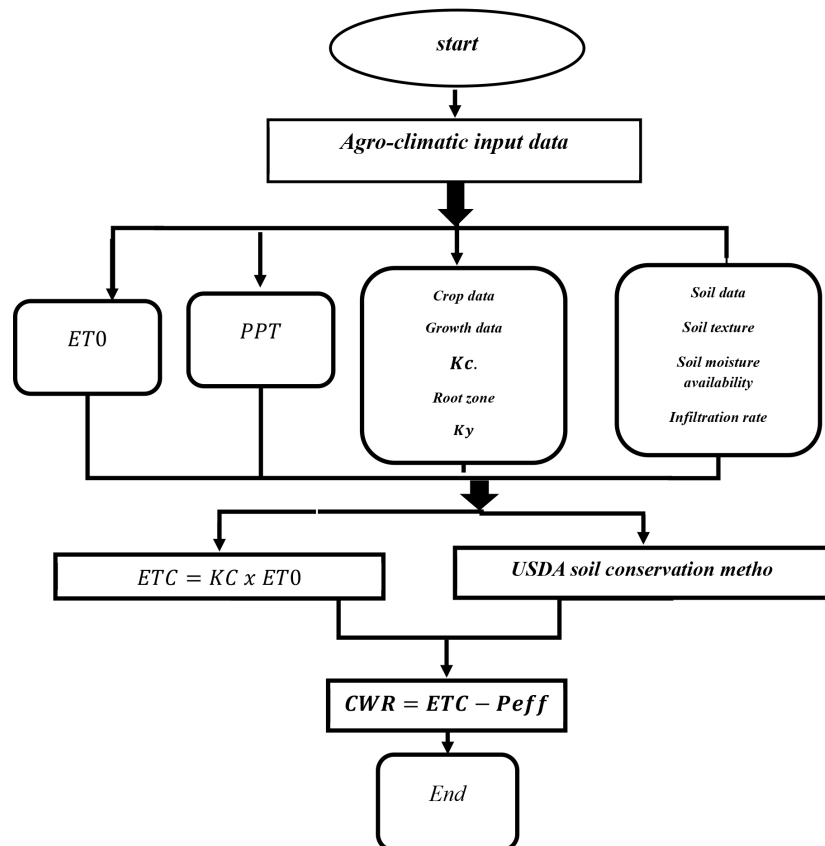


Figure 5. CROPWAT 8.0 algorithm.

Figure 5 shows an algorithm that illustrates the method for calculating crop water requirements (CWR), which is determined by subtracting effective rainfall from crop evapotranspiration (ET_c). The calculation of ET_c combines agro-climatic data (ET_0) with crop characteristics (K_c), while soil properties (texture, available moisture, root zone) and growth stages refine the assessment of water requirements [27].

c. Sizing of the solar pumping system

1. Determination of water needs

The daily flow is obtained from the relation [28]:

The complete cycle of marafalfa is 365 days (cycle = 365).

$$ETJ = \frac{ET_0}{365} \quad (5)$$

2. The flow rate of the pump

The flow rate is obtained using the relation:

$$Q = \frac{KC ET_0 - Peff}{365 \cdot DI} \quad (6)$$

3. Total head (HMT) [29]

The total head is given by the formula:

$$HMT = Ha + Hr + dl + ds + Pr \quad (7)$$

Ha : suction lift (submersible pump $Ha = 0$);

Hr : discharge head;

dl : linear pressure loss;

ds : minor pressure loss;

Pr : residual pressure (atmospheric pressure).

a) Photovoltaic field

• Calculation of hydraulic energy

The hydraulic energy is obtained by the relation:

$$E_h = \frac{2.725 \cdot HMT \cdot (KC ET_0 - Peff)}{365 \cdot DI} \quad (8)$$

b) Calculation of the electrical energy to be supplied to the pump [30]

The electrical energy to be supplied to the motor is obtained using the relation :

$$E_e = \frac{2.725 \cdot HMT \cdot [KC ET_0 - Peff]}{365 \cdot DI \cdot \eta_{MP} \cdot \eta_{motor}} \quad (9)$$

c) Peak power of the photovoltaic generator

$$p_c = \frac{E_e}{k_p} \quad (10)$$

Substituting E_e (Equation (8)) with its expression in Equation (10) yields:

$$P_C = \frac{2.725 \cdot HMT \cdot k_p \cdot \left[KC \left(\frac{0.4 \cdot (Rn - G_H) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 U_2)} \right) - Peff \right]}{365 \cdot DI \cdot G \cdot \eta_{MP} \cdot \eta_{motor}} \quad (11)$$

where

$$G_H = G_{H_0} \left(0.394 - 0.364 \left(\frac{DI}{T_M} \right) - 0.0035 H_A \right)$$

k_p : solar irradiance correction factor;

η_{MP} : pump efficiency;

η_{motor} : motor efficiency;

DE : monthly daily averages of sunshine duration;

G_{H_0} : extraterrestrial radiation calculated on a horizontal plane;

T_m : astronomical day length;

H_a : absolute humidity.

d) Selection of module type [31]

$$T_{moy} = T_a + \left(H_T \cdot \frac{TUC - T_{aref}}{G_{aref}} \right) \quad (12)$$

T_{moy} : average module temperature;

T_a : average annual ambient temperature;

H_T : annual ambient irradiance;

T_{aref} : reference ambient temperature (20°C under standard conditions);

G_{aref} : reference ambient irradiance (800 W/m² under standard conditions);

TUC : cell operating temperature (45°C).

e) Number of PV modules

The number of PV modules is obtained from [32]

$$N_{pv} = \frac{P_{csty}}{P_{pv}} \quad (13)$$

N_{pv} : number of PV modules;

P_{csty} : system power;

P_{pv} : power of a PV module.

3.3.2. Maralfalfa

Maralfalfa or elephant grass (*Pennisetum purpureum*) is a high-yielding, perennial tropical hybrid forage grass selected for intensive livestock feeding. It thrives in deep, well-drained soils (silty-clay and silty-sand), provided there is no risk of prolonged flooding or shading. Annual production can range from 200 to 500 tonnes of fresh matter per hectare, depending on cultivation and management conditions. At the third cut (at an altitude of 1750 m), yields of 285 tonnes of fresh forage per hectare were achieved in 75 days, with plants reaching 2.5 m in height. Agroclimatic conditions: It can be grown at altitudes ranging from sea level to 3000 m. It adapts well to soils of medium to high fertility. Optimal production is achieved on well-drained soils with high organic matter content [33].

Figure 6 shows that Maralfalfa is available throughout the season. From July to mid-November, animals have access to fresh Maralfalfa in addition to pasture. From mid-November through March, hay stocks and irrigated Maralfalfa are also available; hay stocks and irrigated Maralfalfa remain available in late April and July [33].

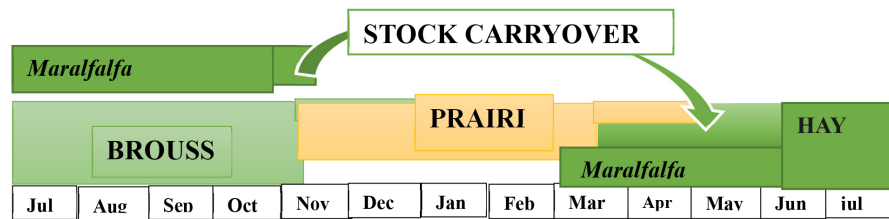


Figure 6. Animal feeding schedule.

3.3.3. Soil-Related Data

Soil parameters allow for the estimation of the soil's available water capacity (AWC). Determining AWC requires data on soil texture and rooting depth.

Table 1 shows that in the Saharan zone, sandy soil retains only about 60 mm of available water per meter (low capacity), whereas in the Sudanian zone, clay soil offers an intermediate capacity of approximately 200 mm/m; the Sahelian zone (loamy/medium soil) has the highest capacity, reaching 290 mm/m. Despite differences in available water capacity across zones, maximum infiltration rates are identical (40 mm/day) and rooting depth is the same (900 cm), meaning the primary difference between zones lies in the soil's water storage capacity (low in the Saharan zone, more favorable in the Sahelian zone, and moderate in the Sudanian zone).

Table 1. Soil data for the different climatic zones of Chad.

	Saharan Zone	Sahelian Zone	Sudanian Zone
Soil type	Sandy (light)	Loamy (medium)	Clayey (heavy)
General soil data:			
Total available water (FC-WP)	60.0 mm/meter	290.0 mm/meter	200.0 mm/meter
Maximum water infiltration rate	40 mm/day	40 mm/day	40 mm/day
Maximum rooting depth	900 centimeters	900 centimeters	900 centimeters
Initial water content depletion	0%	0%	0%
Initial available water	60.0 mm/meter	290.0 mm/meter	200.0 mm/meter

The Saharan zone features sandy, light, and highly free-draining soil. It is characterized by low water retention capacity, storing only 60 mm of water per meter of depth (or 6 mm per 10 cm). High irrigation frequency is required, as water reserves are rapidly depleted by evaporation and crop consumption. While the soil has a high water-absorption capacity with an infiltration rate of 40 mm/day (good infiltration), water drains quickly to greater depths, beyond the reach of the roots.

The Sahelian zone features loamy soil, considered ideal for agriculture due to its balance between water retention and drainage. This soil can store up to 290 mm of water per meter of depth (or 29 mm per 10 cm), allowing forage crops to draw moisture over an extended period without requiring frequent irrigation or rainfall. It combines the benefits of water retention (like clay soil) and drainage (like sandy soil), making it very easy to manage for irrigation purposes.

The Sudanian zone is characterized by clay soil. While it has a high capacity to retain water and nutrients, it can be prone to compaction and has a slow infiltration rate of 40 mm/day, typical of clay soils. The soil provides 200 mm of water available to the crop. Maralfalfa is capable of extending its roots to a depth of up to 9 meters, provided there are no obstructions.

3.3.4. Crop-Related Data

Crop data will specify the water reserve readily available to the plant (crop type, developmental stages, and K_c).

Table 2 presents data for the Maralfalfa production trends, which were assessed through agro-climatic modeling using FAO's CROPWAT 8.0 software. Reference evapotranspiration (ET_0) was determined using the Penman-Monteith equation (FAO-75). Crop coefficients (K_c) were set at 0.40 for the initial 30-day phase, 1.25 for the 180-day mid-season phase, and 0.75 for the 95-day late-season phase. A maximum rooting depth (Z_r) of 1.50 m and a critical depletion fraction (p) of 0.65 were used. Crop response to water stress was simulated using the FAO approach, which linearly relates the relative yield reduction to the evapotranspiration deficit via the following mathematical relationship:

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y \cdot \left(1 - \frac{ET_a}{ET_m}\right) \quad (14)$$

Y_a : the real yield;

Y_m : maximum yield;

K_y : yield response factor;

ET_a : actual evapotranspiration.

Values of K_y range from 0.50 to 1.20, depending on the phenological sensitivity of the crop. An intensive management regime based on a 45-day interval was scheduled, corresponding to a cycle of eight cuts per year. Based on a reference annual yield for the Sahelian zone of 175 - 245 t/ha/year, the yield per cut was simulated under various water supply constraints.

Table 2. Crop data for the various climatic zones of Chad.

Cultivation: Maralfalfa	Planting Date 1/12			Harvest Date: 30/11	
Phase	Initial	Growth	Mid-Season	Late Season	Total
Duration (days)	30	60	180	95	365
Kc	0.40	-	1.25	0.75	
Rooting depth	1.50	-	1.50	1.50	
Maximum exhaustion	0.65	-	0.65	0.65	
Yield response	0.50	0.75	1.20	0.10	1.20
Crop height			3.00		

3.4. Output Data

Once all input data have been entered, the CROPWAT model automatically calcu-

lates the results and displays them in the form of tables or graphs. The model's output data include: potential evapotranspiration, effective precipitation, irrigation water requirements, crop water requirements, and the irrigation schedule. It also determines total gross irrigation, total net irrigation, water deficit at harvest, precipitation efficiency, and average crop coefficient values for each time step [34].

4. Results and Discussion

Crop requirements vary depending on climatic conditions, developmental stages, plant biology, and soil characteristics [29].

4.1. Climatic Factors

Climatic synthesis is an essential step for irrigation planning and the determination of water requirements. It involves determining climatic indices to identify climate trends and characteristics, as well as describing climatic variations [35]. Meteorological parameters are key factors in the seasonal distribution of irrigation and evapotranspiration; some of these appear in all formulas used to determine water requirements. The climatic data provided by Chad's National Meteorology and Aviation Agency (ANAM) primarily cover precipitation, maximum and minimum temperatures, wind, sunshine duration, air humidity, solar radiation, and reference evapotranspiration calculated using the Penman-Monteith method. The climatic factors provided by ANAM are summarized in **Table 2** (Saharan zone), **Table 3** (Sahelian zone), and **Table 4** (Sudanian zone), representing Chad's three climatic zones.

1) Climate in the Saharan Zone

Climatological data for the Saharan zone, generated by the CROPWAT software (**Table 3**), reveal an environment characterized by high temperatures, pronounced aridity, and high evaporative demand. Average maximum temperatures reach 35.7°C, with peaks exceeding 40°C between May and September, while minimum temperatures remain mild, averaging 21.3°C. Relative humidity is consistently low, averaging 26%, which accentuates the dryness of the air. Wind speeds average 317 km/day, and sunshine is abundant, averaging 9.1 hours/day, contributing to significant solar radiation of 21.6 MJ/m²/day. These combined factors result in a very high average annual potential evapotranspiration of 8.5 mm/day, peaking at 9.8 mm/day in May, indicating extreme water demand for vegetation and crops, typical of desert climates.

2) Climate in the Sahelian Zone

The climatological data in **Table 4** show a climate in the Sahelian zone characterized by strong seasonality, with high maximum temperatures year-round (average 34°C, peaking at 38.6°C in March) and relatively stable minimum temperatures (average 19.7°C). Relative humidity varies considerably, ranging from dry conditions in February (26%) to a very humid environment from August to September (81% - 82%). Wind speed (average 140 km/day) and sunshine duration (average 6.8 h/day) show a marked reduction during the austral winter (July-August). Solar radiation remains high (average 18.9 MJ/m²/day), but potential evap-

otranspiration (ET_o) reflects the combined influence of the other parameters: it is high in summer (peaking at 6.67 mm/day in February) and then decreases gradually to a minimum in August (3.59 mm/day), with an annual average of 4.92 mm/day, indicating a moderate to high evaporative demand typical of a tropical climate with a pronounced wet season.

Table 3. Climatological data for the Saharan zone provided by CROPWAT.

Month	Min. Temp.	Max. Temp.	Humidity	Wind	Sunshine	Radiation	ET _o
	°C	°C	%	km/day	hours	MJ/m ² /day	mm/day
January	18.4	26.5	25	389	8.4	17.7	7.05
February	22.4	29.7	25	380	8.9	20.1	8.06
March	25.0	33.8	20	372	8.9	22.0	9.46
April	26.2	39.0	19	311	8.6	22.6	9.75
May	25.8	41.1	22	285	9.6	24.3	9.80
June	26.0	42.1	24	259	9.7	24.3	9.47
July	25.9	40.9	34	225	9.7	24.3	8.43
August	22.5	40.0	34	216	9.4	23.8	8.00
September	18.0	39.6	26	302	9.3	22.8	9.22
October	14.3	36.5	24	337	9.3	21.1	8.69
November	17.6	31.2	29	363	9.2	19.0	7.48
December	13.9	28.1	30	363	8.6	17.3	6.55
Average	21.3	35.7	26	317	9.1	21.6	8.50

Table 4. Climatological data for the Sahelian zone provided by CROPWAT.

Month	Min. Temp.	Max. Temp.	Humidity	Wind	Sunshine	Radiation	ET _o
	°C	°C	%	km/day	hours	MJ/m ² /day	mm/day
January	22.3	34	34	164	8.2	19.7	5.56
February	24.2	36.8	26	181	8.2	20.9	6.67
March	23.6	38.6	29	164	7.3	20.6	6.66
April	22	38	51	173	6.4	19.4	6.02
May	21.2	34.7	64	164	6.9	19.6	5.23
June	21	32.2	74	138	5.8	17.6	4.22
July	20.9	30.2	80	138	5.4	17.1	3.82
August	20.9	30	81	112	4.5	16.2	3.59
September	17.5	30.8	82	104	5.3	17.4	3.74
October	14.7	33.1	75	95	6.5	18.6	4.04
November	15.1	35.1	59	112	8.5	20.3	4.72
December	13	34.2	45	130	8.5	19.7	4.77
Average	19.7	34	58	140	6.8	18.9	4.92

3) Climate in the Sudanian Zone

Table 5 presents climatological data for the Sudanian zone, revealing a tropical climate characterized by strong seasonality. Maximum temperatures remain consistently high throughout the year (averaging 36.3°C, peaking at 40.4°C in April), while minimum temperatures are moderate (averaging 21.4°C). Mean relative humidity is 39%, but exhibits pronounced seasonal variation, with low values (20% - 24%) during the dry season (January to May) and a marked increase during the wet season (July to September, reaching 79% in August). Wind speed (averaging 217 km/day) and sunshine duration (averaging 8.3 hours/day) are relatively constant, though slightly lower during the wet season. Solar radiation is high (averaging 20.8 MJ/m²/day), contributing to high potential evapotranspiration (ET_o) during the dry season (peaking at 8.74 mm/day in April) and a significant decrease during the wet season (dropping to a minimum of 4.28 mm/day in August). The annual average ET_o is 6.74 mm/day, reflecting the strong yet variable atmospheric water demand characteristic of Sudanian zones.

Table 5. Climatological data for the Sudanian zone (CROPWAT).

Month	Min. Temp.	Max. Temp.	Humidity	Wind	Sunshine	Radiation	ET_o
	°C	°C	%	km/day	hours	MJ/m ² /day	mm/day
January	16.1	33.6	24	233	8.9	19.4	6.46
February	18.2	35.6	21	242	9.2	21.4	7.27
March	22	38.2	20	259	8.5	21.9	8.31
April	25.1	40.4	23	251	8.9	23.2	8.74
May	25.6	40	30	225	8.8	22.9	8.14
June	24.9	38.5	46	207	7.7	21	6.93
July	23.1	34.5	65	199	6.9	19.8	5.50
August	21.8	32.1	79	164	5.8	18.3	4.28
September	22	35.1	65	156	7.8	21	5.26
October	22	37.4	37	199	9	21.5	6.68
November	19.7	35.7	28	233	9.1	20	6.86
December	16.9	34	24	233	9.1	19.1	6.48
Average	21.4	36.3	39	217	8.3	20.8	6.74

4.2. Evapotranspiration in the Different Zones

Figure 7 illustrates the monthly evapotranspiration trends across Chad's three climatic zones: the Saharan, Sahelian, and Sudanian zones. Overall, high evapotranspiration values are observed during the dry season, followed by a gradual decline starting in the sixth month, before rising slightly again at the end of the year. The Saharan zone exhibits the most pronounced evapotranspiration levels, reflecting intense evaporation driven by drier conditions and climatic parameters that favor evapotranspiration. The Sudanian zone features a humid tropical climate and vegetation cover

that tend to mitigate evapotranspiration. Situated between these two, the Sahelian zone experiences intermediate climatic conditions and shows significantly more moderate evapotranspiration. Thus, this figure highlights the extent to which the different zones influence evapotranspiration; seasonal variations are striking, and the differences between the zones are entirely consistent with expectations.

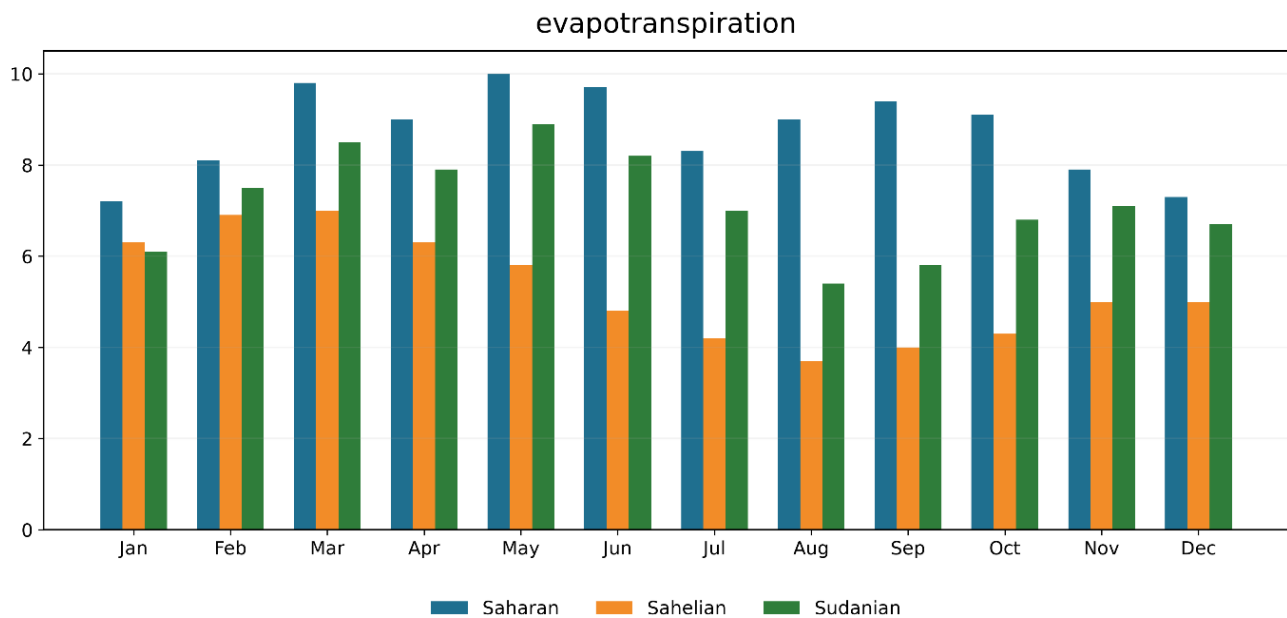


Figure 7. Evapotranspiration in the different zones.

4.3. Hussein's Meteorological Model for Solar Radiation Estimation

4.3.1. Validation of Hussein's Meteorological Model for Solar Radiation Estimation

Validation of Hussein's meteorological model for solar radiation estimation across Chad's various climatic zones, comparing it with standard models studied by Sou-louknga *et al.* (2016) such as Angstrom-Prescott, Allen, and Sabbagh, which have been tested and validated by the local scientific community against reference satellite data.

Table 6 shows that for the Saharan zone, Hussein's model yields a coefficient of determination of 89.1% with a root mean square error of 0.829, followed by Sabbagh's model with a regression coefficient of 64.68% and an error of 0.513; conversely, the Allen and Angström models are not applicable in this zone.

Table 6. Statistical evaluation of the different models in the Saharan zone.

Model	R ² (%)	MPE (%)	RMSE	MBE	Analysis
Angstrom	-1.2293	-13.791	1.289	-0.1379	Bad: Negative R ² = predictions worse than a simple average. High errors.
Sabbagh	0.6468	-6.7662	0.513	-0.07	Acceptable: Better R ² and RMSE, but underestimation (negative MPE/MAD)
Allen	-1.256	-16.724	1.297	-0.1672	Poor: Similar to Angstrom; slightly worse in MPE and MBE.
Hussein	0.891	-21.242	0.829	-4.999	Excellent R ² but very high bias (high MBE) and poor MPE.

Table 7 illustrates that, in the Sahelian zone, Hussein's MMER model performs best, with an R^2 of 93.38% and an error of 0.105, followed by the Sabbagh model, with an R^2 of 9% and a root mean square error of 0.04. The Sabbagh model serves as an alternative to Hussein's MMER model in the Sahelian zone.

Table 7. Statistical evaluation of the different models in the Sahelian zone.

Model	R^2 (%)	MPE (%)	RMSE	MBE	Analysis
Angstrom	-0.04	-1.83	0.56	-0.02	Poor: R^2 close to 0, slight underestimation (negative MPE/MBE).
Sabbagh	0.09	3.70	0.54	0.04	Better than Angstrom, but poor performance (very low R^2).
Allen	-1.42	-5.48	0.88	-0.05	Unacceptable: negative R^2 , high errors.
Hussein	0.93	-18.76	0.105	-2.59	Excellent R^2 with extreme bias (underestimation of 18.76%).

Table 8 shows that, in the Sudanian zone, the Sabbagh model demonstrates exceptional performance, with a coefficient of determination (R^2) of 92.7%, low error dispersion (RMSE of 0.32), and negligible bias (0.08). It is followed by the Angstrom model, which also shows a very good fit ($R^2 = 85.2\%$) but requires a minor bias correction; in third place is Hussein's MMER model, with an R^2 of 65.4% and a bias error of 0.31.

Table 8. Statistical evaluation of the various models in the Saharan zone.

Model	R^2 (%)	MPE (%)	RMSE	MBE	Analysis
Angstrom	0.85	-2.1	0.45	-0.12	Very good R^2 , slight underestimation (negative MPE/MBE).
Sabbagh	0.92	1.5	0.32	0.08	Excellent R^2 , minimal errors, slight positive bias.
Allen	0.78	-4.3	0.61	-0.25	Good R^2 , but more pronounced underestimation.
Hussein	0.65	3.8	0.89	0.31	Acceptable R^2 , but high errors and overestimation (positive MPE/MBE).

Hussein's MMER model demonstrates a coefficient of determination (R^2) of 89% in the Saharan zone, 93% in the Sahelian zone, and 65.4% in the Sudanian zone, with a low bias error. Although the model shows an R^2 of 65.4% and a bias error of 0.31 in the Sudanian zone, it is applicable across all of Chad's climatic zones. This represents a deliberate scientific and methodological choice. It reflects a balanced decision between the need for local precision and the requirement for a general tool applicable to all three zones—one that is conceptually aligned with our research question and robust enough for use across Chad's diverse climatic regions. In the literature, the Allen and Angström models are recommended as the best alternatives for specific zones where their calibration is optimal (Allen for the south of the country and Angström for the north).

4.3.2. Effective Rainfall

Effective rainfall plays a crucial role in irrigation, the requirements of which depend on the amount of such rainfall. In the context of agricultural production, effective rainfall is defined as the fraction of precipitation that can actually be utilized by crops. Interannual variations in total effective rainfall are presented in **Figures 4-6** for Chad's various climatic zones.

1) Water Requirements in the Saharan Zone

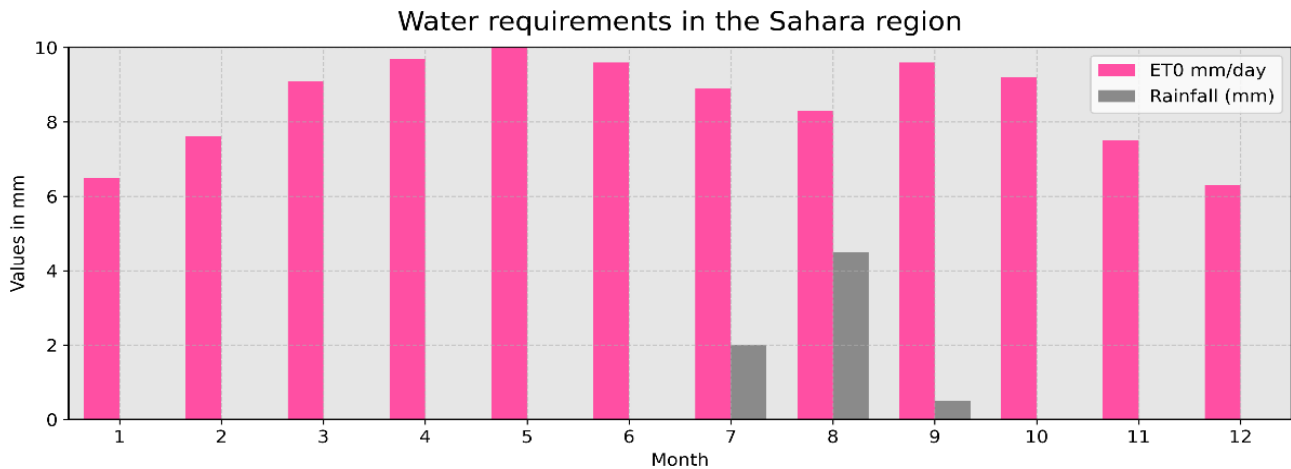


Figure 8. Water requirements in the Saharan zone.

Figure 8 shows that in the Saharan zone, effective rainfall is very low, ranging from 50 to 100 mm. Rain falls for only two months, from July to August. Evapotranspiration significantly exceeds effective rainfall throughout the year.

2) Water Requirements in the Sahelian Zone

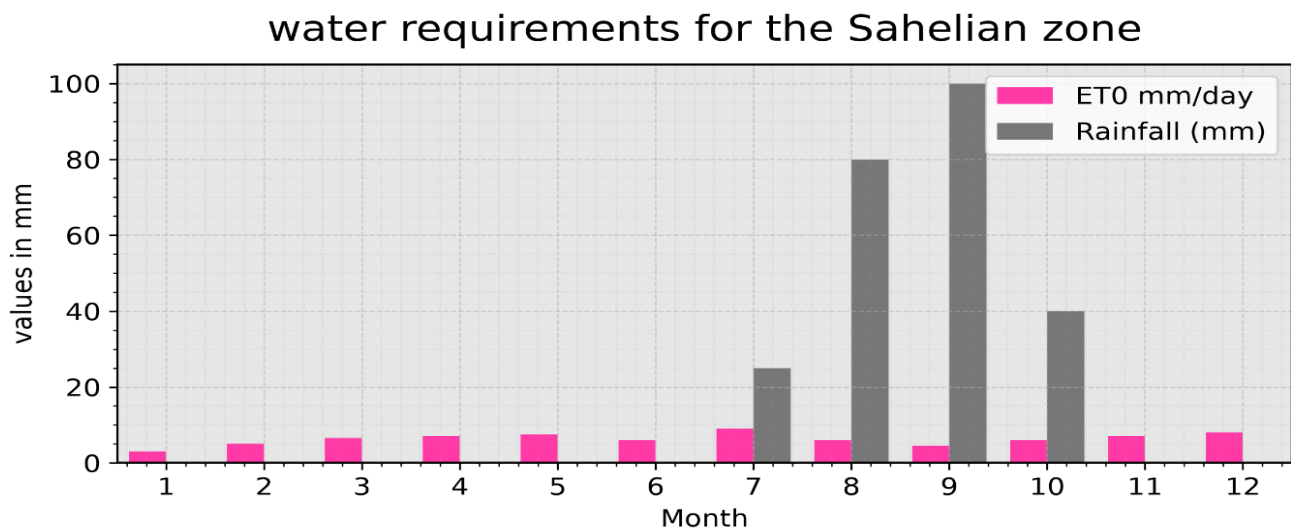


Figure 9. Water requirements in the Sudanian zone.

Figure 9 shows that in the Sahelian zone, effective rainfall ranges from 30 to 130 mm and lasts for four months, from June to October. Effective rainfall exceeds evapotranspiration from June to September.

3) Water Requirements in the Sudanian Zone

Figure 10 shows that the Sudanian zone experiences effective rainfall ranging from 70 to 1200 mm over a six-month period, from May to October. Effective rainfall exceeds evapotranspiration from May to October.

In the Sahelian and Sudanian zones, effective rainfall significantly exceeds evapotranspiration during the rainy season, except in the Saharan zone, where evapotranspiration dominates year-round.

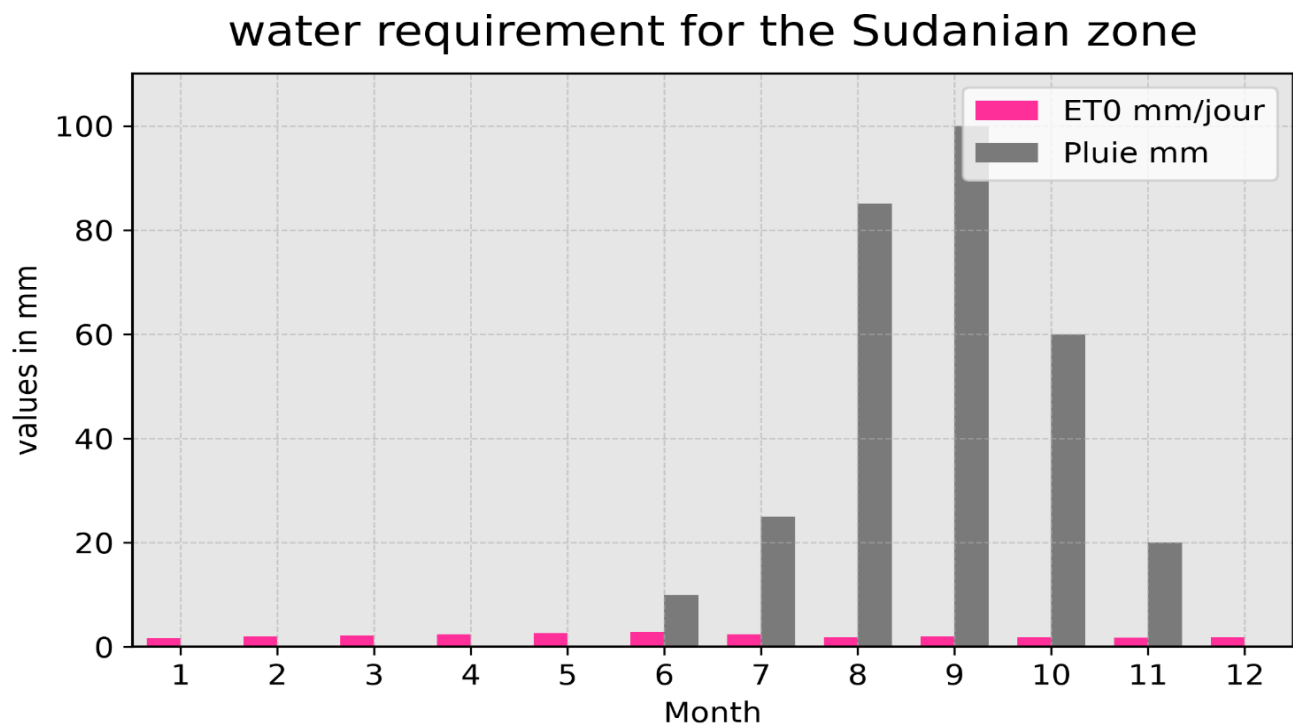


Figure 10. Water requirements in the Sahelian zone.

4.4. Irrigation Requirements

Evapotranspiration is a key parameter for determining irrigation rates and schedules, as well as for planning and managing irrigation water in agriculture [29]. It represents the total amount of water transferred from the soil-plant complex to the atmosphere through evaporation from the soil surface and physiological transpiration by plants. Evapotranspiration rates for Maralfalfa across Chad's various climatic zones, as calculated by Cropwat models, are shown in **Figure 9** through **Figure 10**.

1) Irrigation Needs in the Sahara Zone

Figure 11 shows that in the Sahara region, water demand (irrigation requirement) equals evapotranspiration, except in mid-November, when evapotranspiration is strongly dominant (irrigation is required year-round).

2) Irrigation Needs in the Sahelian Zone

Figure 12 shows that in the Sahelian zone, water demand matches evapotranspiration, except from May to October, when evapotranspiration is higher due to the rainy season. Irrigation also takes place throughout the year.

3) Irrigation Needs in the Sudanian Zone

Figure 13 shows that in the Sudanian zone, water demand equals evapotranspiration, except during the rainy season. During the rainy season, precipitation is very high, and evapotranspiration is negligible—meaning no irrigation is required from May to December (due to high relative humidity).

The study shows that irrigation for the plant in question depends on water requirements; specifically, the plant's water demand equals its evapotranspiration, except during the rainy season, when water demand is significantly lower.

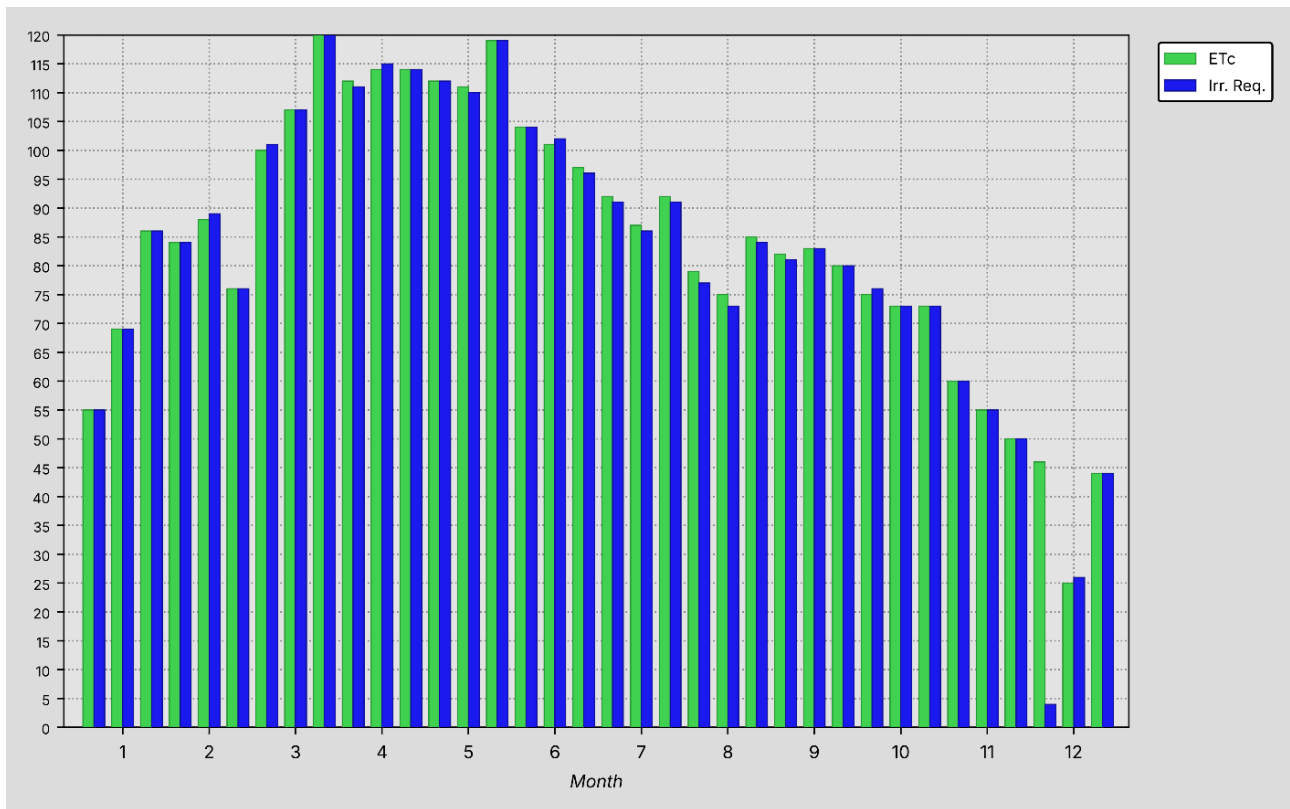


Figure 11. Irrigation and evapotranspiration in the Sahara region.

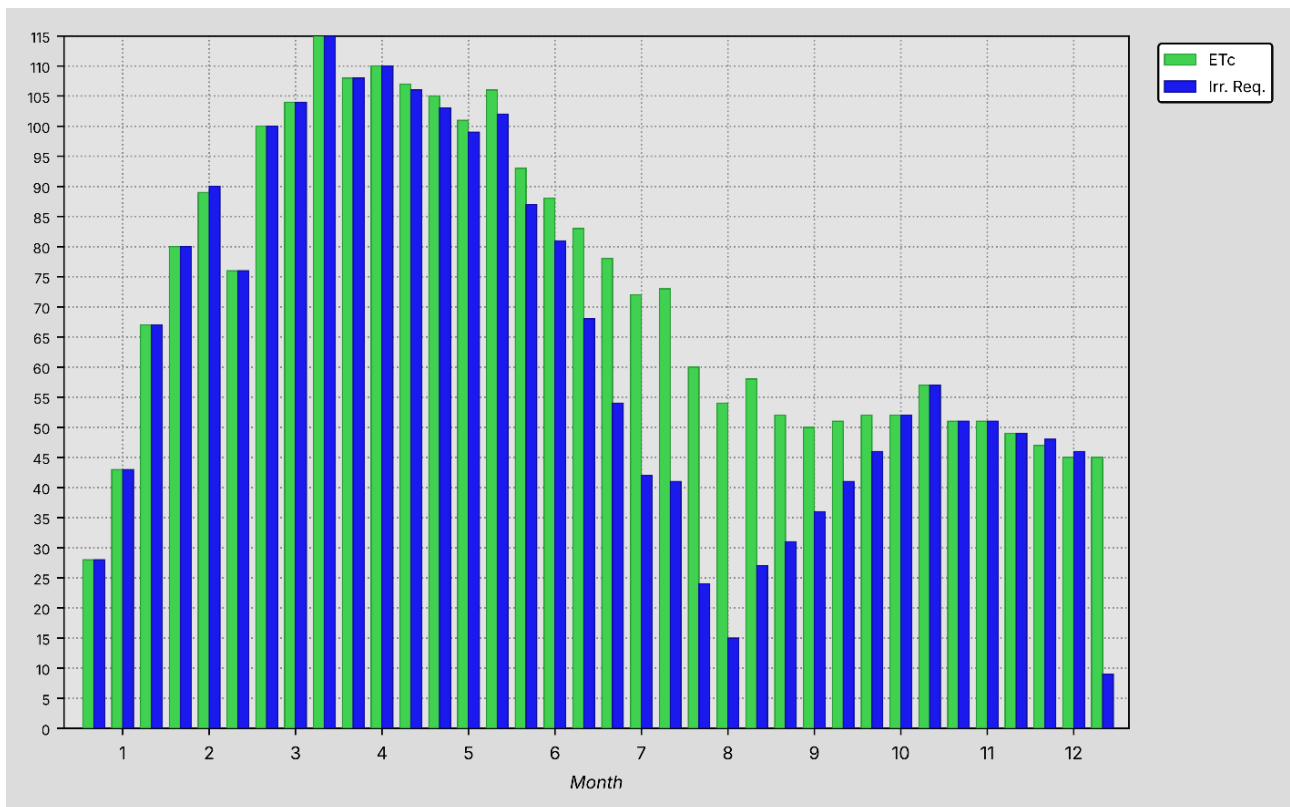


Figure 12. Irrigation and evapotranspiration in the Sahelian zone.

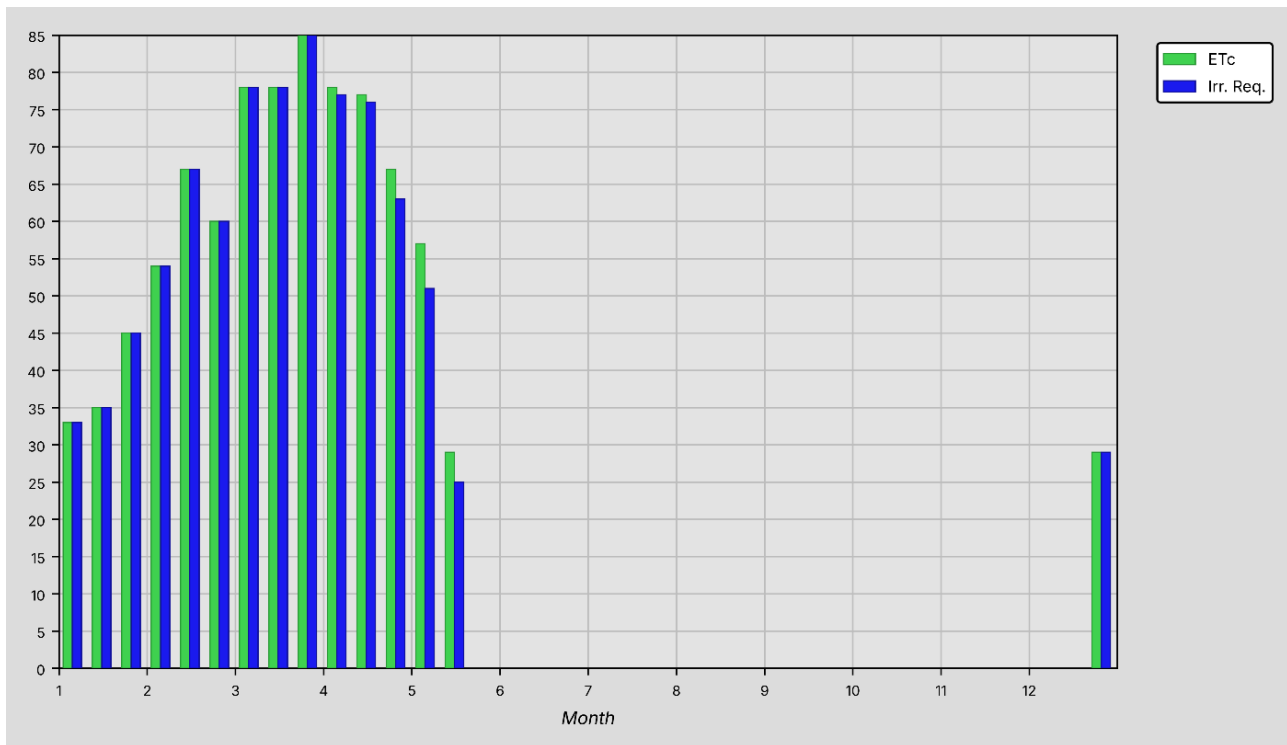


Figure 13. Irrigation and evapotranspiration in the Sudanian zone.

4.5. Soil Water Retention

This refers to the quantity of water required during each irrigation event to replenish the soil water reservoir, supply the plant, and compensate for evapotranspiration [30].

1) Soil Water Retention in the Saharan Zone

Figure 14 shows that soil in the Sahara zone does not retain water. Irrigation efficiency is 90%; therefore, the appropriate irrigation technique is drip irrigation with a very high frequency.

2) Soil Water Retention in the Sahelian Zone

Figure 15 shows that soil in the Sahelian zone has low water retention capacity; given an irrigation efficiency of 90%, the appropriate irrigation technique is drip irrigation with moderate frequency.

3) Soil Water Retention in the Sudanian Zone

Figure 16 shows that soil in the Sudanian zone retains more water when irrigation efficiency is 70%. The irrigation technique used is surface irrigation with very low irrigation frequency.

In the country's northern Saharan zone, the sun is intense, and the average temperature is 28.5°C. Crops require a significant amount of water—90.5 m³/day—in an environment characterized by 26% relative humidity, average solar radiation of 21.6 MJ/m²/day, and 9.1 hours of daily sunshine; given the sandy soil's poor water retention, drip irrigation offers 90% efficiency. The yield per cut is 15 t/ha.

The central Sahelian zone presents less extreme conditions, with an average temperature of 26.85°C, 32% relative humidity, solar radiation dropping to 18.9

MJ/m²/day, and 8.3 hours of daily sunshine; water requirements remain moderate at 63.3 m³/day. The soil is clay-loam, and drip irrigation achieves 90% efficiency. The yield per cut is 35 t/ha.

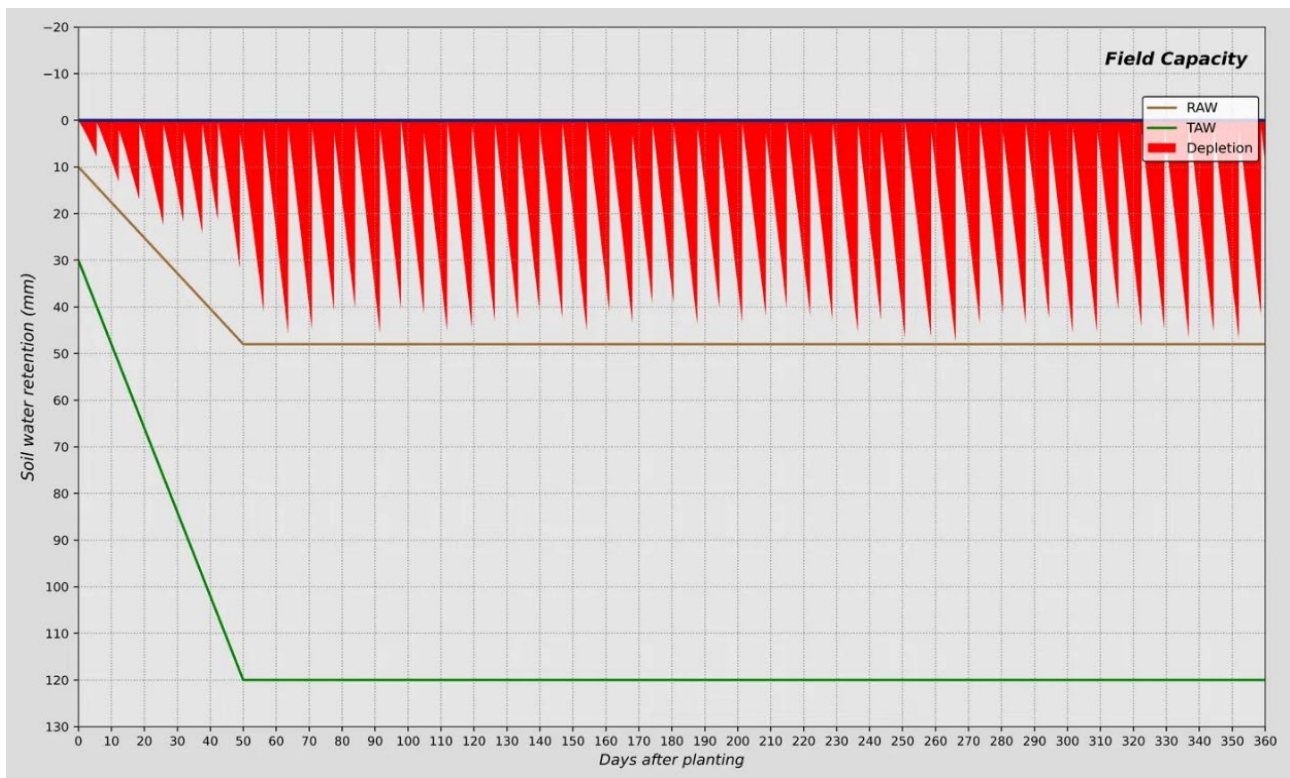


Figure 14. Soil water retention over time in the Sahara zone.

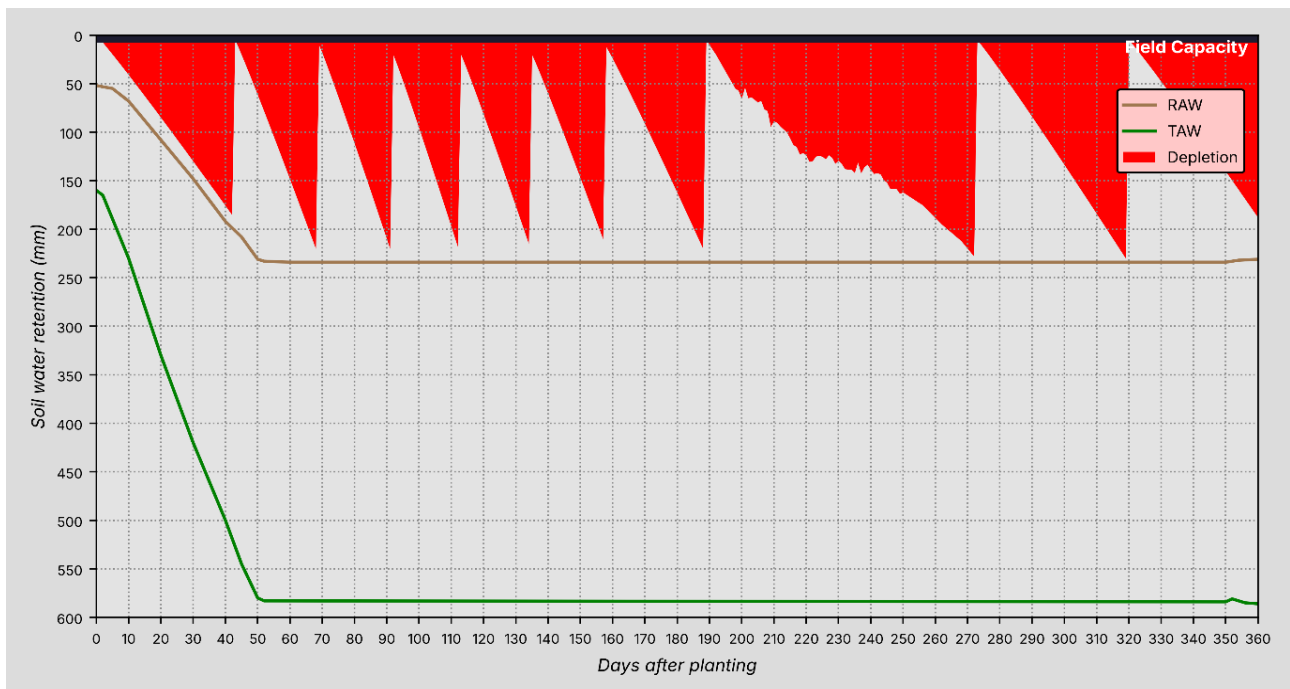


Figure 15. Soil water retention over time in the Sahelian zone.

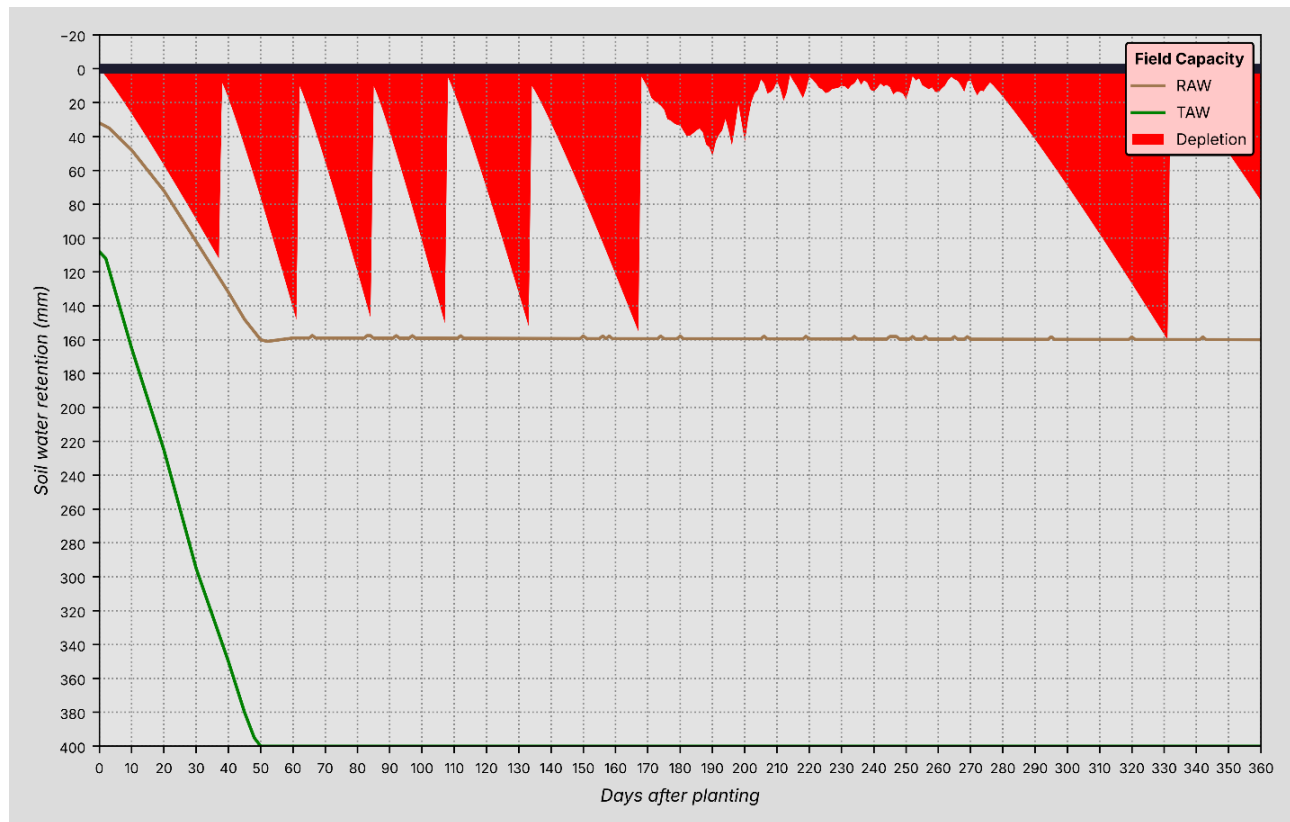


Figure 16. Soil water retention over time in the Sudanian zone.

The Sudanian zone features a more humid tropical climate, with an average temperature of 28.3°C, 39% relative humidity, and radiation of 20.8 MJ/m²/day with only 6.8 hours of sunshine. Water requirements are very low at 43.1 m³/day, and 70% efficiency favors surface irrigation. The yield per cut is 60 t/ha.

According to the study, the reference yield in the Sahelian zone for a one-hectare plot comprising 30% tomatoes and potatoes and 70% Maralfalfa grass ranges from 175 to 245 t/ha/year. During the dry season (November to June), harvesting occurs every 45 days, yielding 23.75 tonnes of fresh forage per cut. Yields reach their peak; harvests can amount to as much as 35 tonnes from 70% of the field area. On an annual basis, this corresponds to 350 t/ha/year in the Sahelian zone.

In the Sahara region, on a one-hectare field planted with 30% tomatoes and potatoes and 70% Maralfalfa, the Saharan climate is ideal during winter, characterized by cool nights and dry air. As a forage crop, Maralfalfa is harvested every six weeks (45 days), yielding 13 tonnes of fresh fodder per cut, with harvests reaching up to 15 tonnes during peak productivity periods. Over the course of the year, total forage production amounts to 120 tonnes/ha/year.

In the Sudanian zone, the period from day 0 to 170 is the dry season, requiring irrigation; from day 170 to 310 is the rainy season (June to November), during which there is no water deficit—meaning no irrigation is needed. Maralfalfa is harvested every 45 days, yielding 60 t/ha per harvest, resulting in a total annual production of 480 t/ha.

Table 9 shows the required water level and the net monthly irrigation volume needed to supply a field consisting of 70% Maralfalfa and 30% tomatoes and potatoes.

Table 9. Summary table.

Month	Net Irrigation Height(Maralfalfa) in mm	Volume Required for Maralfalfa (7,000 m ²) in m ³	Volume Required for Tomatoes/Potatoes (3,000 m ²) in m ³	Total Net Volume to be Pumped (m ³ /Month) in Mm
January	138	966	360	1326
February	245	1715	540	2255
March	319	2233	0	2233
April	325	2275	39 (semi-tardif)	2314
May	308	2156	120	2276
June	248	1736	150	1886
July	137	959	60	1019
August	66	462	0 (fortes pluies)	462
September	108	756	90	846
October	156	1092	240	1332
November	152	1064	300	1364
December	104	728	180	908
Total Annuel	2306	16,142	2079	18,221

The solar system under study relies on solar energy. Peak water demand is 7.5 mm per day for a one-hectare field planted with 70% Maralfalfa and 30% tomatoes and potatoes; in the Saharan and Sahelian zones, a drip irrigation technique achieves 90% efficiency, with respective water requirements of 90,532 m³ and 63.34 m³, whereas the Sudanian zone operates at 70% efficiency using sprinkler irrigation, requiring 43.07 m³ of water.

In the Sahelian zone, an Analysis of the one-hectare field reveals significant seasonal variation in water requirements, with a substantial demand of 2,314 m³ in April. This demand is largely driven by Maralfalfa, a forage crop covering 70% of the area, whose daily water consumption ranges from 2.8 mm during the initial phase in December to a peak of 11.8 mm at the height of the dry season (March-April), before dropping to 7.5 mm during the rainy season in July and August. By combining these growth patterns with the shorter cycles of the vegetable crops occupying the remaining 30% of the field, and factoring in natural precipitation simulated using CROPWAT, a precise map of required water inputs is obtained.

The Sahara zone, with constant sunshine exceeding 9.1 hours per day, allows for a benchmark yield of 150 tonnes/ha/year, based on regular harvests of 13 to 15 tonnes of fresh forage every six weeks. Evapotranspiration rates of 6.5 to 10 mm/day and irrigation requirements reaching 120 mm per ten-day period necessitate massive, regular irrigation. In contrast, the Sudanian zone is a humid tropical area with

significant rainfall that eliminates the need for irrigation entirely, offering a yield of 60 tonnes/ha per harvest.

Due to low sunlight and high humidity driven by evapotranspiration from 70% of the forage crop, which fosters disease, vegetable yields remain moderate across all three zones, ranging from 30 to 40 tonnes per year.

4.6. Tank Capacity

In this study, the water storage is sized such that the reservoir volume equals 20% of the total volume of pumped water: 18.10 m³ in the Saharan zone, 12.66 m³ in the Sahelian zone, and 8.61 m³ in the Sudanian zone.

4.7. Selection of the Photovoltaic Solar Module

Regarding system operation, the choice fell on high-performance polycrystalline solar panels—specifically the SL250CE-36P model. It is fascinating to observe how power requirements decrease as one moves southward into the humid tropical zone. In the Sahara zone, characterized by very high temperatures and low rainfall, the system installation must be robust, requiring 18 modules for a powerful 4.5 kW pump. In the Sahelian zone, where temperatures and rainfall are moderate, 12 panels are needed for a 2.8 kW pump; meanwhile, in the Sudanian zone, characterized by lower temperatures and high rainfall, only 8 panels are required to operate a 1.8 kW pump.

The pump operating curve in the different climatic zones of Chad

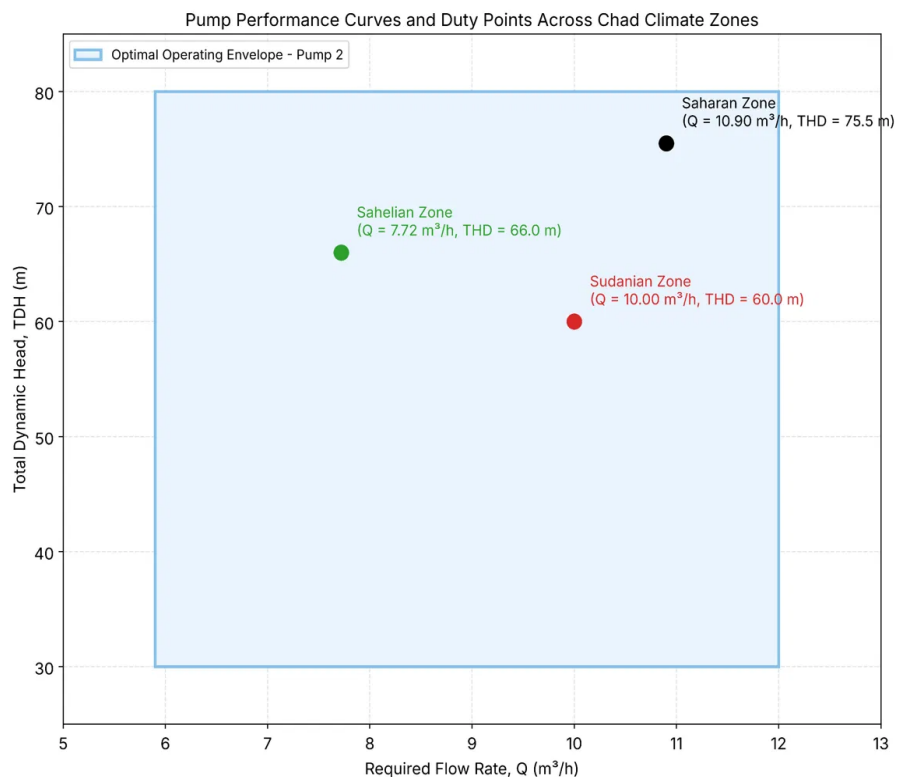


Figure 17. Pump operating curve.

Figure 17 shows the pump operating curve for the various climatic zones in Chad:

In the Saharan zone, the operating point lies perfectly at the center of the blue operating range for Pump 2 (model PS2-4000 C-SJ8-15), despite a high Total Dynamic Head (TDH) of 75.5 m. This pump delivers a flow rate of 10.90 m³/h, which is necessary to offset extreme desert evapotranspiration. The system is optimally sized for 18 panels.

In the Sahelian zone, the operating point falls in the middle of the blue rectangle for Pump 2. Given the moderate water demand, the pump delivers 7.72 m³/h at a TDH of 66 m, achieving maximum efficiency with 12 panels.

In the Sudanian zone, the operating point falls perfectly within the efficiency range. The pump delivers 10 m³/h at a Total Dynamic Head of 60 m; the system operates perfectly with 8 photovoltaic solar panels.

4.8. Summary of Results

The Saharan zone is characterized by harsh conditions—an average temperature of 28.5°C and only 26% relative humidity and a significant daily water requirement of 90.53 m³. The system utilizes a 4.5 kW pump and 18 solar panels, enabling the pump to overcome a total dynamic head of 75.5 m while maintaining a nominal flow rate of 10.90 m³/h. An efficiency rate of 90% dictates the use of a drip irrigation system supplied by an 18.10 m³ water storage tank.

In the Sahelian zone, the climate is more moderate, with a daily water requirement of 63.34 m³. The system operates with a power output of 2.8 kW and 12 solar panels, delivering a flow rate of 7.72 m³/h against a total dynamic head of 66 m; the storage tank capacity is 12.66 m³. This represents a yield of 350t/ha/year.

In the Sudanian zone, an efficiency rate of 70% leads to the selection of sprinkler irrigation, requiring 43.07 m³ of water per day. Pump power is reduced to 1.8 kW via 8 solar panels, paired with an 8.61 m³ storage tank; the pump delivers a flow rate of 10 m³/h at a total dynamic head of 60 m (**Table 10**).

Although these projections appear modest, literature and field trials conducted in Chad at IRED or the ACCEPT farm in 2021 demonstrate that this forage crop can yield over 200 t/ha/year with eight annual cuttings, thereby validating the crop's high potential across the studied zones.

Table 10. Summary of results.

Zone	Water Needs (m ³ /day)	Sunstroke (h/day)	Relative Humidity (%)	Time (°C)	Efficiency (η)	Radiation mj/m ² /day	Etc Net (mm/day)	Yield Per Cut (t/ha/year)
Saharan	90.532	9.1	26	28.5	90%	21.6	8.15	15
Sahelian	63.34	6.8	32	26.85	90%	18.9	5.7	35
Sudanian	43.07	8.3	39	28.3	70%	20.8	3.02	60

The main conclusion is that a solar-powered irrigation system operating in sync with the sun demonstrates that a unified technical approach can effectively ad-

dress climatic variations, particularly regarding relative humidity and average temperature, while also enabling the selection of an irrigation technique perfectly suited to the terrain.

4.9. Discussion of Results

The unified solar photovoltaic pumping system—based on the PS2-4000 C-SJ8-15 pump model—demonstrates perfect technical suitability for the agro-climatic realities of Chad's various climatic zones. This strategy relies on modeling the solar panel array (using SL250CE-36P polycrystalline modules) and sizing storage volumes based on zonal climatic gradients and irrigation efficiency. To meet a peak water requirement of 7.5 mm/day for a plot comprising 70% Maralfalfa and 30% market garden crops, the system operates primarily during the six hours of optimal daily sunshine. In the Saharan zone, characterized by an extreme climate (average temperature of 28.5°C, relative humidity of 26%) and a water demand of 90.53 m³/day, a 4.5 kW system equipped with 18 panels enables the pump to overcome a total dynamic head of 75.5 m while maintaining a nominal flow rate of 10.90 m³/h; this setup utilizes drip irrigation (90% efficiency) and an 18.10 m³ storage tank, achieving a yield of 15 t/ha per cut, or 120 t/ha/year. In the Sahelian zone, where environmental conditions are more moderate and water demand stands at 63.34 m³/day, the system is powered by a 2.8 kW pump paired with 12 panels; This configuration provides a flow rate of 7.72 m³/h at a total dynamic head of 66 m, requiring a 12.66 m³ reservoir and enabling a yield of 350 t/ha/year—or 35 t/ha per six-week cut. Under Sudanian climatic conditions, a 70% efficiency rate allows for the use of a sprinkler irrigation system requiring 43.07 m³ of water per day; this entails a pumping power of 1.8 kW, supplied by 8 solar panels, and an 8.61 m³ storage reservoir. The pump delivers a flow rate of 10.00 m³/h at a total dynamic head of 60 m, resulting in a yield of 60 t/ha per 45-day cut and an annual yield of 480 t/ha.

This configuration demonstrates that a single, appropriately sized pump model can provide a highly resilient technical and economic solution to meet the water needs of Chad's various climatic zones.

5. Conclusions

Simulations show that in the Saharan zone—characterized by an extreme climate (average temperature of 28.5°C, relative humidity of 26%) and a water requirement of 90.53 m³/day—a 4.5 kW system comprising 18 panels enables the pump to overcome a total dynamic head of 75.5 m while maintaining a nominal flow rate of 10.90 m³/h; this setup utilizes drip irrigation (with 90% efficiency) and an 18.10 m³ storage tank, achieving a yield of 15 t/ha per cut every six weeks, or 120 t/ha/year. In the Sahelian zone, where environmental conditions are milder and the water requirement is 63.34 m³/day, the system is powered by a 2.8 kW pump coupled with 12 panels; this configuration delivers a flow rate of 7.72 m³/h against a total dynamic head of 66 m and requires a 12.66 m³ storage tank, enabling a crop

yield of 350 t/ha/year based on 35 t/ha per 45-day cut. Under a Sudanian climate, a 70% efficiency rate allows for the use of a sprinkler irrigation system requiring 43.07 m³ of water per day; this entails a pumping power of 1.8 kW, supplied by 8 solar panels, and an 8.61 m³ storage tank. The pump delivers a flow rate of 10.00 m³/h against a total dynamic head of 60 m... representing a simulated yield of 60 t/ha every 45 days, or 480 t/ha/year.

The evaluation of this solar irrigation system demonstrates that a unified technical approach effectively addresses Chad's stark climatic contrasts. Irrigation performance depends not only on the system itself but also requires techniques adapted to the terrain and a thorough consideration of climatic factors, particularly relative humidity and average temperature. This study presents a new decision-support tool for solar photovoltaic irrigation applied to Maralfalfa forage cultivation. It stands out by focusing on a crop that is essential to livestock farming yet often overlooked by research. Furthermore, it goes beyond conventional models by developing configurations tailored to Chad's various climatic zones, thereby enabling optimization aligned with actual field conditions.

Author Contributions

Yacoub Nassian Nimir designed the study and defined its methodology. He carried out data collection, performed simulations, analyzed the results, and wrote the manuscript. Moussa Ahmat participated in data collection and provided input on the interpretation of the results. Haroun Abba Laban was responsible for the development and programming of the computational tools, as well as the validation of the results. Djongyang Noël and Mackaye Hassan Taïso supervised the research and were directly involved in developing the methodology and validating the findings. All authors contributed to the interpretation of the data and reviewed, revised, and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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