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CONCEPTUAL ANALYSIS AND PROTOTYPICAL DESIGN OF A REAL-TIME CROP WATER DEMAND MONITORING SYSTEM FOR IRRIGATION: CASE STUDY OF AN AGROPHOTOVOLTAIC SYSTEM IN MALI

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CONCEPTUAL ANALYSIS AND PROTOTYTICAL DESIGN OF A REAL-TIME CROP WATER DEMAND MONITORING SYSTEM FOR IRRIGATION: CASE STUDY OF AN AGROPHOTOVOLTAIC SYSTEM IN MALI

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DEDICATION

To Allah Almighty, I give all the credit.

I could never find the exact action to honor my late father, Nouroudin DJIBRIL, and my grandmother Adjara TRAORE who both laid the foundation of my first steps to the academic journey, my loving mother Naliétou ADHRIKAH, To my grandfather Ibrahim DJIBRIL, and all my siblings.

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ABSTRACT

The emergence of new technologies such as internet of things, wireless communication, affordable microcontrollers, and sensors facilitates the optimization of water use. This advancement in technology is an opportunity for the west African countries and the rest of the African continent to move from rainfall dependent farming to an autonomous and irrigated farming system. The transfer to irrigation systems may lead the continent to new issues such as competition between food, energy and water production and unsustainable resource usage. An innovative approach to solve this problem is the implementation of Agrophotovoltaic (APV) system. To ensure water and energy usage efficiency of an APV system, a smart irrigation system needs to be set up. This study will focus on the design of an integrated irrigation management system that will allow minimum interaction of farmers on fields and ensure appropriate and real-time crop water need monitoring and water allocation for optimal crop production. Different data was first collected to establish a proper irrigation scheduling using the FAO CROPWAT 8.0 software. The established irrigation scheduling allows the evaluation of the designed real-time crop water monitoring system. With the hardware consisting of two sensors, communication devices, a pump, a power unit on one hand, and a web-based software (Vegecloud) on the other hand, the remote access and control of crop water requirement through the visualization of data gathered by sensors was achieved. The developed system was able to ensure real-time crop water need monitoring by allowing an instant data collection, transferring, processing and analysis based on the data representation illustrated on Vegecloud.

RESUMÉ

L'émergence de nouvelles technologies telles que l'Internet des objets, les communications sans fil, les microcontrôleurs abordables et les capteurs facilite l'optimisation de l'utilisation de l'eau. Cette avancée technologique est une opportunité pour les pays d'Afrique de l'Ouest et le reste du continent africain de passer d'une agriculture dépendante des précipitations à un système agricole autonome et irrigué. Le transfert vers les systèmes d'irrigation peut conduire le continent à de nouveaux problèmes tels que la concurrence entre la production de nourriture, d'énergie et d'eau et l'utilisation non durable des ressources. Une approche innovante pour résoudre ce problème est la mise en œuvre du système agrophotovoltaïque (APV). Pour garantir l'efficacité d'utilisation de l'eau et de l'énergie d'un système APV, un système d'irrigation intelligent doit être mis en place. Cette étude se concentrera sur la conception d'un système intégré de gestion de l'irrigation qui permettra une interaction minimale des agriculteurs sur les champs et assurera une surveillance appropriée et en temps réel des besoins en eau des cultures et une allocation de l'eau pour une production agricole optimale. Différentes données ont d'abord été collectées pour établir un calendrier d'irrigation approprié à l'aide du logiciel FAO CROPWAT 8.0. La programmation d'irrigation établie permet l'évaluation du système de surveillance de l'eau des cultures en temps réel conçu. Avec le matériel composé de deux capteurs, d'appareils de communication, d'une pompe, d'une unité d'alimentation d'une part et d'un logiciel Web (Vegecloud) d'autre part, l'accès et le contrôle à distance des besoins en eau des cultures grâce à la visualisation des données recueillies par des capteurs a été atteint. Le système développé a pu assurer une surveillance en temps réel des besoins en eau des cultures en permettant une collecte, un transfert, un traitement et une analyse instantanés des données sur la base de la représentation des données illustrée sur Vegecloud.

ABBREVIATIONS AND ACRONYMS

API	Application Programming Interface
APV	Agrophotovoltaic
CRW	Crop Water Requirement
EPDM	Ethylene-Propylene- Diene Monomer
ET	Evapotranspiration
ET_C or ET crop	Actual Crop Evapotranspiration
ET_O	Reference Evapotranspiration
FAO	Food and Agriculture Organization
FC	Field Capacity
IA	Irrigation Association
ICT	Information and Communication Technologies
IN	Irrigation water need
IoT	Internet of Things
IP	Internet Protocol
K_C	Crop Coefficient
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
PA	Precision Agriculture
PDI	Proportional–Integral–Derivative
Pe	Effective rainfall
PV	Photovoltaic
WSNs	Wireless Sensor Networks

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1. INTRODUCTION

1.1. Background of Study

Water, energy, and food are fundamental fuels of development. The shortage of one of the three resources can seriously slow the sustainable development and lead to the vulnerability of other resources necessary to ensure a durable growth. Considering the susceptibility of our water, energy, and food systems to forecast climatic change, building adaptability in food production and renewable energy is a primary challenge (Barron-Gafford et al., 2019).

Mali is located in Sahel region and the agriculture sector of the country is heavily dependent on rainfall, rainwater management technologies are not developed in both countries. Thus, the agriculture sector in Mali remains so vulnerable to climate change. According to (USAID, 2017), Sahel is the world’s most environmentally degraded region and most vulnerable to climate change, with temperature increase of 1.5 times higher than the rest of the world.

In Africa, only 6% of cultivable land is irrigated. Only 4% of the Sub-Saharan Africa’s arable lands are irrigated. That means that 97% of the continent’s agricultural land relies on rainfall (FAO, 2008). There is therefore the need of development of irrigation technologies and the implementation of innovative approaches that could not only increase the crop yield but also ensure the sustainability of water and energy resources of the continent. The land use factor also must be considered as the arable land is in rapid decrease because of desertification and socio-economic development.

Th APV system has never been implemented in West African countries especially in the dry sunny and hot Sahel region where most agricultural crops can be expected to give higher yield as crop will benefit from the protection of solar panels against severe weather conditions. The APV system will provide the possibility for rainwater harvesting, this may end the rainfall dependency of local farmers.

A proper response to the challenge mentioned above will be to build resilience by maintaining growth in all sectors (food, energy and water), which is quite challenging because of the competition between food, electricity supply and water usage. The Agrophotovoltaics system may be a sustainable solution to this problem as it allows the colocation of agriculture and solar photovoltaics (PV) facilitating a close monitoring of all the resources involved.

The APV system has never been implemented in West African countries especially in the dry sunny and hot Sahel region where most agricultural crops can be expected to give higher yield as crop will benefit from the protection of solar panels against severe weather conditions. The APV system will provide the possibility for rainwater harvesting, this may end the rainfall dependency of local farmers. To guarantee the productivity and the sustainability of the farm, a smart farm monitoring system needs to be set up.

Current technologies in particular sensors and opensource software in the domain of weather prediction and agricultural management has tremendously reduce the costs related to the application of the internet of things (IoT). The introduction of efficient agricultural methods through the use of real-time monitoring systems becomes accessible.

Putting in place a decision-making support system for farm irrigation and allowing remote accessibility of different users require the production, transfer, storage and processing of data. The use of wireless sensor networks (WSNs) and long-range wide-area network (LoRaWAN) technologies. Digital agriculture utilizes smart networks and data processing devices and software to make possible the computerization of farming activities (Borrero & Zabalo, 2020).

The implementation of precision agriculture (PA) is pass thought a close monitoring of soil and weather parameters. The irrigation frequency and the amount of water to be applied are the main guidelines when it comes to ensuring adequate irrigation scheduling. The actual evapotranspiration (ET_c) is the main values that governs the overall irrigation system. The application of sensor (soil moisture, temperature, water level, etc.) is meant to provide extra information to facilitate the process of setting up an effective irrigation schedule (Capraro, Tosetti, Rossomando, Mut, & Vita Serman, 2018).

1.2. Problem statement and justification

Mali like any sub-Saharan African country is considerably affected by the negative effects of climate change which leads the country to extreme poverty. Mali has always made food security and poverty eradication their priorities. This has increased the need for sufficient water supply for agricultural irrigation and therefore food production. A sustainable food and water supplying systems obviously require a climatic resilient energy source (renewable energy) and sound water demand monitoring system.

One of innovative approaches to address these challenges is the implementation of Agrophotovoltaic (APV) systems that will provide food, water, and electricity to the local population while increasing the resilience of the agriculture sector against climate change. The implementation of the system will involve the irrigation of multiple crops, a rainwater harvesting system, and an APV demonstration plant. To ensure the efficiency, profitability, and sustainability of the farm, an integrated and efficient farm management system needs to be put in place.

The emergence of new digital technologies such as the internet of things, and low-cost sensors provide an opportunity to optimize the use of available resources (water, energy), allow the interconnection of the different elements of the farm, and generate enough data to inform decisions regarding farm's irrigation, and remotely control and supervise farm's activities. The question is how to reduce the interaction of farmers on the field while guaranteeing an efficient and real-time water distribution in an environment with low internet and information technologies access. A commixture of water engineering, computer sciences, electronics and ICT system engineering skills is needed for the better solving of this problem.

1.3. Objectives

1.3.1. Main objective

The main objective of this study is to design an integrated management system that will allow the minimum interaction of farmers on the fields and ensure appropriate and real-time crop water monitoring and water allocation in the farm through irrigation for optimal crop production.

1.3.2. Specific objectives

The specific objectives of this research are as follow:

(i) Review the current irrigation water management methods and different parameters monitored to ensure efficient water use

(ii) Propose a convenient irrigation schedule that will ensure precise amount of water is supplied to crops at the right moment

(iii) Propose a system architecture design for an efficient water use

(iv) Make an appropriate selection of different elements of the system and build a prototype

1.4. Research questions

(i) What are the current irrigation water management methods and what are the different parameters monitored to ensure efficient water use?

(ii) What is the convenient irrigation schedule for the farm?

(iii) How the mixture of recent IoT and Wireless Sensor Network (WSN) technologies can ensure an efficient water use?

(iv) How can we build a real-time crop water need monitoring system through the integration of hardware and software based on WNS?

1.5. Scope and limitations

The study focuses on the technological part of the automatic irrigation system, which will be part of the whole farm management of an APV system. This work targets the use of IoT and WSNs systems to monitor the crop water need of an APV system to be implemented in Katibougou. This study will contribute to prove the feasibility of a real-time water crop demand monitoring system in a region with low internet access terms of contributing to a more ecological and socio-economic sustainable development of the beneficiary countries. By opening the door to the discovery of challenges and opportunities of the implementation of IoT and WSNs systems for agricultural purposes, this study will trigger the use of advanced technologies in the west African agricultural sector. This work will fulfil its major goal of contributing to the UN agenda 2030 “SDGs” (SDG 1, 2, 7, 13 and 15) as well as the

African Union agenda 2063 (Aspiration 1: A prosperous Africa based on inclusive growth and sustainable development).

At the end of this study, the suggested prototype can be used for different use cases where the user can add sensors or actuators according to his need but though the real-time crop water need monitoring system was tested successfully, a complete evaluation of the prototype require data collection during a long period.

2. LITERATURE REVIEW

2.1. Introduction

In this chapter a broad review of literature on the context of crop water need, real-time crop water monitoring systems and approaches is addressed. While the first part is mainly about the crop water need and irrigation management strategies, in the second part of this chapter, the topic of irrigation scheduling and real-time (smart) crop water need monitoring system is widely discussed.

2.2. Crop water requirement (CWR)

The crop water demand is the amount of water required by a crop to grow optimally. That amount of water is supplied thought rainfall alone in certain situation and through irrigation and rainfall in the situation where the effective rainfall less than the crop water demand (CWR) or ET crop. The CWR is influenced by certain factors such as climate, crop type and growth level of the crop (C. Brouwer & M. Heibloem, 1986).

Crop evapotranspiration and crop water demand have the same value since the amount of water consumed by the crop during its growth is considerably small compare to the amount of water lost through evapotranspiration (R.-S. Wu, Liu, Chang, & Hussain, 2017). Crop water demand can be obtained by directly integrating the crop resistance albedo and air resistance factors in the Penman-Monteith method (Richard G. Allen, Luis S. Pereira, Dirk Raes, & Martin Smith, 1998). The amount of water required by a crop depends on the crop growth stage, crop type and the meteorological data. At the initial stage, crop water need is low but as crop grows, its demand in water also increases up to flowering stage. When the crop becomes mature, its crop water requirement decreases (Intergovernmental Panel on Climate Change, 2014).

The irrigation water needs is calculated from the equation given below (C. Brouwer & M. Heibloem, 1986).

$$IN = ET\ crop - Pe \qquad (1)$$

Where (IN) is the irrigation water need, (ET crop) the crop evapotranspiration and (Pe) the effective rainfall. In his thesis, (Kennedy Ochieng Okuku, 2016) has derived the crop water requirement (CWR) from the equation (1) above. He has pointed out that IN can be calculated from the equation (2) below.

$$CWR = IN + Pe \tag{2}$$

From the equation (1) and (2) , the equation (3) can be deduced.

$$CWR = ET\ crop \tag{3}$$

From the equation (3) proves that the values for crop evapotranspiration and the crop water need are the same. This equality is also confirmed by (Richard G. Allen et al., 1998).

2.3. Evapotranspiration

Expressed in millimeter (mm) per unit time, evapotranspiration is a mixture of two processes (evaporation and transpiration) leading to water loss from the plant and the soil. Evaporation and transpiration occur concurrently and distinguishing between both phenomena is difficult. When crop is at its early stage of development, evaporation is the most significant process through which crops loss water to the atmosphere. During the development stage, crops loss water though the mechanism of transpiration (Richard G. Allen et al., 1998).

Evaporation is the process leading to the transformation of the state of water noticeable by its removal from a surface (rivers, soils, pavements, ...). This process is also known as vaporization. The direct solar radiation is the main source of energy for evaporation. The degree of crop shading and the water availability are two main factors that influence the evaporation rate (Richard G. Allen et al., 1998).

Transpiration on the other hand is the vaporization of liquid water from inside the crop tissues (mostly stomata) and the vapor depletion in the atmosphere. Factors such as radiation, air temperature, air humidity, wind speed, vapor pressure should be considered while determining the transpiration (Richard G. Allen et al., 1998).

2.4. Crop evapotranspiration (ET_C)

A proper estimation of crop evapotranspiration (ETc) can help farmers in their struggle to increase agricultural water use efficiency (T. Wang et al., 2021). When determining the ETo, the reference surface (grass) with unlimited amount of water is considered but when the crop evapotranspiration is calculated factors such as ground cover, aerodynamic resistance and canopy properties of the crop are considered. These factors can be regrouped into one coefficient termed crop coefficient Kc (Richard G. Allen et al., 1998). Depending on the available data, various methods are used in the determination of the ETc.

2.4.1. Reference crop evapotranspiration (ETO)

The reference crop evapotranspiration is the estimated water usage from a reference surface with (hypothetical grass reference crop) (Kennedy Ochieng Okuku, 2016; Richard G. Allen et al., 1998). The ETo is a crucial parameter for a clear-cup crop water content monitoring (Z. Wu et al., 2020). The term reference evapotranspiration refers to the evapotranspiration rate of the atmosphere separately from the crop type, crop development stage and management practices.

There are many approaches leading to the computation of the ETo but the FAO Penman-Monteith model has the highest accuracy (Z. Wu et al., 2020). Since ETo is only affected by climatic parameters, it can be calculated using weather data. The ETo is influenced by the location and the time as illustrated in the **Table 1**. Considered to be a only standard formula for ETo calculation according to (Richard G. Allen et al., 1998) , the FAO Penman-Monteith formula is given in the equation (4) below.

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T + 273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{4}$$

Where

ETo – Reference evapotranspiration [mm day^{-1}],

Rn – Net radiation at the crop surface [MJ m^{-2} day^{-1}],

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

T – Daily air temperature at 2 m height [^{o}C],

u2 – Wind speed at 2 m height [m s]-1,

e_S – Saturation vapor pressure [KPa],

e_a – Actual vapor pressure [KPa],

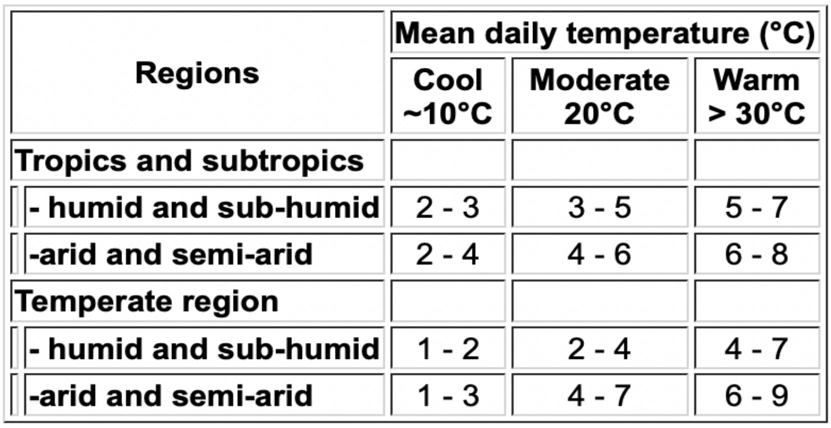
$(e_s - e_a)$ – Saturation vapor pressure deficit [KPa],

Δ – Slope vapor pressure curve [KPa $^{o}C^{-1}$],

γ – Psychometric constant [KPa $^{o}C^{-1}$].

From the equation (4), it is noticeable that the location data is not sufficient for the calculation of the ETo, data such as air temperature, humidity, radiation, and wind speed data for daily, weekly, ten-day, or monthly calculations. The Penman Monteith equation is obtained from the mixture of different equations containing some expression of different factors that participate in the determination of the ETo (Kennedy Ochieng Okuku, 2016).

Table 1. Average ETO for different agroclimatic regions in mm/day (Richard G. Allen et al., 1998)



Regions	Mean daily temperature (°C)		
	Cool ~10°C	Moderate 20°C	Warm > 30°C
Tropics and subtropics			
- humid and sub-humid	2 - 3	3 - 5	5 - 7
-arid and semi-arid	2 - 4	4 - 6	6 - 8
Temperate region			
- humid and sub-humid	1 - 2	2 - 4	4 - 7
-arid and semi-arid	1 - 3	4 - 7	6 - 9

2.4.1.1. Meteorological factors participating in the determination of ETo

The weather parameters which determine the evapotranspiration are presented below.

- ***Solar or shortwave radiation (R_s)***

The amount of energy leading to water vaporization is one of the factors that determine the evapotranspiration. Solar radiation is the most significant energy that transforms the physical state of water from liquid to gas (Richard G. Allen et al., 1998). The solar radiation is obtained from the formula shown below.

$$R_s = \left[0.25 + 0.5\frac{n}{N}\right] R_a \tag{5}$$

Where

R_S – Solar or shortwave radiation (MJ/m^2 per day)

n – Actual sunshine hours (hour)

N – Maximum possible duration of sunshine hours or daylight hours (hours) n/N – Relative sunshine duration

R_a – Extraterrestrial radiation (MJ/m^2 per day)

The solar radiation factor used in the equation (4) is the net radiation at the crop surface (R_n).

- ***Net radiation (R_n)***

The net radiation (R_n) is calculated from the equation (6) given below.

$$R_n = R_{ns} - R_{nl} \tag{6}$$

Where

R_n – Net radiation (MJ/m^2 per day),

R_{ns} – Net incoming shortwave radiation (MJ/m^2 per day),

R_{nl} – Net outgoing longwave radiation (MJ/m^2 per day).

- ***Soil heat flux (G)***

The soil heat flux (G) is a type of energy that participate in soil heating. It can be ignored although it is smaller than the R_n. The soil heat flux can be positive or negative depending on whether the soil is warming or heating the soil (Richard G. Allen et al., 1998). The soil heat flux is given by the equation (7) below.

$$G = C_s \frac{T_i - T_{i-1}}{\Delta t} \Delta z \tag{7}$$

Where

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

c_s soil heat capacity [MJ m^{-3} °C^{-1}],

T_i air temperature at time i [°C],

T_{i-1} air temperature at time i-1 [°C],

D t length of time interval [day],
D z effective soil depth [m].

- ***Main daily temperature (T_{mean})***

The main daily temperature is computed using the equation (8) shown below.

$$T_{mean} = \frac{T_{max} + T_{min}}{2} \tag{8}$$

Where

T_{mean} – Mean daily temperature (^{0}C),

T_{max} – Mean daily maximum temperature (^{0}C),

T_{min} – Mean daily minimum temperature (^{0}C).

- ***Psychrometric constant (γ)***

The psychrometric constant is given by the equation (9) below.

$$\gamma = \frac{C_p}{\mathcal{E}\lambda} = 0.665\ x\ 10^{-3}\ P \tag{9}$$

Where

γ – psychrometric constant [kPa °C^{-1}],
P – atmospheric pressure [kPa],
C_p – specific heat at constant pressure, 1.013 10^{-3} [MJ kg^{-1} °C^{-1}],
$\mathcal{E}$ – ratio molecular weight of water vapor/dry air = 0.622.

- ***Wind speed at 2m above the surface (u_2)***

The wind participates largely to evaporation process through the transfer of air to the evaporating surface. The wind speed increases with the high and is different at any level of measurement. For the computation of the ET_O, the wind speed at 2m above the surface is used (Richard G. Allen et al., 1998). The equation (10) given below allows the calculation of the wind speed at 2m above the surface.

$$u_2 = u_z \frac{4.87}{ln(67.8z - 5.42)} \tag{10}$$

Where

u_2 – wind speed at 2 m above ground surface [m s^{-1}],
u_z – measured wind speed at z m above ground surface [m s^{-1}],
z – height of measurement above ground surface [m].

- ***Mean saturation vapor pressure (e_s)***

The saturation vapor pressure is related to air temperature and its value, and its mean values are obtained respectively through the equation (11) and (12) shown below.

$$e^0(T) = 0.6108\, exp\left(\frac{17.27T}{T + 237.3}\right) \tag{11}$$

Where

e°(T) – saturation vapor pressure at the air temperature T [kPa],
T – air temperature [°C],
exp[..] 2.7183 (base of natural logarithm) raised to the power [..].

$$e_s = \frac{e^0(T_{max}) + e^0(T_{min})}{2} \tag{12}$$

- ***Actual vapor pressure (e_a)***

The actual vapor pressure can be calculated from the relative humidity, from the difference between the dry and wet bulb temperatures and from the dewpoint temperature (Richard G. Allen et al., 1998). (Kennedy Ochieng Okuku, 2016) has used the equation (13) derived the from relative humidity data to compute the (e_a). This is probably based on the type of data available in his case study.

$$e^a = \frac{e^0(T_{min})\frac{RH_{max}}{100} + e^0(Tmax)\frac{RH_{min}}{100}}{2} \tag{13}$$

Where

e_a – actual vapor pressure [kPa],
$e°(T_{min})$ – saturation vapor pressure at daily minimum temperature [kPa],
$e°(T_{max})$ – saturation vapor pressure at daily maximum temperature [kPa],
RH_{max} – maximum relative humidity [%],
RH_{min} – minimum relative humidity [%].

- ***Slope of saturation vapor pressure curve (Δ)***

The slope of saturation vapor pressure curve is purely dependent on the air temperature (T). The relationship is given by the equation (14).

$$\Delta = \frac{4098\left[0.6108\, exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \tag{14}$$

2.4.1.2. Crop growth stage

Conventionally, crop growth stage is determined manually through visual observation (Rasti et al., 2021). The crop growing period is divided into four different growth stages. The length of each stage is given in the Table 11 of the FAO Irrigation and drainage paper 56. The duration of each growth stage varies according to the locations, climates, and crop types (Kennedy Ochieng Okuku, 2016; Richard G. Allen et al., 1998). In a study conducted in the Amravati district in India, (Sawant, Chakraborty, Suradhaniwar, Adinarayana, & Durbha, 2016) have tried to determine the citrus growth stages through the Normalized Difference Time Series (NDVI) time series data obtained from Landsat archives. The study has provided better information about the growth stages of the citrus orchards. Below is the description of each growth stage:

Initial stage: Crop cover in this stage is less than 10%, the length of crop at this stage varies with crop type.

Crop development stage: This stage is characterized by a crop cover varying between 10% to 80%. At the beginning of flowering the crop cover can reach 80% (effective full cover).

Mid-season stage: This period of growth goes from the effective full cover to the start of maturity. At this stage the crop coefficient is optimal.

Late stage: This stage is limited by the full maturation period, and it start at the beginning of maturity.

2.4.1.3. Crop coefficient (K_C)

Crop coefficient allows the adjustment of reference evapotranspiration values to the actual crop evapotranspiration (Kennedy Ochieng Okuku, 2016). The K_C coefficient integrates crop characteristics and impacts of soil evaporation. Even though (Glenn, Neale, Hunsaker, & Nagler, 2011) has proven that FAO-56 based generic K_C is not always accurate in the determination of the crop water use, the average crop coefficients are consistent and more advantageous for small irrigation scheduling and for most hydrologic water balance investigations. The crop coefficient varies all along the crop growth stages dues to the changes in ground cover and vegetation of crops (Richard G. Allen et al., 1998).

The variation of the K_C is shown on the **Figure 1**. Three values of K_C are needed to construct the K_C curve. These values are the K_C during the initial stage ($K_{C\ ini}$), the mid-season stage ($K_{C\ mid}$) and at the end of the late season stage ($K_{C\ end}$).

Determination of $K_{C\ ini}$, $K_{C\ mid}$ and $K_{C\ end}$

The **Table 2** below adapted from the FAO Irrigation and drainage paper 56. In the table, (Richard G. Allen et al., 1998) gave the typical values of K_C corresponding to each stage of growth has been given. Several agricultural crops were considered. Crops were organized in several groups such as small vegetables, cereals, roots, and tubers, etc. The team support the idea according to which the crops belonging to the same group in the table have similar coefficients. The supported their view by stating that individual crops of the same crop group have resemblance in terms of ground coverage, water management, leaf area, and plant height.

The coefficients given in the table combine cumulated effects of both transpiration and evaporation. The average wetting frequency for a ‘standard’ crop under typical growing conditions in an irrigated environment is represented by the impacts of the integration over time. It should be noticed that for persistent wettings, the values for $K_{C\ ini}$ can increase considerably (Richard G. Allen et al., 1998).

Table 2. Single crop coefficients, K_C adapted from (Richard G. Allen et al., 1998).

Crop	*$K_{C\ ini}$*	*$K_{C\ mid}$*	*$K_{C\ end}$*	*Maximum Crop Height (h) (m)*
a. Small Vegetables	0.7	1.05	0.95	
Broccoli		1.05	0.95	0.3
Brussel Sprouts		1.05	0.95	0.4
Cabbage		1.05	0.95	0.4
Carrots		1.05	0.95	0.3
Cauliflower		1.05	0.95	0.4
Celery		1.05	1.00	0.6
Garlic		1.00	0.70	0.3
Lettuce		1.00	0.95	0.3
Onions				
- dry		1.05	0.75	0.4
- green		1.00	1.00	0.3
- seed		1.05	0.80	0.5
Spinach		1.00	0.95	0.3
Radish		0.90	0.85	0.3
b. Vegetables - Solanum Family *(Solanaceae)*	0.6	1.15	0.80	
Egg Plant		1.05	0.90	0.8
Sweet Peppers (bell)		1.05[2]	0.90	0.7
Tomato		1.15[2]	0.70-0.90	0.6
c. Vegetables - Cucumber Family *(Cucurbitaceae)*	0.5	1.00	0.80	
Cantaloupe	0.5	0.85	0.60	0.3
Cucumber				
- Fresh Market	0.6	1.00[2]	0.75	0.3
- Machine harvest	0.5	1.00	0.90	0.3
Pumpkin, Winter Squash		1.00	0.80	0.4
Squash, Zucchini		0.95	0.75	0.3
Sweet Melons		1.05	0.75	0.4
Watermelon	0.4	1.00	0.75	0.4
d. Roots and Tubers	0.5	1.10	0.95	
Beets, table		1.05	0.95	0.4
Cassava				
- year 1	0.3	0.80[3]	0.30	1.0
- year 2	0.3	1.10	0.50	1.5
Parsnip	0.5	1.05	0.95	0.4
Potato		1.15	0.75[4]	0.6
Sweet Potato		1.15	0.65	0.4
Turnip (and Rutabaga)		1.10	0.95	0.6

Sugar Beet	0.35	1.20	0.70[5]	0.5
e. Legumes *(Leguminosae)*	0.4	1.15	0.55	
Beans, green	0.5	1.05[2]	0.90	0.4
Beans, dry and Pulses	0.4	1.15[2]	0.35	0.4
Chick pea		1.00	0.35	0.4
Fababean (broad bean)				
- Fresh	0.5	1.15[2]	1.10	0.8
- Dry/Seed	0.5	1.15[2]	0.30	0.8
Grabanzo	0.4	1.15	0.35	0.8
Green Gram and Cowpeas		1.05	0.60-0.35[6]	0.4
Groundnut (Peanut)		1.15	0.60	0.4
Lentil		1.10	0.30	0.5
Peas				
- Fresh	0.5	1.15[2]	1.10	0.5
- Dry/Seed		1.15	0.30	0.5
Soybeans		1.15	0.50	0.5-1.0
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)	0.5	1.00	0.80	
Artichokes	0.5	1.00	0.95	0.7
Asparagus	0.5	0.95[7]	0.30	0.2-0.8
Mint	0.60	1.15	1.10	0.6-0.8
Strawberries	0.40	0.85	0.75	0.2
g. Fibre Crops	0.35			
Cotton		1.15-1.20	0.70-0.50	1.2-1.5
Flax		1.10	0.25	1.2
Sisal [8]		0.4-0.7	0.4-0.7	1.5
h. Oil Crops	0.35	1.15	0.35	
Castorbean (*Ricinus*)		1.15	0.55	0.3
Rapeseed, Canola		1.0-1.15[9]	0.35	0.6
Safflower		1.0-1.15[9]	0.25	0.8
Sesame		1.10	0.25	1.0
Sunflower		1.0-1.15[9]	0.35	2.0
i. Cereals	0.3	1.15	0.4	
Barley		1.15	0.25	1
Oats		1.15	0.25	1
Spring Wheat		1.15	0.25-0.4[10]	1
Winter Wheat				
- with frozen soils	0.4	1.15	0.25-0.4[10]	1
- with non-frozen soils	0.7	1.15	0.25-0.4[10]	

Maize, Field (grain) *(field corn)*		1.20	0.60-0.35[11]	2
Maize, Sweet *(sweet corn)*		1.15	1.05[12]	1.5
Millet		1.00	0.30	1.5
Sorghum				
- grain		1.00-1.10	0.55	1-2
- sweet		1.20	1.05	2-4
Rice	1.05	1.20	0.90-0.60	1
j. Forages				
Alfalfa Hay				
- averaged cutting effects	0.40	0.95[13]	0.90	0.7
- individual cutting periods	0.40[14]	1.20[14]	1.15[14]	0.7
- for seed	0.40	0.50	0.50	0.7
Bermuda hay				
- averaged cutting effects	0.55	1.00[13]	0.85	0.35
- Spring crop for seed	0.35	0.90	0.65	0.4
Clover hay, Berseem				
- averaged cutting effects	0.40	0.90[13]	0.85	0.6
- individual cutting periods	0.40[14]	1.15[14]	1.10[14]	0.6
Rye Grass hay				
- averaged cutting effects	0.95	1.05	1.00	0.3
Sudan Grass hay (annual)				
- averaged cutting effects	0.50	0.90[14]	0.85	1.2
- individual cutting periods	0.50[14]	1.15[14]	1.10[14]	1.2
Grazing Pasture				
- Rotated Grazing	0.40	0.85-1.05	0.85	0.15-0.30
- Extensive Grazing	0.30	0.75	0.75	0.10
Turf grass				
- cool season [15]	0.90	0.95	0.95	0.10
- warm season [15]	0.80	0.85	0.85	0.10
k. Sugar Cane	0.40	1.25	0.75	3
l. Tropical Fruits and Trees				
Banana				
- 1st year	0.50	1.10	1.00	3
- 2nd year	1.00	1.20	1.10	4
Cacao	1.00	1.05	1.05	3
Coffee				
- bare ground cover	0.90	0.95	0.95	2-3
- with weeds	1.05	1.10	1.10	2-3
Date Palms	0.90	0.95	0.95	8
Palm Trees	0.95	1.00	1.00	8
Pineapple [16]				
- bare soil	0.50	0.30	0.30	0.6-1.2
- with grass cover	0.50	0.50	0.50	0.6-1.2
Rubber Trees	0.95	1.00	1.00	10
Tea				

- non-shaded	0.95	1.00	1.00	1.5
- shaded [17]	1.10	1.15	1.15	2
m. Grapes and Berries				
Berries (bushes)	0.30	1.05	0.50	1.5
Grapes				
- Table or Raisin	0.30	0.85	0.45	2
- Wine	0.30	0.70	0.45	1.5-2
Hops	0.3	1.05	0.85	5
n. Fruit Trees				
Almonds, no ground cover	0.40	0.90	0.65[18]	5
Apples, Cherries, Pears [19]				
- no ground cover, killing frost	0.45	0.95	0.70[18]	4
- no ground cover, no frosts	0.60	0.95	0.75[18]	4
- active ground cover, killing frost	0.50	1.20	0.95[18]	4
- active ground cover, no frosts	0.80	1.20	0.85[18]	4
Apricots, Peaches, Stone Fruit [19, 20]				
- no ground cover, killing frost	0.45	0.90	0.65[18]	3
- no ground cover, no frosts	0.55	0.90	0.65[18]	3
- active ground cover, killing frost	0.50	1.15	0.90[18]	3
- active ground cover, no frosts	0.80	1.15	0.85[18]	3
Avocado, no ground cover	0.60	0.85	0.75	3
Citrus, no ground cover [21]				
- 70% canopy	0.70	0.65	0.70	4
- 50% canopy	0.65	0.60	0.65	3
- 20% canopy	0.50	0.45	0.55	2
Citrus, with active ground cover or weeds [22]				
- 70% canopy	0.75	0.70	0.75	4
- 50% canopy	0.80	0.80	0.80	3
- 20% canopy	0.85	0.85	0.85	2
Conifer Trees [23]	1.00	1.00	1.00	10
Kiwi	0.40	1.05	1.05	3
Olives (40 to 60% ground coverage by canopy) [24]	0.65	0.70	0.70	3-5
Pistachios, no ground cover	0.40	1.10	0.45	3-5
Walnut Orchard [19]	0.50	1.10	0.6518	4-5
o. Wetlands - temperate climate				
Cattails, Bulrushes, killing frost	0.30	1.20	0.30	2
Cattails, Bulrushes, no frost	0.60	1.20	0.60	2
Short Veg., no frost	1.05	1.10	1.10	0.3
Reed Swamp, standing water	1.00	1.20	1.00	1-3
Reed Swamp, moist soil	0.90	1.20	0.70	1-3
p. Special				
Open Water, < 2 m depth or in subhumid climates or tropics		1.05	1.05	
Open Water, > 5 m depth, clear of turbidity, temperate climate		0.6525	1.2525	

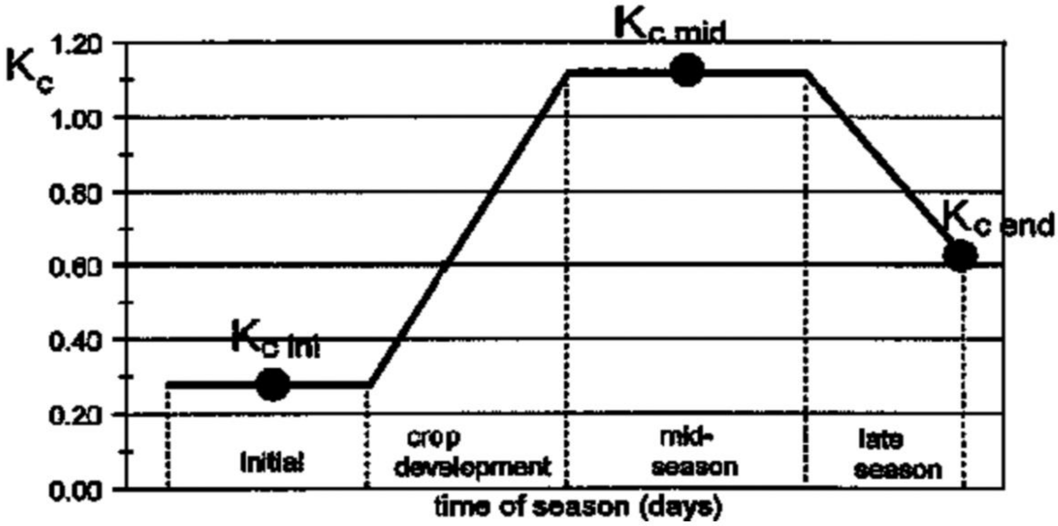


Figure 1. Crop coefficient curve (Richard G. Allen et al., 1998)

2.4.1.4. Determination of the crop evapotranspiration as a function of Kc and ETo

The first step is about the determination of the reference evapotranspiration using the climatic data and geographic information. The obtained ETo is then multiplied by the crop coefficient Kc to obtain the crop evapotranspiration ETc (Surendran, Sushanth, Joseph, Al-Ansari, & Yaseen, 2019; Surendran, Sushanth, Mammen, & Joseph, 2015). The equation (15) shown below allows the computation of the ETc.

$$ET_C = ET_O \ x \ K_C \tag{15}$$

Where

ETc – crop evapotranspiration [mm d^{-1}],
Kc – crop coefficient [dimensionless],
ETo – reference crop evapotranspiration [mm d^{-1}].

According to (Richard G. Allen et al., 1998), the calculation procedure for crop evapotranspiration, ETc, consists of :

1. Identification of the growth stages, determination of crop lengths and selection of the corresponding Kc coefficients.

2. Adaptation of the selected K_C coefficients for frequency of wetting or climatic conditions during the stage.

3. Construction of the crop coefficient curve and

4. Calculation of the ET_C as the product of the ET_O and K_C

2.4.3. Soil water balance

Several studies about the estimation of ET has been conducted at the continent level. (Djaman, Rudnick, Moukoumbi, Sow, & Irmak, 2019) have computed the ET_C and the crop coefficient (K_C) of the irrigated lowland rice using the soil water balance equation represented below by the equation (16).

$$P + I + U = R + D \pm \Delta W + ETC. \tag{16}$$

Where

I – the irrigation water supplied (mm),
P – the rainfall,
RO – the surface runoff,
DP – the deep percolation which recharges the water table.
CR – the capillary rise.
Δ SF – subsurface flow in (SF_{in}) or outflow (SF_{out}) of the root zone. Δ SW – change in the soil water content.

The study was conducted in the Senegal River Valley shared by Guinea, Mali, Mauritania, and Senegal. Though the measurements were taken from Senegal the obtained results can be the same with several changes as the four countries share the same valley. The estimation of the ETo was done through the Penman-Monteith method, the same method was used by (Surendran et al., 2019, 2015) in the case of India. The reported rice seasonal ET_C was 841.5 mm in 2014 and 855.4 mm in 2015. The obtained rice K_C values were between 0.77 to 1.51 in 2014 and 0.85 to 1.50 in 2015.

Apart from the two approaches described above (reference evapotranspiration and soil balance approach), several methods have been used in the determination of the actual evapotranspiration. (Ghaderi, Dasineh, Shokri, & Abraham, 2020) have used a different approach to compute the Actual Evapotranspiration (ETc). The Surface Energy Balance Algorithm for Land (SEBAL) and remote sensing served as tools to estimate the ETC. The comparison of SEBAL with the FAO-Penman–Monteith method (Richard G. Allen et al., 1998) showed a high correlation (0.97) between the values of the two methods. SEBAL was therefore found to provide acceptable accuracy for the ETc computation. The satellite images had indicated that apart from the last month of cultivation the rainfall furnish the needed water and there was no need for irrigation except early June and late May.

2.5. Irrigation water need (IN)

2.5.1. Irrigation

The crop evaporation (ETC) or the crop water requirement (CWR) indicate the amount of water that need to be supplied to the crop for their growth. This water can be provided to crops through three different methods such as irrigation, rainfall and the combination of both (C. Brouwer & M. Heibloem, 1986). Irrigation is artificial water supply in the soil for crop use (Richard G. Allen et al., 1998). To sustain efficiency in crop production, an appropriate irrigation system is a must, in a recent research report, (Cai, Sharma, Matin, Sharma, & Gunasinghe, 2010) have demonstrated that crop could suffer from water shortage as well as flooding after an heavy rainfall.

Inventive irrigation methods have the potential to increase water efficiency leading to an economic gain and reducing environmental impacts. Irrigation productivity and water use efficiency are important in the evaluation of water management systems (Levidow et al., 2014). Irrigation efficiency and water productivity have important uses in water management and irrigation systems evaluations (Nazari, Liaghat, & Parsinejad, 2013). The decision to use preference of water productivity or irrigation efficiency for water management or irrigation depends on the objective of the research or the preference of the researcher (Kijne, Barker, & Molden, 2003) .

2.5.2. Calculation of irrigation water need

When the needed water (ETC) for an appropriate water growth is fully supplied by rainfall, the irrigation is not needed, and the value of the Irrigation Water need (IN) is zero. This situate=ion can be illustrated by the equation (17) below.

$$IN = 0 \tag{17}$$

On the other hand, a total or a partial irrigation is needed to ensure an optimal water growth when there is no rainfall of the rainwater is not sufficient during the growing season. Here we have two situations. The eventuality in which there is no rainfall, and the needed water (ET_C) is totally supplied by irrigation is illustrated in the equation (18) and the situation where the crop water need is fulfilled by both rainfall (P_e) and irrigation (IN) is shown by the equation (19) below. In the most cases, the farmer is expected to face the last situation.

$$IN = ET_C \tag{18}$$

$$IN = ET_C - Pe \tag{19}$$

In the equation (26) above, the (Pe) represents the effective rainfall.

2.5.2.1. Effective rainfall

From the **Figure 2**, when it rains, the rainwater (1) encounters the soil, then a part of it enters the soil (2), another part remains on the surface (3). The runoff (4) is generated another part of it.

When it stops raining, some of the stagnant water (3) is change the phase and becomes water vapor through the evaporation process (5) and the rest will infiltrate into the soil (6).

The percolation (7) below the root zone of (2) and (6) occurs while the remaining water will be stocked in the root zone (8). The effective rainfall (8) is therefore, the difference of the total rainfall (1) minus the runoff minus the evaporation (5) and minus the percolation (7). The only part of rainfall that can be used by the crop is the water stored in the root zone (8). The expression ‘effective rainfall’ basically means the amount of water that is useful for the fulfillment of the crop water need (ET_C).

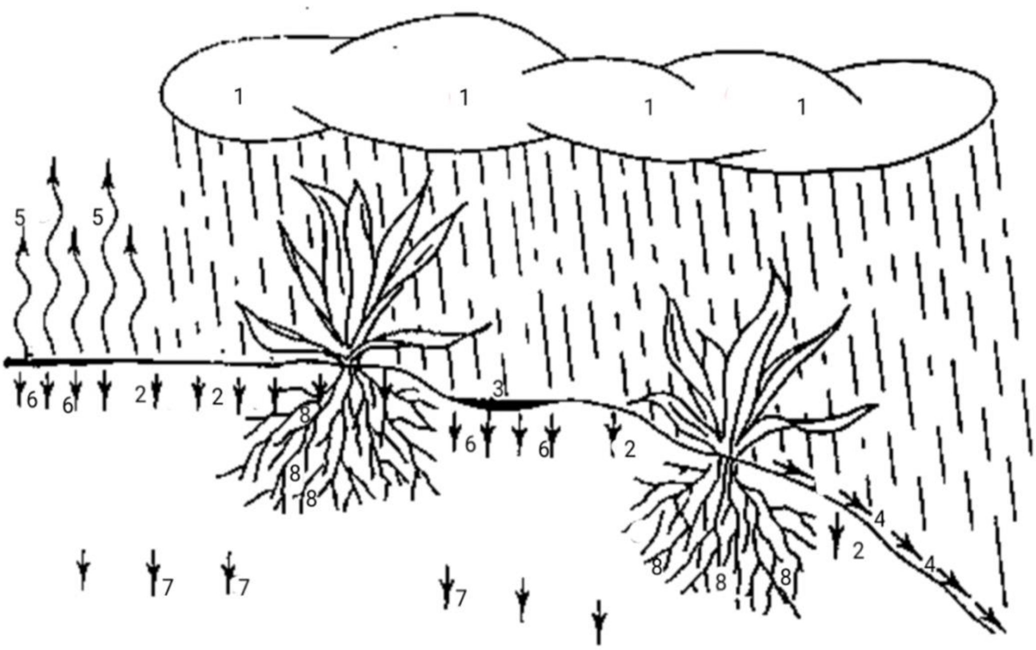


Figure 2. Effective rainfall (8) = (1) - (4) = (5) = (7) (C. Brouwer & M. Heibloem, 1986)

2.5.2.2. Determination of effective rainfall (Pe)

Assuming the maximum slope is between 4 and 5%, the equation (20) and (21) can be used for the determination of Pe when the precipitation (P) is known.

$$P_e = 0.8P - 25\ , with\ P > 75\ mm/month \qquad (20)$$

$$P_e = 0.8P - 10\ , with\ P < 75\ mm/month \qquad (21)$$

Where

P = rainfall or precipitation (mm/month)

Pe = effective rainfall or effective precipitation (mm/month)

2.6. Irrigation water management methods

Well-scheduled appropriate and water supply to crops is important for an optimal crop growth. An adequate quantity of water should be provided to crops when there is a need of meeting the ET_C, water should not be wasted as nowadays, water shortage constitute a major problem in many African states (Kennedy Ochieng Okuku, 2016). Given the emergency of the water scarcity problem, different technics have been developed for an effective irrigation water management.

2.6.1. Water miser BMP

Water Miser BMP irrigation management strategy saves water when the crop water need is low (less sensitive vegetative period of growth) and full waters the crops during critical growth stages such as flowering and or reproduction phases. The available soil water of the crop is kept between field capacity and 50% depletion. A noticeably yield loss is note remarked when the irrigation water is reduced during the vegetative growth stage (Steve Melvin & Jose Payero, 2002).

2.6.2. Volumetric Measurement of Irrigation Water

This method is based on the measurement of the water available in the soil or the water directly up taken by irrigated crops. This is done though sensors such as water level sensors, humidity sensors. Particularly, the Time Domain Reflectometry (TDR) sensor has been used widely in a variety of application (Janik et al., 2021). Early in 2008, (Starr, Rowland, Griffin, & Olanya, 2008) have used TDR to determine the water regime in potato farming in the field. The same study conducted recently by (Jama-Rodzeńska et al., 2020) aimed to repeat (Starr et al., 2008) but this time in controlled conditions. In 2002, (Y. Li, Fuchs, Cohen, Cohen, & Wallach, 2002) have also applied the TDR technique to estimate the water use by maize crop.

2.6.3. Soil crop matching technique

This method consists of matching the crop water need with the water supply availability. In this method, the farmer knowing the water requirement of the crop he intends to plant, he can make sure the field he will select has sufficient water to get optimal yield. If water provision is short, crops with low ET_C should be plant (C.C. Shock, B.M. Shock, & T. Welch, 2013).

2.6.4. Conservation tillage practices

This method aims to conserve soil water by reducing the tillage frequency through minimum tillage, strip till and no till. Added to the reduction of tillage, the crop remains of previous season is kept on the soil surface reducing water evaporation and ensuring soil cooling. Soil is exposed to drying when it is tilled, therefore, no till permits soil water conservation (C.C. Shock et al., 2013).

2.6.5. Careful management of surface irrigation

In the crop fields where the surface irrigation is practiced, the upper part of the field is generally flooded with water while the bottom is under-watered. Another disadvantage of the surface irrigation is the fact that it provokes surface irrigation because of the permanent contact between soil and water. It appears then that to save irrigation water with furrow irrigation, it is necessary to change irrigation set as soon as supplied water arrives at the end of the furrow instead of waiting until a specific moment of the day (C.C. Shock et al., 2013).

2.6.6. Lining of On-Farm Irrigation Ditches and Replacement of canals with Pipelines

This strategy is based on the covering an impervious material on recently set irrigation field trench. Water is saved by using materials such as concrete, urethane and Ethylene-Propylene- Diene Monomer (EPDM). The layers of the set material prevent water seepage from the canals. According to (Andrew A. Keller & Jack Keller, 1995), the amount of water lost through seepage is greater compared to the water lost from evaporation and the water saved by reducing the evaporation is less than 10 percent of the amount of water lost through seepage.

2.6.7. Avoiding over-irrigation

Over-irrigation leads to soil, water, and fertilizer loss. Though this approach may seem simple to applied, many farmers practice over-irrigation without noticing. Irrigation should be made frequently with an adequate amount of water to keep water moving in the root zone and facilitate its use by crops (C.C. Shock et al., 2013).

2.6.8. Deficit irrigation

This technique is about applying less water than the crop requirement for total growth. When applied, this method leads to the little yield loss. This method is good for crops with deep roots such as wheat and corn. Though small weight and yield loss I noticed, these crops have been grown with careful controlled deficit irrigation with success. Before use of this method, drought tolerance of each crop must be known, and the irrigation must be done accordingly.

Deficit irrigation does not work with non-stress tolerant crops. This group of crops is composed of potato and other vegetable crops such as onion. While some varieties of potato (Russet Burbank potatoes, …) suffer tremendously from drought, others (Umatilla and Shepody potatoes, …) are more resistant. As solution for potatoes farming associated with deficit water irrigation techniques, crops should be stressed slightly every year before the tubers appear. While water stress practicing (deficit irrigation) on onion is not recommended unless the amount of water is considerably less than the ET_C, the method work on crops such as almonds, wine grapes, and alfalfa seed which are greatly water-stress resistant (C.C. Shock et al., 2013).

This strategy is to delay water supply until approximately two weeks before tassel emergence for corn if soil-water does not become 70% depleted. At the stage of reproduction, the available soil-water active in the root zone is kept between 30 and 60%. The depletion numbers should be varied based on the water availability (Steve Melvin & Jose Payero, 2002). The method is based on the precise measurement of water availability along crop growth to balance the yield by supplying water based on water depletion basis (Geerts & Raes, 2009).

2.6.9. Irrigation scheduling

The irrigation scheduling is made based on two factors, the ET and soil water content. Considering the irrigation scheduling based on the ET, the evapotranspiration predictions are used to decide when and which amount of water should be applied to crops. It is important to mention that the soil water retention capacity should be known for an appropriate use of this method. The scheduling based on soil water content is the approach that will be followed in this work though a further investigation of the automation side of irrigation will be considered too.

Using soil moisture sensors, the soil water content can be estimated. For this purpose, neutron probes, capacitance sensors, … can be used. An amalgamation of both ET predictions and soil moisture sensors can facilitate an accurate estimation of the most wanted frequencies and depths of irrigation. (C.C. Shock et al., 2013; Kennedy Ochieng Okuku, 2016). A sound comprehension of soil water holding capacity, crop water use, and crop drought sensitivity at different phases of growth (Levidow et al., 2014).

2.6.10. Land management systems

This approach aims to increase the water supply efficiency. It is mostly used on field where surface irrigation is practiced. The amount of water saved from this strategy is difficult to measure (Kennedy Ochieng Okuku, 2016).

2.6.11. Crop selection and irrigation needs

Crop characteristics are important and must be considered while choosing the farming yard. For instance, crop with deep root system can resist water-stress and vegetable crops are very sensitive to drought. Factors such as crop water requirement, canopy and leave surface must be taken into account for a good water management.

2.6.12. Crop rotation and selection

Aiming to increase water use efficiency, this method suggests an alternance between different crop on the same field. For instance, farming potato, a crop with shallow root system, after harvesting wheat can help to reduce the ET_C.

2.7. Irrigation scheduling Methods

Irrigation scheduling responds to two main questions:

1. What is the water requirement of the crop?
2. What is the time of irrigation?

Various methods have been developed to know when to irrigate crops and how much water should be supplied to the crops. Methods are classified into four groups: Soil indicator methods, weather monitoring techniques, crop monitoring methods, water budget techniques.

2.7.1. Soil indicator methods

The time of irrigation is most of time determined through soil water monitoring (Kennedy Ochieng Okuku, 2016). The required force to remove the next amount of water added to the soil is the soil water potential (C.C. Shock et al., 2013). Methods used in soil water content monitoring are as following:

(i) Tensiometer measurements
(ii) Nuclear methods
(iii) Hand feeling and appearance of soil
(iv) Gravimetric soil moisture sampling
(v) Electrical resistance blocks
(vi) Water budget approach
(vii) TDR (Time Domain Reflectometers)
(viii) The monitoring of crop canopy temperature by remote sensing with an infrared radiation

2.7.2. Weather monitoring techniques

This approach is about gathering meteorological data to calculate the ETo and the crop irrigation water need. The irrigation timing can be determined with reference to the soil moisture, relative humidity, or other weather parameters.

2.7.3. Crop monitoring methods

Appearance and growth, leaf temperature, leaf water potential and stomatal resistance are different crop monitoring methods that are used to schedule irrigation. Crop type and its growth stage determine the level of stress that can reduce the crop yield (Kennedy Ochieng Okuku, 2016). Leaf water potential helps in determining the irrigation scheduling. Crop monitoring methods are the most direct approaches of developing irrigation schedule (S. A. Gulma, S. Haruna, M. Kigumi, & P. Home, 2005).

2.7.4. Water budget techniques

This group of methods suggest that the available water is stored in the root zone of the crop. An eventual rainfall or irrigation water supply will increase the volume of water in the root zone and the opposite effect will occur through absorption, transpiration by the crop and evaporation from the soil surface (Simonne, Hochmuth, Breman, Lamont, & Treadwell, 2012, p. 1). The pan evaporation data and crop curves are the two methods used in water budgeting. This approach determines the quantity of water lost from the soil which will in return the amount of water that should be added to keep the optimal soil moisture required for crop growth. Checkbook scheduling is one of major approach used in water budgeting methods.

2.8. Monitored parameters and sensors in real-time water demand monitoring

A majority of river systems and irrigation networks in the world need remarkable automation and decision support systems to ensure a good water delivery efficiency and improve system health (Ahmad & Muhammad, 2014). The expensiveness of commercial sensors used in agriculture used to keep developing countries from automatizing their farms. Nowadays, the development of low-cost sensors has facilitated the implementation of low-cost systems for agricultural monitoring (García, Parra, Jimenez, Lloret, & Lorenz, 2020).

Researchers think that smart irrigation systems and monitors compared to traditional irrigation controllers are more water savers in different scenarios (Ismail et al., 2019). Some studies conducted in the domain of irrigation automation show an important water saving of 40-70% (Kishor et al., 2018; Krishna Anne, R V Siva Naga Durg, Krishna Muddineni, & Gowtham Peri, 2018; Taneja & Bhatia, 2017). A report of the Irrigation Association (IA) and the International Centre for Water Technology at California State University in Fresno, showed that up to 20% water is saved while using smart irrigation methods compared to traditional irrigation controllers (I. HydroPoint Data Systems, 2019).

2.8.1. Monitored parameters

(García et al., 2020) have suggested that most of studies conducted in the domain of agricultural monitoring have focused on three to four parameters. Authors have discovered that soil moisture is the most monitored soil parameters and air temperature, and humidity are the widely checked atmospheric parameter. Other parameters covered by some papers are soil temperature, luminosity and electrical conductivity (López et al., 2015).

Intending to ensure a sustainable environment, (Adenugba et al., 2019) have used an humiture sensor to monitor both humidity and temperature parameters of the soil. In the study, the atmospheric pressure was monitored to allow weather forecasting. Using IoT technologies, (Ismail et al., 2019) have monitored the temperature, soil moisture, humidity and barometric pressure in a smart irrigation system developed with the aim of controlling irrigation water use from a mobile application.

Unexpectedly, wind pressure and radiation was monitored by (Sheikh, Javed, Anas, & Ahmed, 2018) while designing a solar based smart irrigation system using PID controller.

The system was developed through a combination of Arduino and four real-time sensors collecting data from the farmyard.

2.8.2. Sensors used for agricultural monitoring

Sensors are important in irrigation automation. Sensor nodes are event-driven, cheap, self-organized. They are efficient in providing low-cost and low-energy application in the WSNs and IoT oriented automation problems (Adenugba et al., 2019).

Many examples of sensors used by researchers have been developed to reduce the cost of overall automation in the domain of research. In a recent article, (Daskalakis, Goussetis, Assimonis, Tentzeris, & Georgiadis, 2018) have presented a low-cost and low-power sensor. The sensor measures of the differential temperature between the leaf and the air allowing water stress detection and preventing water waste. In 2013, (Zak et al., 2013) have used a water salinity monitoring sensor fabricated from copper coils. The multi-level soil moisture sensor developed by (Guruprasadh et al., 2017) should also be mentioned. Using infrared led emitters and receptors, (Sandra Sendra, Lorena Parra, Vicente Ortuño, & Jaime Lloret, 2013) have developed a low-cost turbidity sensor.
To ensure an efficient water level measurement in a study conducted in a Southern Punjab province of Pakistan, (Muhammad, Haider, & Ahmad, 2016) have used non-contact ultrasonic sensors with frequency value of 10 minutes.

Most studies used the low-cost YL69 and VH400 to measure soil moisture parameter, others s works used commercial sensors such as ECH2O, HydraProbe and MP406 (Borrero & Zabalo, 2020). Some details regarding the listed commercial sensors are given in the **Table *3*** below.

Table 3. Popular wireless nodes used in the agriculture domain adapted from (Borrero & Zabalo, 2020)

Sensor Name	Parameters Captured	Company
ECH2O	Soil moisture, Soil temperature, Electrical conductivity	Meter Group, Inc, Pullman, WA, USA
HydraProbe	Soil moisture, Soil temperature, Electrical conductivity	Stevens Water Monitoring Systems, Inc, Portland, OR, USA
MP406	Soil moisture, Soil temperature	ICT International, Armidale, Australia

One of the problems that can be challenging in using sensor for real-time water need monitoring is the excessive power consumption. Recently, (Borrero & Zabalo, 2020) come up with a solution to excessive power usage in real-time monitoring. The team have developed a monitoring device by setting up an IoT system composed by WSNs and LoRaWAN technologies. The designed device allows farmers to monitor their crops through a low-power wide-area network (LPWAN) and sensors placed in the farm. Although in this study will not focus on energy efficiency, while selecting different components for the constitution of the system, low consuming devices will be considered due to the impressive results obtained by (Borrero & Zabalo, 2020). In fact, compared to the energy consumption results obtained by (Y. Wang, Wang, Qi, & Xu, 2009) through an open-architecture precision agriculture information monitoring system he has developed using a wide range of energy limited low tier nodes (LNs).

The design of (Parameswaran & Sivaprasath, 2016) is quite similar to the one developed in 2019 by (Sudharshan, Karthik, Kiran, & Geetha, 2019). The designed system is composed of the Arduino ATMega 328P as the microcontroller. The LM35 sensor was used for temperature and the SY-HS-220 was used to measure the soil humidity. The software for data processing was developed using Java and the data were store in MySQL. The data store in the server is then send to the network system for processing. The clear functioning of the system is not described in the study done by the team. It is clear that the irrigation and water efficiency aspects are again neglected in this study.

2.9. IoT Methods and Architectures

In their recent editorial, (Masseroni, Arbat, & de Lima, 2020) have provided a clear state of art of the use of smart irrigation systems in four different research domains. The study was conducted using nine different papers published in 2019. Different works was categorized in four main groups. Though the category of "Precision irrigation models and controls" has regrouped five published works, the distribution of the nine studies was quite heterogeneous. There was only one paper for the category of 'Remote sensing-based estimates of crop evapotranspiration' and "Price of natural resources". Two works have been listed under the group of 'Information and Communication Technologies (ICTs) for smart-irrigation'. From this study, it is obvious that each one the three works was conducted under specific conditions and has used different methodologies. This work of (Masseroni et al., 2020) is important for my thesis because of the fact that it provides late information on different methods used by previous nine studies in the domain of smart irrigation.

2.9.1. Multi-agent architectures

Taking advantage of the cloud computing technologies, (González-Briones, Castellanos-Garzón, Mezquita Martín, Prieto, & Corchado, 2018) designed a multi-agent system (MAS). With the help of a Wireless Sensor Network (WSN) system deployed in a rural area, authors aimed to improve irrigation decision making and optimize the use of different actuators. The functioning of the SIS set up by (González-Briones, Mezquita, Castellanos-Garzón, Prieto, & Corchado, 2019) was clearly explained but the study focused on MAS . Data is collected from all the sections to feed the new designed upper MAS thanks to a WSNs placed in the field. The crop used in the study is potato which is not a common crop cultivated in west Africa. The group have developed their system based on the concept of sectioning the field into small parts to facilitate the control and allow an efficient use of water and fertilizers. This method is also supported in a study conducted by (González-Briones et al., 2018).

The **Figure 3** shown below illustrate the relation between the manager agent (MA), who is responsible for managing nearby agents and the rest of the system. The heterogeneous data supervisor agent (HDMA) oversees the transforming data received from sensors into consistent information that is stored for upcoming use. The irrigation manager (IMA) facilitates the interpretation of the results given by the KDVO virtual organization to an action provoked by irrigation control device. The UIVO consist of a system user that allowing them to get sensor readings and analyze information. The DRVO is composed of agents overseeing the collection of field data using data capture agents (DCA).

The MAS handles data for multiple crops. Therefore, each DCA focus on capturing data from one crop sent by the sensor attached to it. The DTVO transform data into a format accepted by the MAS.

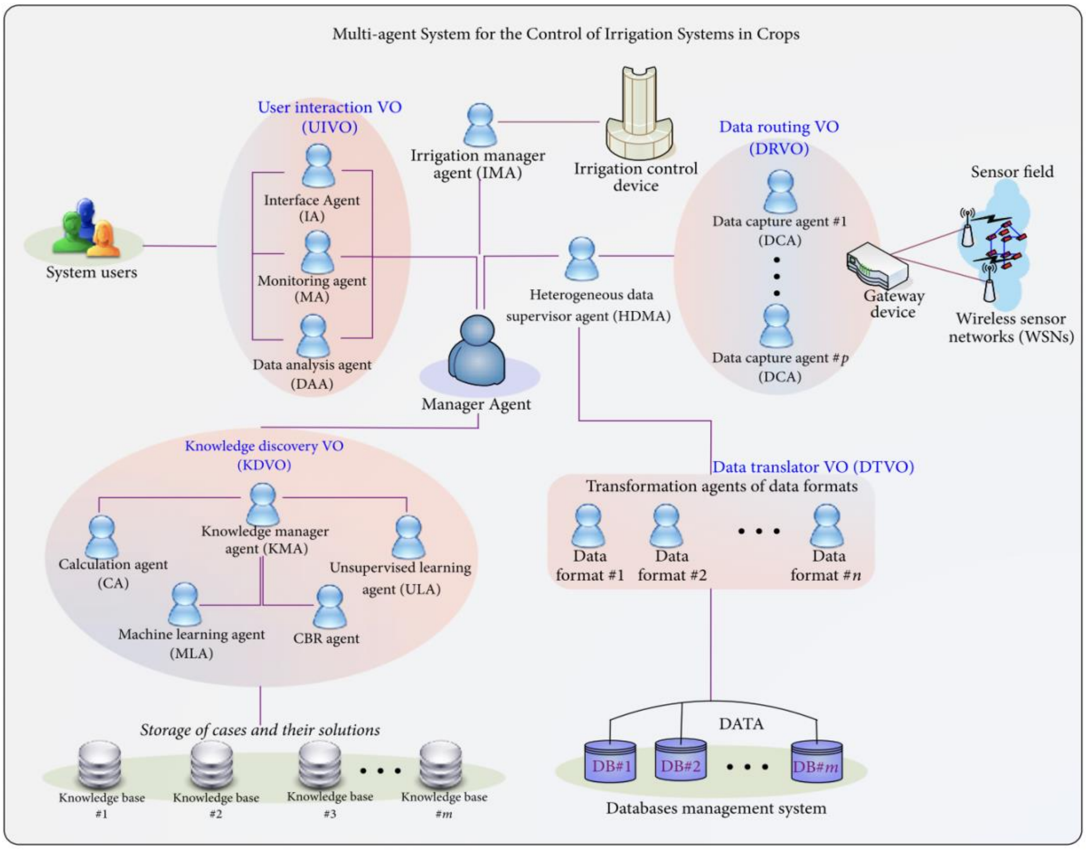


Figure 3. Structured multiagent system for irrigation control Adapted from (González-Briones et al., 2018).

Focusing on how to remotely control a drip irrigation system, (Capraro et al., 2018) have designed a web-based software for the management of smart irrigation. The developed system is a result of a combination of different components (weather station, field measurement stations, radio modem, Wi-Fi network, ...) which interact together to make possible data collection, transferring, processing and storage. The main software of the system (web) is the interface that ensure the interaction of a user (remote user) with irrigated farm. Using programming languages like Python, JavaScript and PHP, the web application was designed not only to inform the user about the real-time situation of the irrigated farm but also to collect information and allow some configurations. The proposed system allowed soil moisture and water allocation management. Compared to the model developed by (R.-S. Wu et al., 2017), this system has considered more weather parameters and irrigation strategies which obviously can make the design more reliable and efficient.

2.9.2. OpenMTC

Implemented from an IoT/M2M middleware, the OpenMTC platform is a prototype that provide a standard-compliant working place for IoT services. The platform links various sensors and actuators from various vertical domains. Within the OpenMTC, collected data are aggregated, forwarded to applications. The platform ensures the conciliation of the instructions to the end devices for events-related controls (OpenMTC, n.d.).

The REST APIs allow developers to access data from devices without precising the technical specifics of the devices linked to the gateway. Data is retrieved from the devices and stored in an oneM2M-compliant data model. Though the OpenMTC software is developed using Python, it could be deployed on machines using various operation systems such as ARM and x86 (OpenMTC, n.d.).

The OpenMTC architecture represented on the below is complemented by a user interface with external machine to machine (M2M) applications (Ali, Shah, Farooq, & Ghani, 2017).

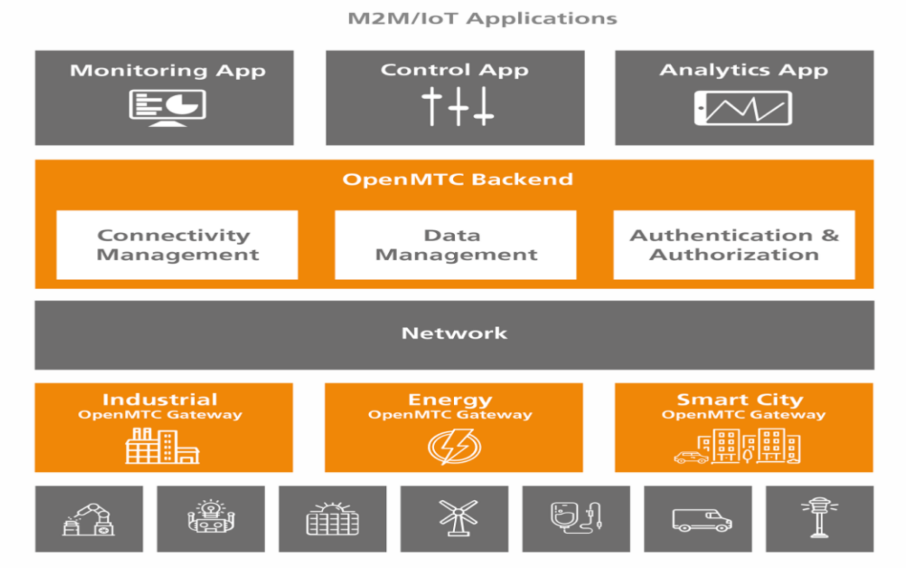


Figure 4. OpenMTC architecture adapted from (OpenMTC, n.d.)

2.9.3. SiteWhere

SiteWhere is a certified open source for the Internet of Things (IoT). The platform provides all keys features necessary for the development and deployment of an IoT application. Many facets of IoT processing into microservices. Microservices handles specific task such as event ingestion, integration of device data with external systems, big-data event persistence, device state management, etc. A docker container wraps Spring Boot applications (microservices). Available REST APIs, Asset SPIs, and data storage SPIs allow the development and linking of more applications to the platform (SiteWhere, n.d.).

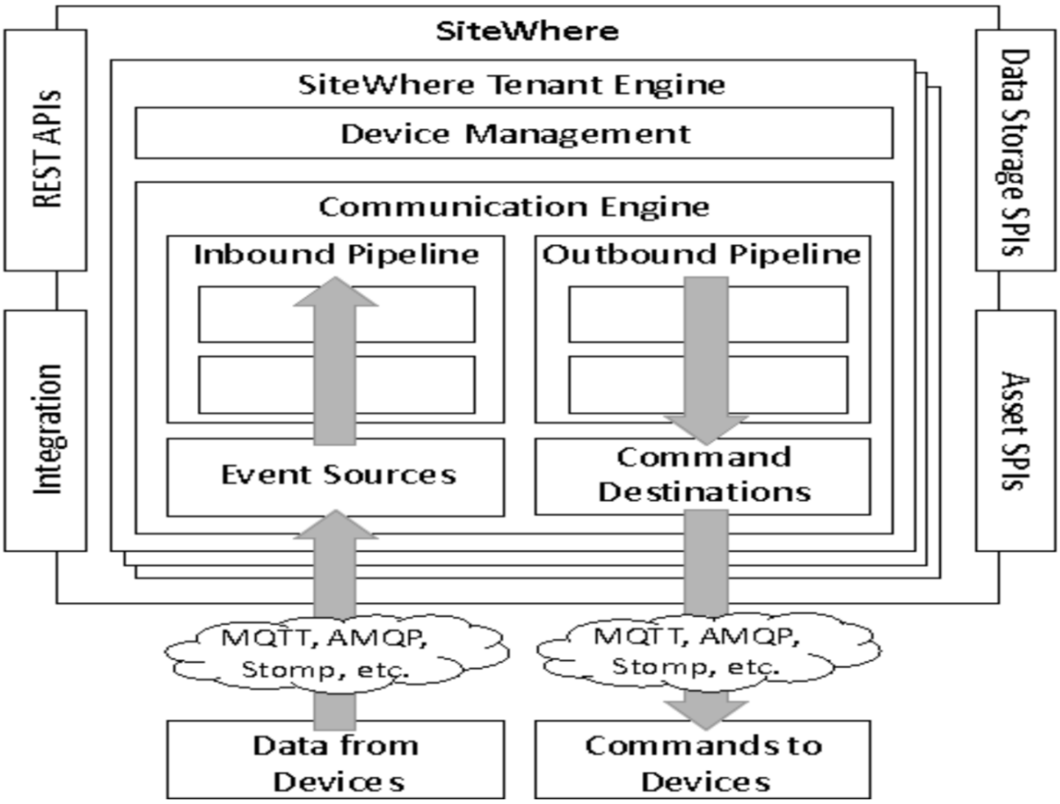


Figure 5. SiteWhere IoT architecture Adopted from (Guth, Breitenbucher, Falkenthal, Leymann, & Reinfurt, 2016)

2.9.4. Example non-open source IoT system architecture

2.9.4.1. PLC based precision irrigation system

(Capraro et al., 2018) has developed an IoT-based system architecture that is composed by four main layers:

- All components and devices of the system is grouped under the “In-field devices” layer. The block is marked in green color in the
- **Figure *6*** below. The **Table 4** below classified all devices of the “In-field devices” with their functions.

Table 4. Illustration of the In-field building block components and their respective roles

Device	*Function*
Local Server (personal computer)	Irrigation system and variables monitoring platform
2.4 GHz Wi-Fi	System remote control
Radio modem device at 470 MHz	Communication with weather and measurement stations
GPRS-GSM modem	Notification via texting
Internet connection	Data transfer to the server
Weather Station	Measurement of parameters for ET_O computing such as ambient temperature, relative humidity, solar radiation, wind speed, etc.
Programable Logic Controller	Irrigation control
Sensors	Measurement of soil parameters such as soil moisture, ambient relative humidity, ambient relative humidity, pressure, and temperature

- Web services layer marked in blue allows remote controlling and system backup. Users such as consultants, operators and managers can quickly find irrigation process and weather-related information by entering their user information.

- Clients and remote user layer marked in orange is the illustration of the users who can connect to the system and control the irrigation system installation and different variables from any point of the farm. The basic requirement is a device having internet and supporting web browsing. Managers and growers constitute this group of users.

- External supervisor layer marked in red is the hierarchical position of a controller who can access the information of multiple orchards through the web server.

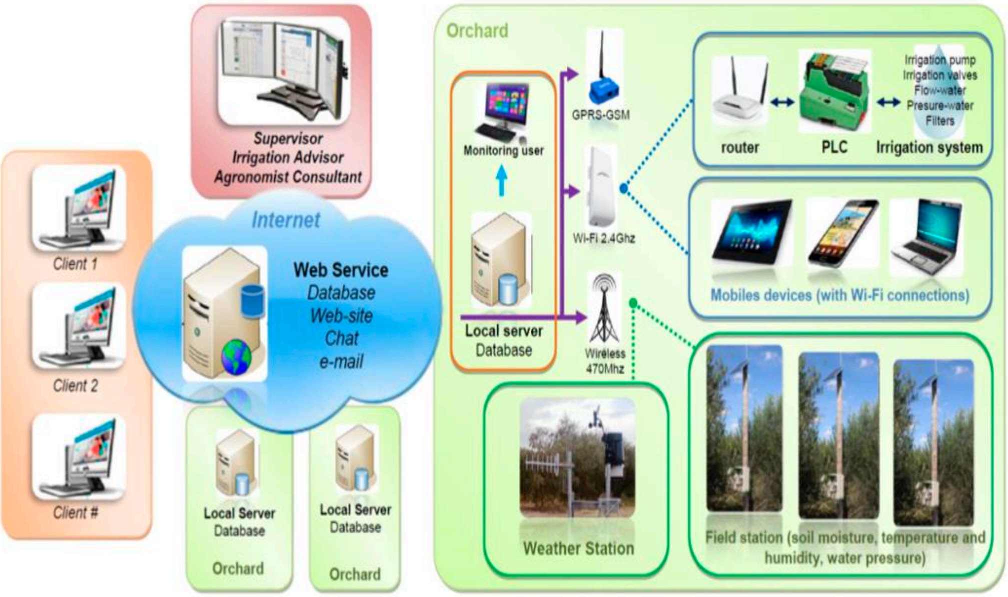


Figure 6. PLC based precision irrigation system adapted from (Capraro et al., 2018)

2.9.4.2. Example real-time low-cost architecture

Aiming to develop a low-cost autonomous irrigation system, (Abba, Namkusong, Lee, & Crespo, 2019) has followed the IoT-based approach to design a system architecture that allow note only the reduction of supervision level of the farm but also enable remote monitoring of crop water requirement. The **Figure 7** shown below present the almost perfect link between sensors and actuators to facilitate a smart supply of adequate water to crop. Using Wi-Fi as the system's wireless communication protocol, the Arduino UNO as the microprocessor, authors have been able to ensure a remote monitoring of the irrigation process at an affordable price. Such system can be applied in the African context as access to later communication protocols such as Zigbee and LoRaWAN technologies most farmers.

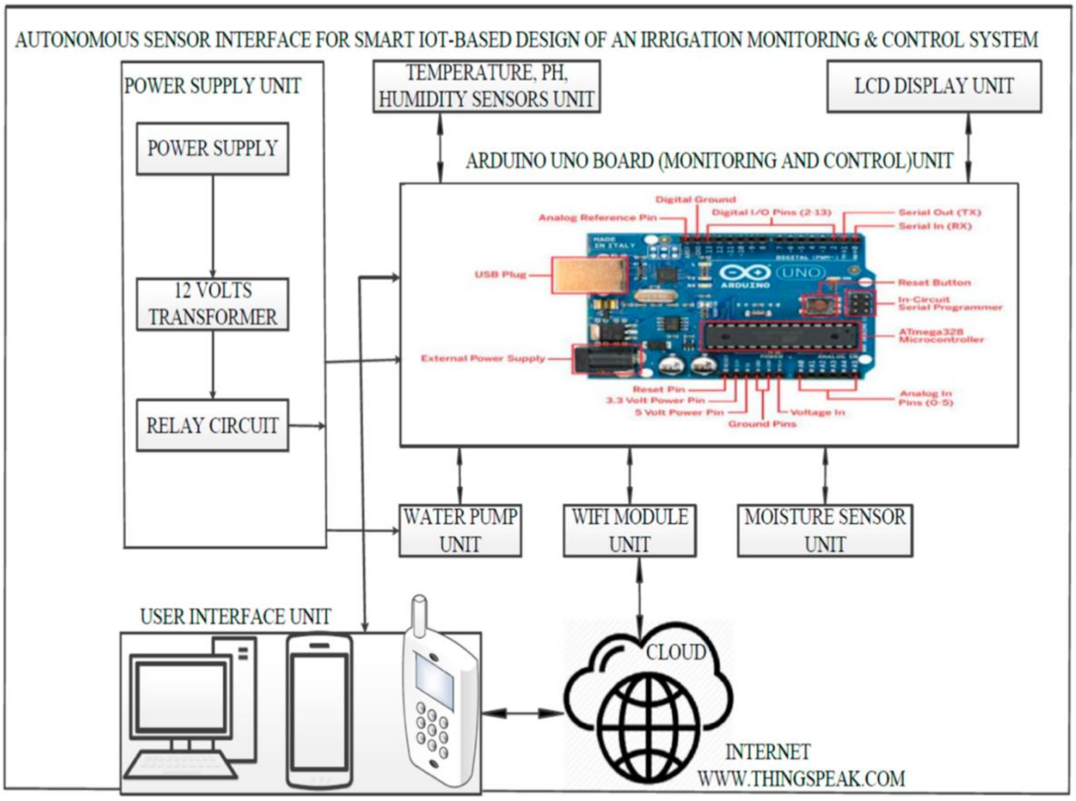


Figure 7. Example of a low-cost real-time irrigation monitoring system adapted from (Abba et al., 2019)

2.10. IoT wireless communication protocols

Various communication protocols are nowadays available for the different IoT application. Wireless communication protocols essentially differ from attenuation, data throughput, power consumption, coverage range (Abdelkader SALLEMINE, 2019). Depending on their characteristics and specifications (frequency, power consumption, coverage range, security, …), IoT wireless communication protocols can be classified as follow. The **Table 5** below illustrate a comparative analysis of various communication protocols enabling an easy and efficient selection IoT communication protocol for specific condition considering various parameters.

Table 5. Comparison of different wireless communication technologies adapted form (Jawad, Nordin, Gharghan, Jawad, & Ismail, 2017)

Parameters	*Zigbee*	*Classic BT*	*BLE*	*Wi-Fi*	*GPRS*	*LoRa*	*SigFox*
Standard	IEEE 802.15.4	IEEE 802.15.1	IEEE 802.15.1	IEEE802.11a,b,g,n	N/A	IEEE 802.15.4 g	IEEE 802.15.4g
Frequency band	868/915 MHz and 2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz	900–1800 MHz	869/915 MHz	868/915 MHz
Number of RF channels	1, 10, and 16	79	40	11	124	10 in EU, 8 in US	360
Channel bandwidth	2 MHz	1 MHz	1 MHz	22 MHz	200 kHz	< 500 kHz	<100 Hz
Power consumption in Tx mode	Low	Medium	Ultra-low	High	Medium	Low	Low
Data rate	20, 40 and 250 kbps	1-3 Mbps	1 Mbps	11-54 and 150 Mbps	Up to 150 kbps	50 kbps	100 bps
Communication range	100 m	10-50 m	10 m	100 m	1-10 Km	5 Km	10 Km
Network size	65,000	8	Limited by the application	32	1000	10,000 (nodes per BS)	1,000,000 (nodes per BS)
Security capability	128 bits AES	64 or 128 bits AES	64 or 128 bits AES	128 bits AES	GEA, MS-SGSN,	128b Encryption	not supported

					MS-host AES		
Network Topologies	P2P, tree, star, mesh	Scatternet	Star-bus	Point-to-hub	Cellular system	Star-of- stars	Stars
Application	WPANs, WSNs, and Agriculture	WPANs	WPANs	WLANs	AMI, demand response HAN	Agriculture, Smart grid, environment control, and lighting control	Agriculture and environment, automotive, buildings, and consumer electronics
Limitations	short communication distance	Short communication range	Concise communication range	High power consumption	Power consumption problem	The low data rate, scalability	Low data rate

2.11. Wireless Sensor Networks in the Context of real time crop water demand monitoring

In the **Table 6** illustrated below, several papers have been compared in terms of sensors, IoT devices, sensors, IoT platforms and actuators. From the table it can be noticed that authors most of time have the same aim, which consist of controlling different parameters involved in crop growth and water usage. Temperature and humidity are the most considered parameters while salinity and sunlight are less monitored. The Zigbee and LoRa communication protocols are used in most cases due to its low power consumption. Both have low power consumption, but LoRa is for long range networking while Zigbee is for short range.

Table 6. Comparation of several sensors, actuators, and platforms used in smart agriculture adapted from (Jawad et al., 2017)

Authors	**Sensors/ Actuators**	**IoT end device wireless protocol**	**IoT platform/ Device**	**IoT application layer**
(Mois, Folea, & Sanislav, 2017)	Soil moisture, salinity, and temperature	Wi-Fi/ZigBee/ Bluetooth	Wi-Fi, cloud	HTTP protocol and smartphone applications
(Navarro-Hellín et al., 2015)	Soil moisture, temperature, pressure, and water electrical conductivity and temperature	Bluetooth and mobile device	4G and cloud computing	Intelligent management (neural network)
(Sarangi, Umadikar, & Kar, 2016)	Camera to monitor the rice leaf disease	Sensor networks	Wisekar and cloud Computing	Web application and user-defined
(Yelamarthi, Aman, & Abdelgawad, 2017)	Temperature, humidity, soil moisture, and wind direction and speed	nRF wireless protocol	intel Edison and cloud computing	User interface and custom server
(Sales, Remedios, & Arsenio, 2015)	Temperature and soil moisture/ electrovalve	eZ430-RF2500 (IEEE802.15.4 / ZigBee-based CC2500)	1 Mbps	11-54 and 150 Mbps
(Jayaraman, Yavari, Georgakopoulos, Morshed, & Zaslavsky, 2016)	Temperature and soil moisture/irrigation system	Libelium WaspMotes, Remote, Netatmo, etc.	SmartFarmNet and Cloud computing	Server application, user interface, and do-it-yourself visualization

(Dan, Xin, Chongwei, & Liangliang, 2015)	Temperature, humidity, light, pressure, camera, CO_2, and wind direction and speed/air flow, sprinkler, and sunlight screen	ZigBee	Ethernet shield and GPRS	User applications and server applications
(Harun, Kassim, Mat, & Ramli, 2015)	Ambient temperature, soil moisture, pH value, and humidity/valves and pumps	ZigBee (XBee)	Ethernet/Wi-Fi/GSM	User applications
(Chen, Zhang, & Wang, 2015)	Air temperature, wind speed/direction, air humidity, air pressure, net radiation, sunshine duration, and precipitation/irrigation system	IEEE 802.11 or Bluetooth	GPRS	User applications (desktop client, web client, and mobile client) and web processing service
(Martínez, Pastor, Álvarez, & Iborra, 2016)	Air temperature, relative humidity, solar radiation, precipitation, water, and nutrients/irrigation system	IEEE 802.15.4/ZigBee	FIWARE platform and cloud computing	Web services, data analysis, and database
(Ferrández-Pastor, García-Chamizo, Nieto-Hidalgo, Mora-Pascual, & Mora-Martínez, 2016)	Temperature, Luminosity, PH, moisture, EC/lamps, electro-valves, and pumps	IEEE 802.15.4/ZigBee	Cloud computing	Web services, data analysis, database, and HMI interfaces

(F. Li, Li, Wang, Chen, & Zhao, 2016)	Temperature, light intensity CO_2 concentration, and humidity	ZigBee (CC2530)	GPRS (SIM300 module)	User application
(Mat, Mohd Kassim, Harun, & Mat Yusoff, 2016)	Soil moisture/water pumps, fan, and mist	ZigBee (XBee)	Wi-Fi and GSM/GPRS	Graphical user interface
(Khattab, Abdelgawad, & Yelmarthi, 2016)	Air temperature, wind speed and direction, leaf wetness, soil moisture, air humidity, rain volume/fertilizers or spraying chemicals and watering system	nRF24L01	IEEE 802.11b/g/n (Wi-Fi) and Cloud computing	Data visualization, data storage, data analysis, and application program interface

2.12. Microcontrollers used in crop water demand monitoring

In 2018, (Capraro et al., 2018) have used the MC9S08QE32 (8 bit) to empower the precision irrigation system developed to allow remote farm controlling. Produced by NXP Semiconductors, the microcontroller was embedded in a device called “Agromet”. (Abdelkader SALLEMINE, 2019) built a prototype based on a Pycom LoPy4. According to the author, the Pycom LoPy4 is the right choice when it comes to price, power, performance, and support for different communication protocols. From the LoPy4 datasheet it is mentioned that it supports networks such as LoRa, Sigfox, Wi-Fi, and Bluetooth. The choice of microprocessor is highly dependent on the communication protocol to be used.

Other microcontrollers used in the domain of precision agricultures are as follow: ATmega128L, Marvell PXA271, TIMSP430, TIMSP430, Cortex M3 LPC 17xx, ARM 920T, MSP430F2274, MSP430, MSP430G2553, MSP430F149, PIC24FJ64GB004, AT89C52, PIC18F452, PIC18F455, ATmega2560, AT86RF230, ATMega64L, 8051, JN5148, ATmega1284P, ARM9, ATmega328, MSP430F1611, PIC16F877A, MSP430FR5739, AT89S52, STM 32/F4, ATmega1281, ATMEGA 16 and PIC 18F452 (Jawad et al., 2017). It is noticeable that the ATmega processors are preferred in agriculture automation.

2.13. IoT data visualization platforms

The use of IoT technologies in water demand monitoring has huge advantages including collection of many data such as temperature, humidity, wind speed, etc. but the collected data cannot be analyzed and interpreted manually due to the huge volume of data being gathered every second. The solution is to illustrated data using appropriate chart type, that will considerably increase its value (Kamil Szydlowski, n.d.). The table below gives a comprehensive comparison between several IoT data visualization software.

Table 7. IoT data visualization platform examples

Platform	Key features	Source
Thingspeak	▪ Uses popular IoT protocols. ▪ Visualize sensor data in **real-time.** ▪ Supports third-party sources. ▪ Uses MATLAB ▪ Runs IoT analytics automatically based on schedules or events. ▪ No servers or web software development required. ▪ Automatically acts on data and communicate using third-party services like Twilio® or Twitter®.	https://thingspeak.com
ThingsBroad	▪ Allows Asset management & Data collection ▪ Provides End-user **real-time** dashboards ▪ Provides customizable rule chains, widgets ▪ Supports MQTT, HTTP, CoAP, OPC-UA transport ▪ **Supports NB-IoT, SigFox, LoRaWAN support** ▪ Scheduler available	https://thingsboard.io
Vegecloud	▪ VegeCloud allows you to	https://vegecloud.com

	▪ Data collect and management ▪ Graph viewing ▪ Alerts and texts data passes threshold ▪ Allows control of relays, pump, and valves. ▪ **Supports Wi-Fi** communication protocol	

3. MATERIALS AND METHODS

3.1. Introduction

This part is about the description of strategies and approaches adopted to fulfill the objectives listed in the first chapter. The chapter start with the description of the case study field, it continues with the use of FAO CROPWAT to design a water scheduling system for the farm, and it ends by describing the architecture, hardware and software of the real time crop water need monitoring system conceived as a prototype.

3.2. Description of case study area

Mali is the case study country of this research. The country has an estimated population of about 18 million and a land size of over 1,241,000 square km. Mali is in the Sahel region of Africa. "The Sahel region is one of the poorest and most environmentally degraded in the world. The region is considered one of the world's most vulnerable regions to climate change, as temperature increases are projected to be 1.5 times higher than in the rest of the world" (USAID, 2017).

Mean temperatures in the region range from 21.9° to 36.4°C but the mountainous regions of northern Chad, Niger, Mali, and the coastal zone of Mauritania are cooler. While the mean annual rainfall is limited to summer months (June-September) every year and every decade, it is higher in the south (500-600 mm) compared to the north (100-200 mm) (USAID, 2017).

The development of the irrigation scheduling and the design of the real-time water monitoring prototype will be based on the data collected from Katibougou. At about 66km from Bamako, an APV pilot demonstrator of 200kWp (see **Figure 8**) will be installed on an approximately one hectare (ha) of land reserved for research activities of the Rural Polytechnic Institute of Training and Applied Research (IPR/IFRA) in Katibougou. 50% of the land will be covered with APV under which selected crops will be cultivated and analyzed in an interdisciplinary approach. The remaining 50% will be used as a reference area to provide valuable comparative data on agricultural yield. Shade-tolerant farming procedures promote the expansion of renewable energies without taking additional land.

The campus of IPR/IFRA covers an area of 380 ha along the left bank of the Niger River with the following coordinates: 12-56' north latitude, 7-37' west longitude, 326 m altitude (see **Figure 9**).

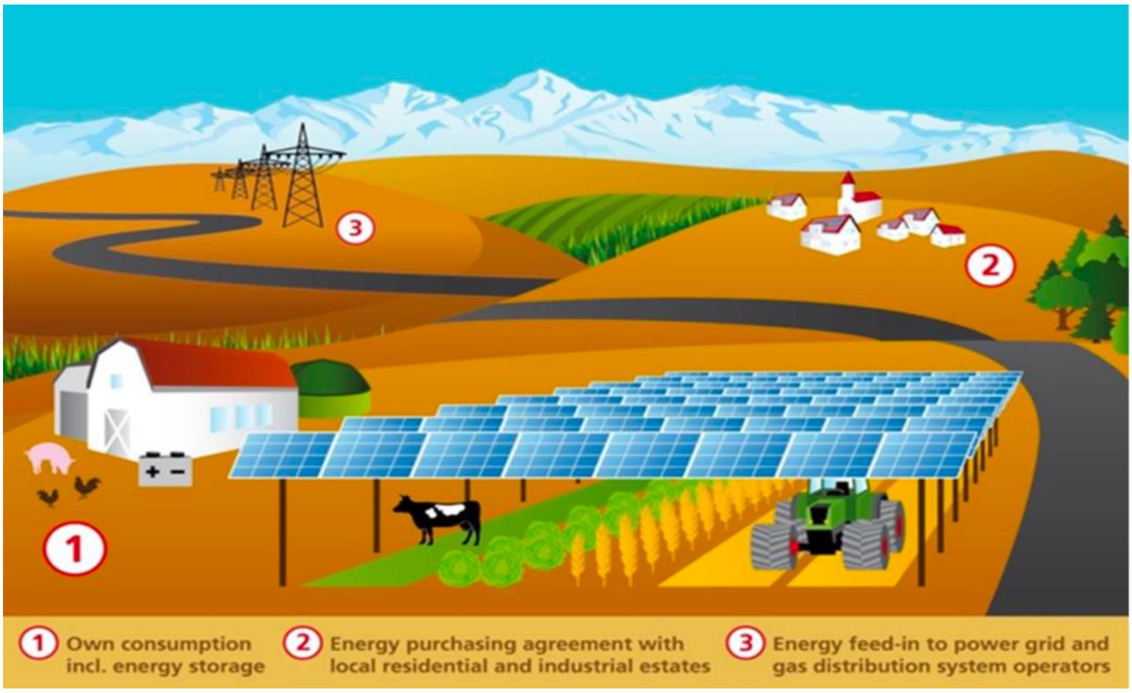


Figure 8. Illustration of an APV system adapted from (APV-MaGa, 2019)

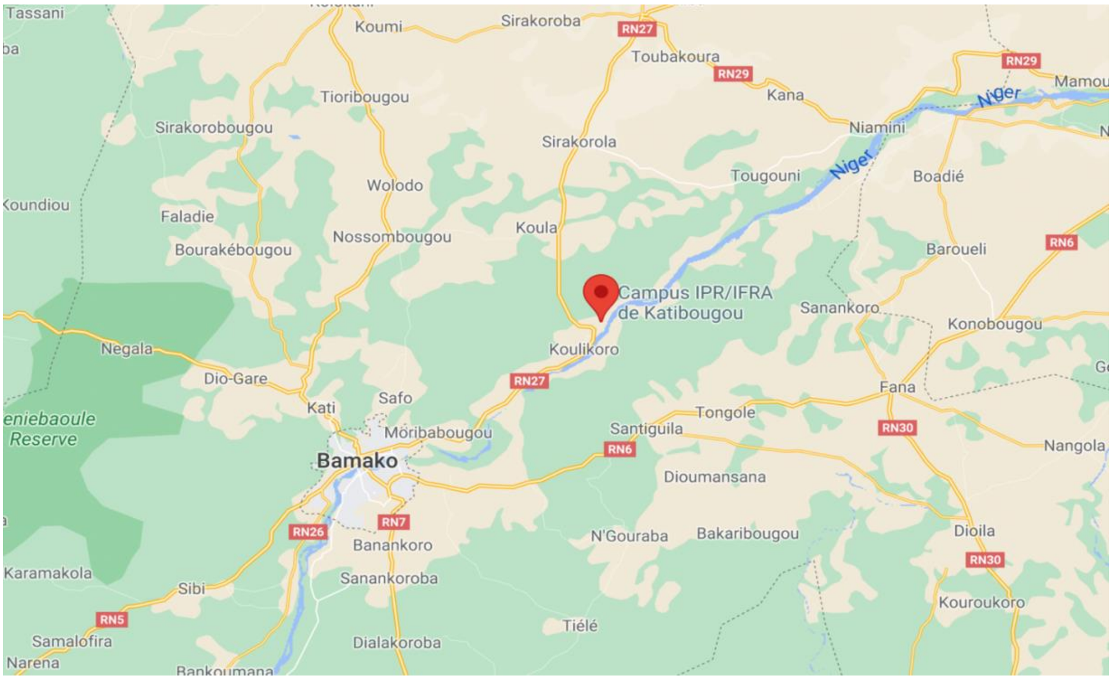


Figure 9. Localization of IPR/IFRA in Katibougou (source: Google Maps)

3.3. Data collection and data analysis

3.3.1. Data collection

The data used in this study are originated from “Meteonorm V7.1.11.24422”, which is a software developed by a leading swiss start-up called “Meteotest”. Meteotest works four main domains including weather, environment, climate, and computer science. The web address of the Meteonorm is a follow: https://meteonorm.com/en/. While the data acquisition period of the temperature is from 2000 to 2009, the radiation period is from 1991 to 2010. The data file was in PDF format but for a profound analysis and comprehension, we have used them to produce different graphics and tables (see Data analysis). The data concerning the country profile and some meteorological data (in Excel format) was collected from the “Mali Meto, http://www.malimeteo.ml” which is the national meteorological institute of the country.

Collected data include:

- Mali country profile data,
- Air temperature,
- minimum temperature,
- maximum temperature,
- relative humidity,
- sunshine hours,
- precipitation,
- solar radiation,
- Wind speed, and
- Wind direction

3.3.2. Data analysis and interpretation

The meteorological data collected and used in this study belongs to a nearby location named Koulikoro. Koulikoro has the following coordinates:

293: Altitude [m a.s.l.]
12.892: Latitude [°N]
-7.555: Longitude [°E]
V, 3: Climate region

Temperature interpolation locations: Bamako/Senou (58 km), Bobo Dioulasso (402 km), Mopti (414 km), Ouagadougou (600 km), Tambacounda (670 km)

3.3.2.1. Temperature

I it must be noticed that all the year is characterized by high temperatures with the highest maximum temperature of 41.3°C and the lowest minimum temperature of 14.4 (see **Figure 10**).

The hottest period lasts for approximately 6 months, from February to June. The average daily maximum temperature is above 38°C. While the highest temperature is observed in March, April and May Where the temperature is 41.3°C. The lowest temperature in the hottest period is observed in February with a value of 17.6.

The cool season starts in July and ends in October after which month we see temperatures increasing.

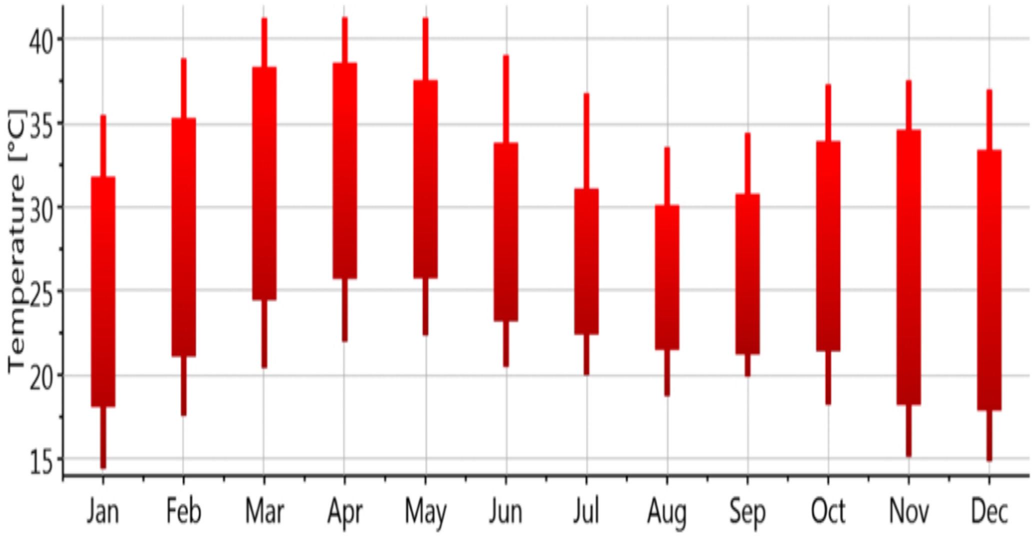


Figure 10. Monthly temperature in Koulikoro obtained from meteonorm V7.1.11.24422 (2000-2009)

3.3.2.2. Precipitation

In Katibougou, the annual total rainfall is around 916 mm (see

Figure *11*). January and December are month with no precipitation. From February to April and October to November, the total amount of rainfall is less than 50 mm. The wetter period of the year is between April and November with the peak precipitation of 283 in August. From this perspective, it is obvious that irrigation must be done to sustain crop productivity. Irrigation is not needed only in months with no precipitation (January and December) but also for the remaining months based on the ETc and Pe values. It is important to notice that both values are dependent on radiation and other meteorological parameters. Establishing an appropriate irrigation scheduling or monitoring the humidity to know when and how much water should be supplied to crop can help to practice a proper irrigation in this region suffering from water scarcity.

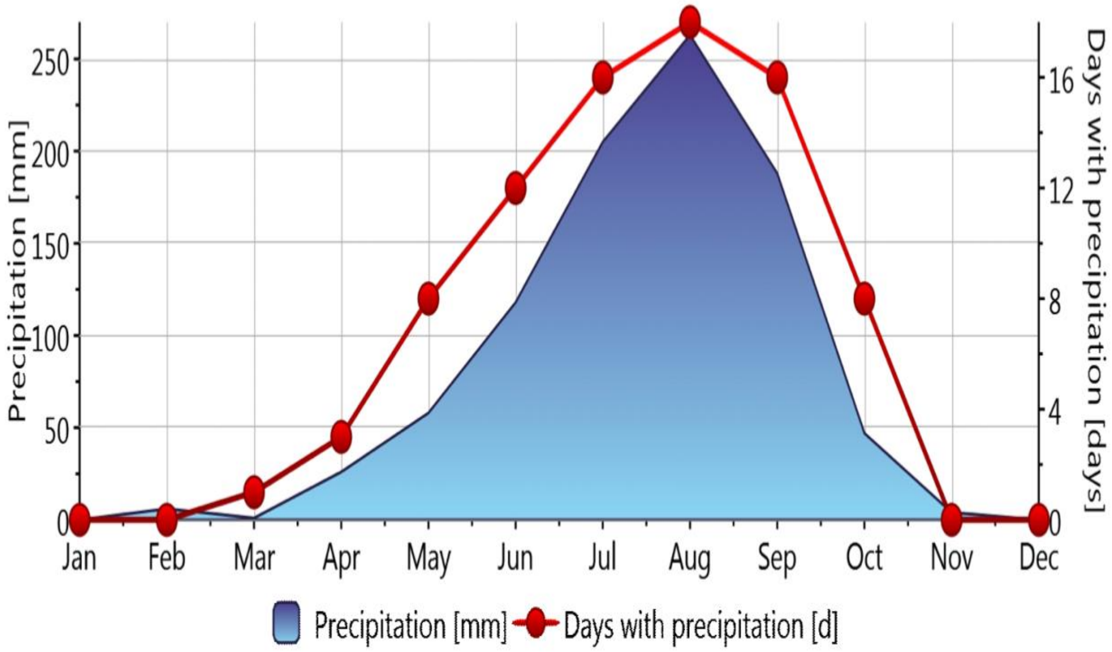


Figure 11. Monthly precipitation in Koulikoro obtained from meteonorm V7.1.11.24422

3.3.2.3. Sunshine duration

As opposite to the precipitation, the sunshine duration in Koulikoro is high all over the year with the highest value of 9.1 hours in February followed by 9.0 in November (see **Figure 12**). The lowest sunshine duration is obtained in August with a value of 7.0 hours. With high sunshine duration, the ET_O will be high due to increase evapotranspiration, therefore the ET_C will be high and if the Pe is low the amount of water to be supplied to the crops will also increase in this region.

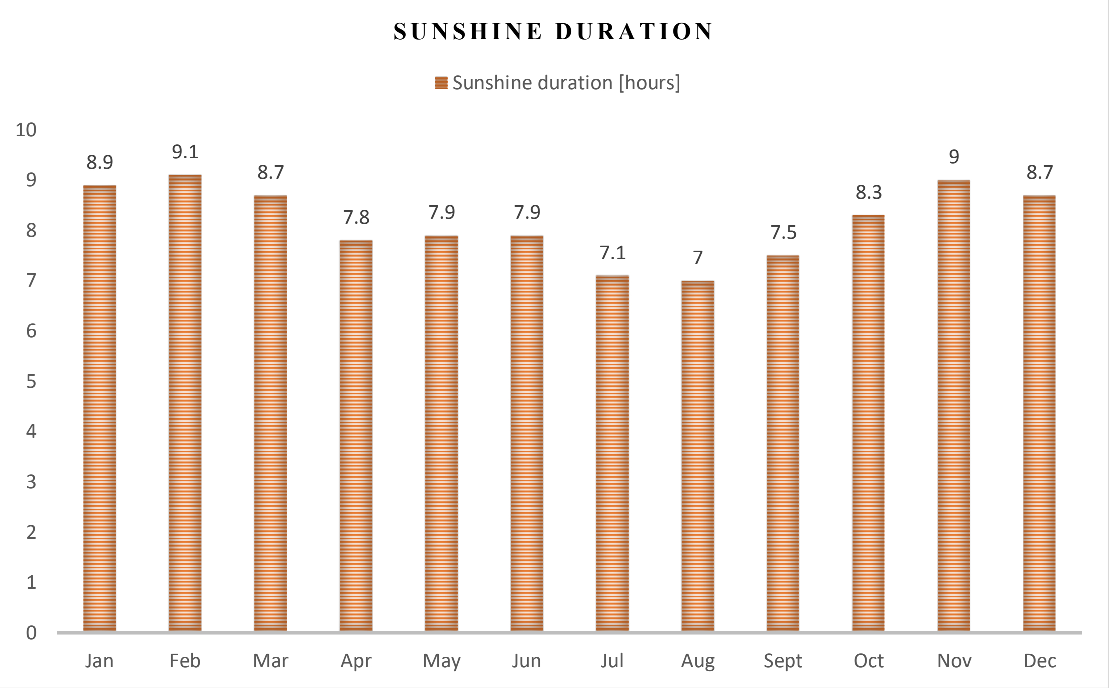


Figure 12. Monthly sunshine duration in Koulikoro

3.3.2.4. Wind speed

The speed at which the wind is moving is one of the important parameters that influence the ET_O value. The wind speed at a given location is highly related to the topography of the location. The wind speed at Koulikoro decrease from 3.3 to 1.7 m/s from January to October (**Figure 13**). The peak is observed in February and the lowest wind speed is observed in October. From the

Figure *11*, we have noticed a rainfall inferior to 50 mm in October and from the **Figure 12** a sunshine duration of 8.3 hours. We can suggest that the during October, the ET_C will be high resulting to a high irrigation water demand.

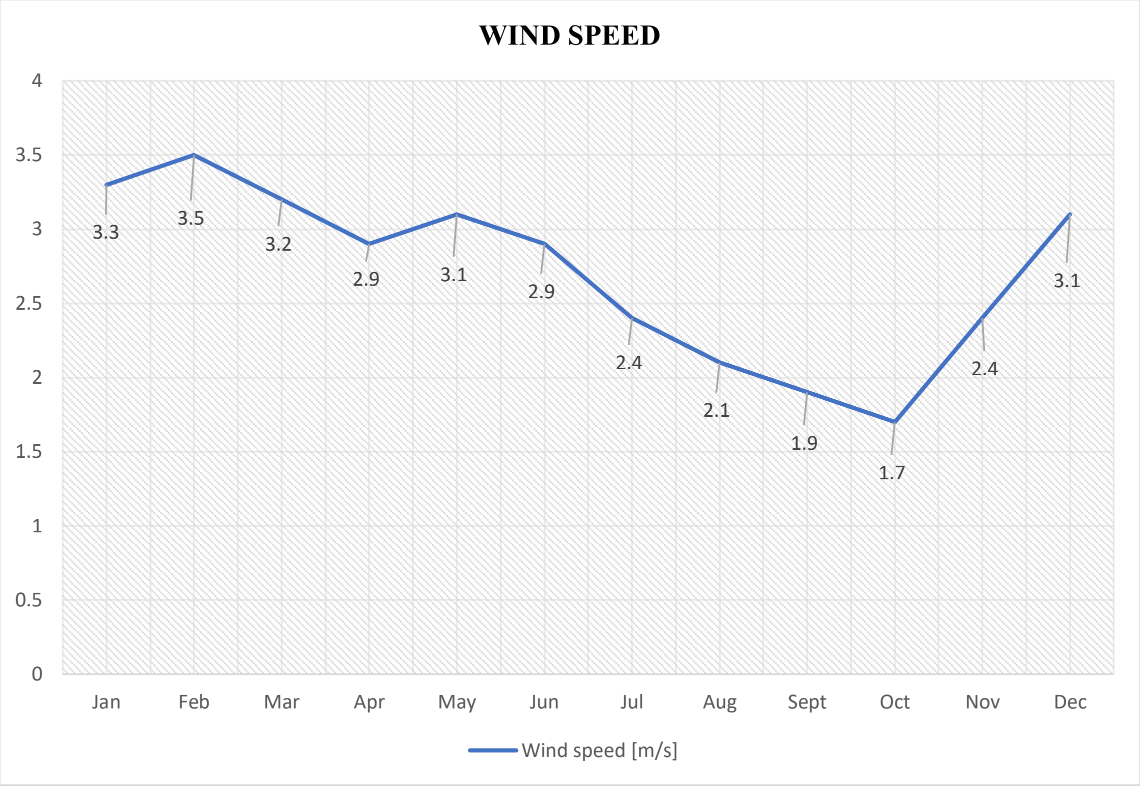


Figure 13. Monthly wind speed in Koulikoro

3.3.2.5. Relative humidity

Koulikoro experiences a seasonal variation when humidity is concerned. With a maximum relative humidity of 85 % observed in August, the region sees the muggier period of five month from June to October (see **Figure 14**). The first quarter of the year and the month of December have a very low relative humidity, this may be the result of high wind speed and high sunshine duration observed in that period of the year (see **Figure 11** and **Figure 12**). Because an APV system will be implemented for the farming, the relative humidly is expected to be high compared to the values presented on the **Figure 14**.

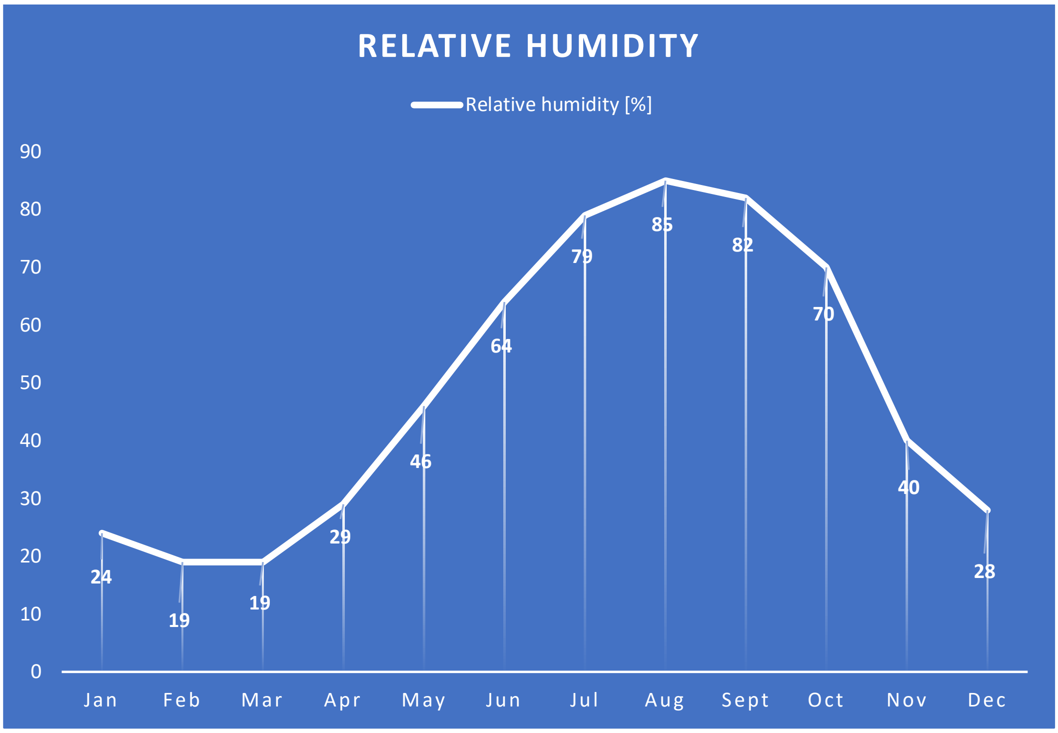


Figure 14. Monthly relative humidity in Koulikoro

3.3.2.6. Monthly radiation

The monthly global radiation increases from January to March, with the maximum value observed in March (212kWh/m^2). The lowest global radiation occurs in January. The farm is expected to be covers by solar PVs; this means that the solar radiation reaching crops will be decreased if we consider the suggestion (Fraunhofer ISE, 2019) according to which the solar radiation in an APV System is 30% lower than the normal traditional field.

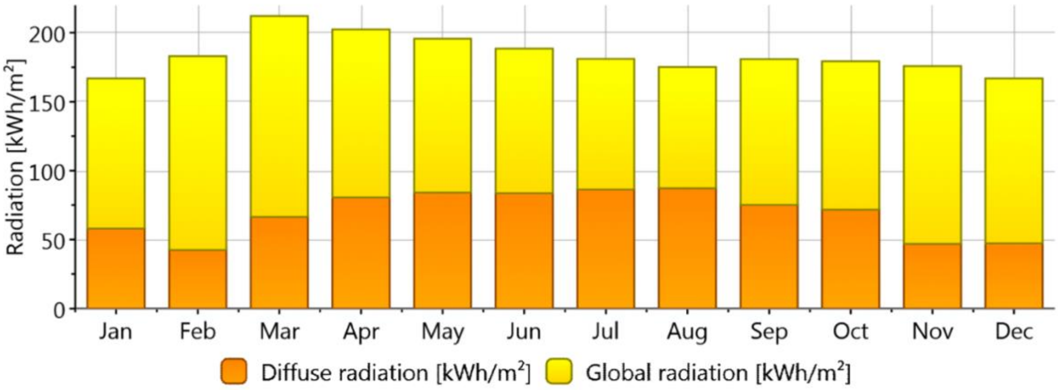


Figure 15. monthly radiation obtained from meteonorm V7.1.11.24422 (1991-2010)

3.4.Development of Irrigation scheduling

3.4.1. CROPWAT 8.0 usage and calibration

To develop an irrigation scheduling, climate data presented above are used.

3.4.1.1. Determination of ETo

CROPWAT 8.0 uses the FAO Penman-Monteith method to determine the ETo (see Equation (4)). The equation is directly integrated to the CROPWAT software. The meteorological used for the calculation of the ETO are as follow:

Location data: latitude, longitude, and altitude.
Meteorological data: maximum and minimum relative humidity, wind speed, sunshine hours, and maximum and minimum temperature.

3.4.1.2. Determination of effective rainfall

The United States Department of Agriculture Soil Conservation Services method show below is used for the calculation of the P_e. The Equation (22) and (23) below illustrate the formula used.

$$P_e = 124.8P_t\text{ , for } P < 250 \text{ mm} \tag{22}$$

$$P_e = 125 + 0.1P_t\text{ , for } P > 250 \text{ mm} \tag{23}$$

3.4.1.3. Soil data

- ***Soil water content***

For the determination of CRW, available water content, depth of the plant root zone, total available water, readily available water, and depletion volume are necessary. Equations given below facilitate the computation of those parameters.

$$AWC = FC - WP \tag{24}$$

$$TAW = AWC \ x \ R_d \tag{25}$$

$$RAW = pxTAW \tag{26}$$

Where;

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

AWC – available water capacity of the soil, (m^3/m^3)

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

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

- ***Physical and chemical properties***

The results of the laboratory analysis showed that the soil is a loamy-sand texture based on the USDA particle-size classification with a PH of 7.68. The soil data collected from the SEP-IER are presented in the **Table 8** below.

Table 8. Soil properties adapted from Laboratory SEP-IER, Mali

Soil properties	**Amount**
Texture: Sand (%) Silt (%) Clay (%)	72.00 26.00 2.00
PH in water	7.68
PH in KCl	6.96
Organic carbon (%)	0.65
Nitrogen total (%)	0.05
Phosphorous assimilable (ppm/100g)	78.32
Potassium assimilable (mg/100g)	10.64

3.4.1.4. Crop data

In a recent study conducted by (J.-L. FUSILLER, 1994), millet and sorghum are the popular crops in the savannah region of the West and Central Africa but maize is progressively being preferred. For this reason, in this study, maize has been chosen for CROPWAT simulation to give an insight on how maize farming can be as advantageous as sorghum and millet.

Planting date, harvesting dates, and crop coefficient are used in CROPWAT. The planting date and harvesting date were obtained from (FAO, 2020) and the crop coefficient and the length of growth stages form (Richard G. Allen et al., 1998).

3.4.1.5. Crop evapotranspiration

The product of the obtained ET_O at 3.4.1.1 is and the crop coefficient (K_C) derived from FAO 56 gives an estimated crop evapotranspiration (ET_C) (see Equation (15)).

3.5. Using CROPWAT to determine the irrigation water need

First all required data (input data) are used to adjust the CROPWAT model, then the software is run to obtain the output data.

Table 9. CROPWAT input data adapted from (Kennedy Ochieng Okuku, 2016)

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

Table 10. CROPWAT output data adapted from(Kennedy Ochieng Okuku, 2016)

OUTPUT	
Reference crop evapotranspiration (mm/period)	Actual crop evapotranspiration (mm)
Average values of crop coefficient for each stage	Effective rain (mm/period)
Irrigation requirements (mm/period)	Readily available moisture(mm)
Daily soil moisture deficit (mm)	Total available moisture (mm)
Ratio of actual crop evapotranspiration to the maximum crop evapotranspiration (%)	Crop water requirements (mm/period)
	Irrigation depth applied (mm)
Estimated yields reduction due to crop stress (when ETc/ETm falls below 100%)	Irrigation interval (days)
	Lost irrigation (mm)

3.6. Design of the real-time crop water need monitoring system

3.6.1. Architecture design

The **Figure 1** below illustrates the real-time crop water need monitoring system architecture. The system is composed of seven units: data processing and transferring unit incorporated with a control and monitoring unit (VG-HUB4-RELAY), which has a relay integrated into it, actuator unit (VG-PERISTALTIC PUMP), Wi-Fi module unit, sensor unit, the user interface unit, and the power supply unit.

All system is controlled by the monitoring and control unit which is directly connected to the sensor unit installed in the farm. The sensor unit is composed of soil moisture sensor, soil temperature sensor and the relative humidity sensor. The actuator node is essentially composed of a pump. The power supply unit is integrated into the monitoring and control unit. Using Wi-Fi communication protocol, data collected from the field using the sensor node is transferred to a remote server and displayed on “Vegecloud (vegecloud.com)”. Any user can remotely access data through vegecloud.com using a computer, mobile phone or any other device enabling internet browsing.

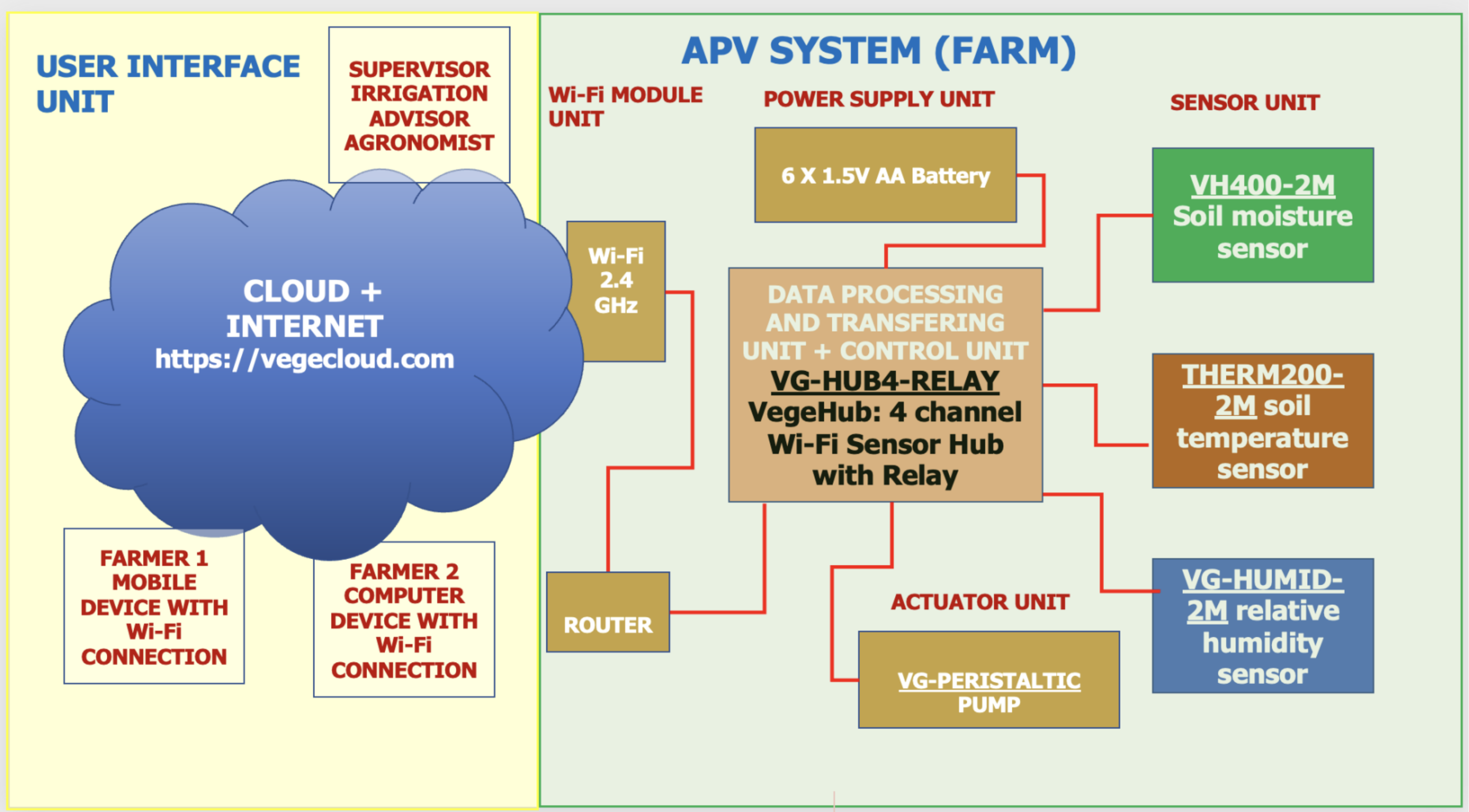


Figure 16. Real-time crop water demand monitoring system architecture

3.6.1.1. Hardware selection

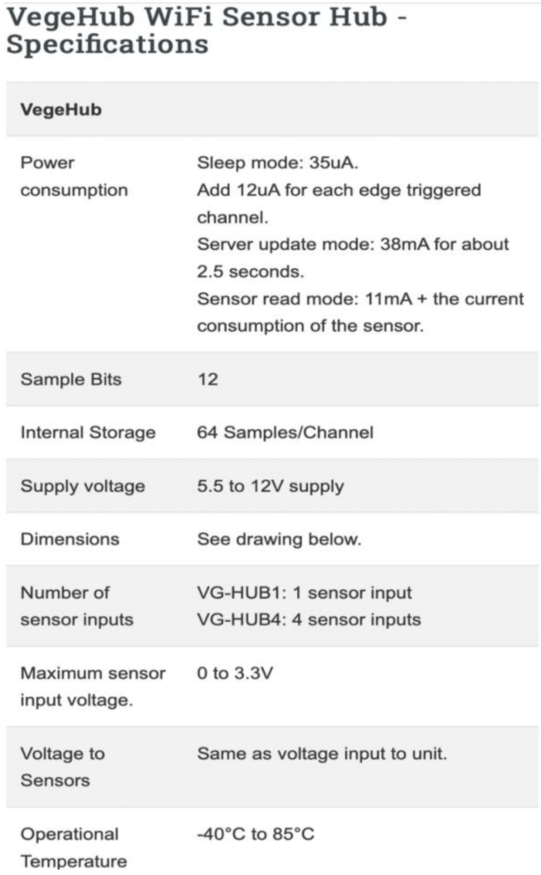
The selection of the physical components for prototyping is prominent. Factors like efficiency, durability and reliability are the most important characteristics to consider during the components' selection stage. We should bear in mind that the prototype is being designed for a particular case study country which is Mali. We considered the ability for farmers to use an advanced controlling system. Different climatic and environmental aspects of Katibougou have been taken into account while selecting the components.

3.6.1.2. Description of different unites

3.6.1.2.1. Data processing and transferring and control unit (VG-HUB4-RELAY) Vegehub: 4 channel wi-fi sensor hub with relay

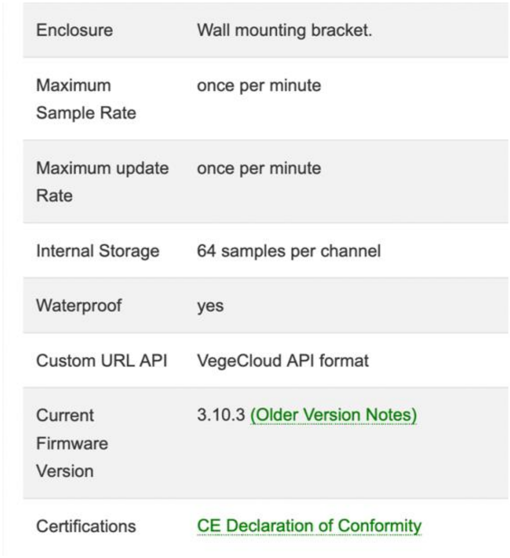
We have selected the Vegehub Wi-Fi sensor hub because of its simple setup, watertight enclosure. The enclosure protects it from the extreme weather conditions (dust, high temperature, irrigation water) in Katibougou. The Vegehub will fulfill our main requirement which is to post data to regular HTTP connection. The data display is also quick on the third-party websites such as Thingspeak and any other website because of its configurable URL. Vegehub allows to avoid long cable to connect sensors and woks with most the most deployable, mobile, and convenient communication protocol (Wi-Fi). The internal storage of 64 samples for each channel. Long battery life. The **Table 11** below shows the technical specifications and dimensions of the wi-fi sensor hub. The integrated relay facilitates the control of the peristaltic water pump by switching it on and off manually or automatically according to some threshold values of sensor values set by the user.

Table 11. Vegehub datasheet adapted from Vegetronix



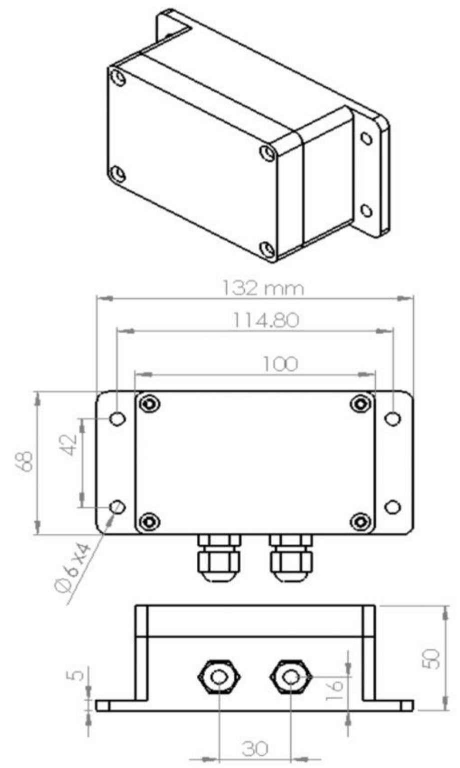
VegeHub WiFi Sensor Hub - Specifications

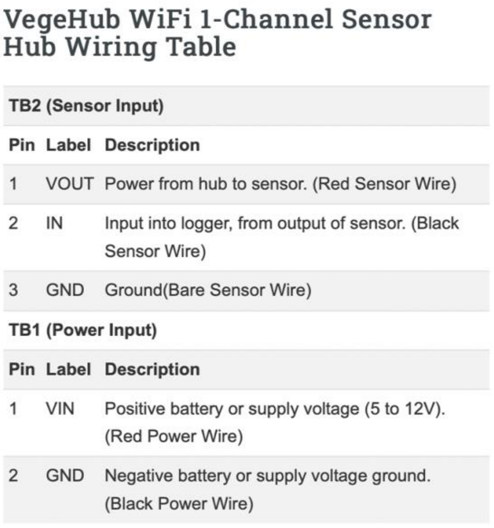
VegeHub	
Power consumption	Sleep mode: 35uA. Add 12uA for each edge triggered channel. Server update mode: 38mA for about 2.5 seconds. Sensor read mode: 11mA + the current consumption of the sensor.
Sample Bits	12
Internal Storage	64 Samples/Channel
Supply voltage	5.5 to 12V supply
Dimensions	See drawing below.
Number of sensor inputs	VG-HUB1: 1 sensor input VG-HUB4: 4 sensor inputs
Maximum sensor input voltage.	0 to 3.3V
Voltage to Sensors	Same as voltage input to unit.
Operational Temperature	-40°C to 85°C



Enclosure	Wall mounting bracket.
Maximum Sample Rate	once per minute
Maximum update Rate	once per minute
Internal Storage	64 samples per channel
Waterproof	yes
Custom URL API	VegeCloud API format
Current Firmware Version	3.10.3 (Older Version Notes)
Certifications	CE Declaration of Conformity

VegeHub WiFi Sensor Hub - Dimensions





VegeHub WiFi 1-Channel Sensor Hub Wiring Table

TB2 (Sensor Input)		
Pin	**Label**	**Description**
1	VOUT	Power from hub to sensor. (Red Sensor Wire)
2	IN	Input into logger, from output of sensor. (Black Sensor Wire)
3	GND	Ground(Bare Sensor Wire)
TB1 (Power Input)		
Pin	**Label**	**Description**
1	VIN	Positive battery or supply voltage (5 to 12V). (Red Power Wire)
2	GND	Negative battery or supply voltage ground. (Black Power Wire)

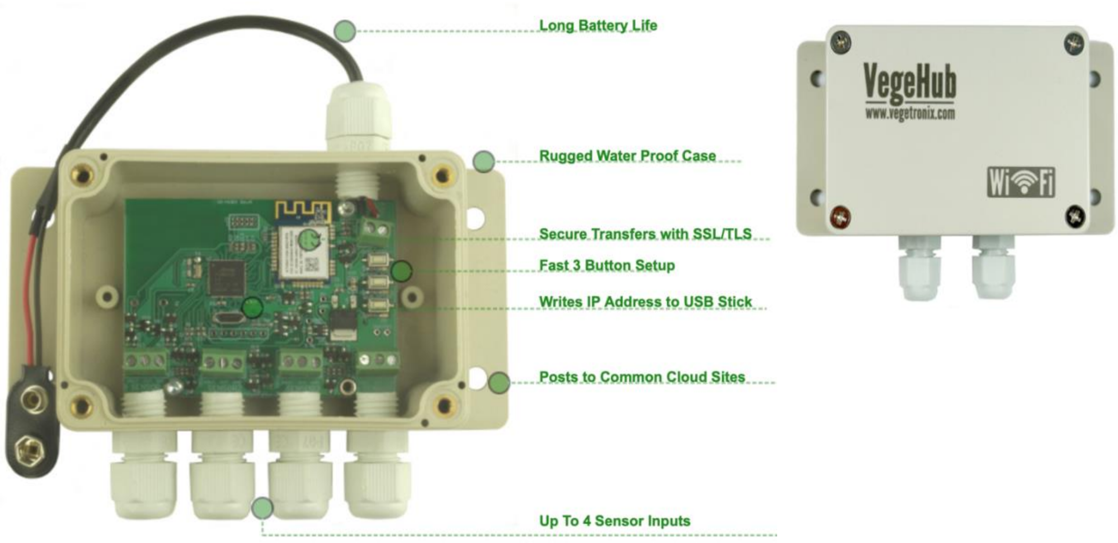


Figure 17. VG-HUB4-RELAY VegeHub: 4 channel Wi-Fi Sensor Hub with Relay adopted from Vegetronix

3.6.1.2.2. Sensor unit (soil moisture sensor, temperature sensor and relative humidity sensor)

From the literature review we have noticed that the most common monitored parameters in automated irrigation are soil moisture, temperature, and relative humidity (see **Table 6**). These sensors were selected not only to ensure an easy demonstration of the system but also to make sure the most relevant parameters influencing the CWR or ET_O are monitored. The system will automatically irrigate the crops based on the sensor readings. An approximate CRW can be determine and a decision on whether crop need to be irrigated will be done based on the temperature, relative humidity, and soil moisture values. The **Table** below illustrates the relation between the ET_C and different climatic parameters. In the table the soil moisture is not mentioned but it is obvious that a high soil moisture result to a low ET_C. Depending on the specific conditions and needs of a farm, several sensors can be added. Even its possible to add sensors that allow the monitoring of the parameters participating the calculation of ET_O as it was in the case of a study of (Capraro et al., 2018).

Table 11. Effect of major climatic factors on crop water needs adapted from (Will Critchley & Klaus Siegert, 1991)

Climatic factor	Crop water need (ETc)		
	High	Low	
Sunshine	Sunny (no cloud)	Cloudy (no sun)	
Temperature	Hot	cool	
Humidity	Low (dry)	High (humid)	
Wind speed	windy	Little wind	
Climatic zone	Mean daily temperature		
	Low (<15°C)	Medium (<15-25°C)	High (>25°C)
Desert/ arid	4-6	7-8	9-10
Semi-arid	4-5	6-7	8-9

For this study we have selected the VH400-2M soil moisture sensor, the THERM200-2M soil temperature sensor and the VG-HUMID-2M relative humidity sensor produce by an US based agricultural startup Vegetronix. The two sensors are shown respectively in the **Figure 18**, and **Figure 19** their main characteristics and advantages.

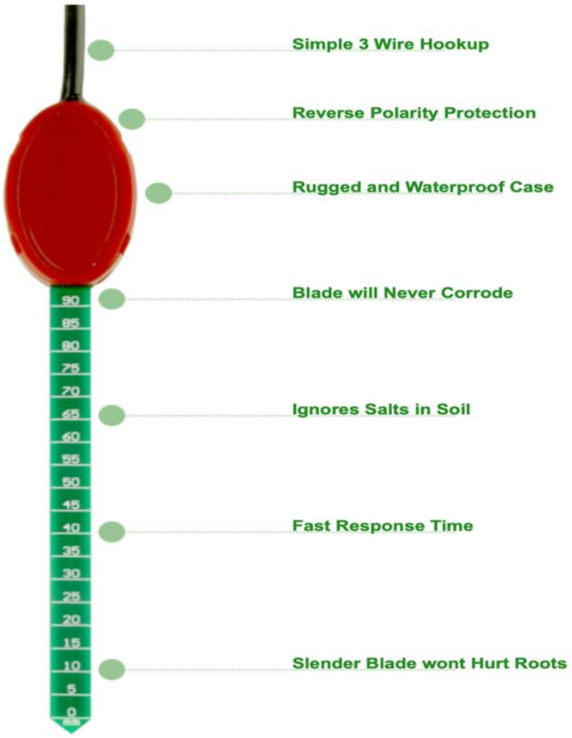


Figure 18. VH400-2M Soil moisture sensor adapted from Vegetronix

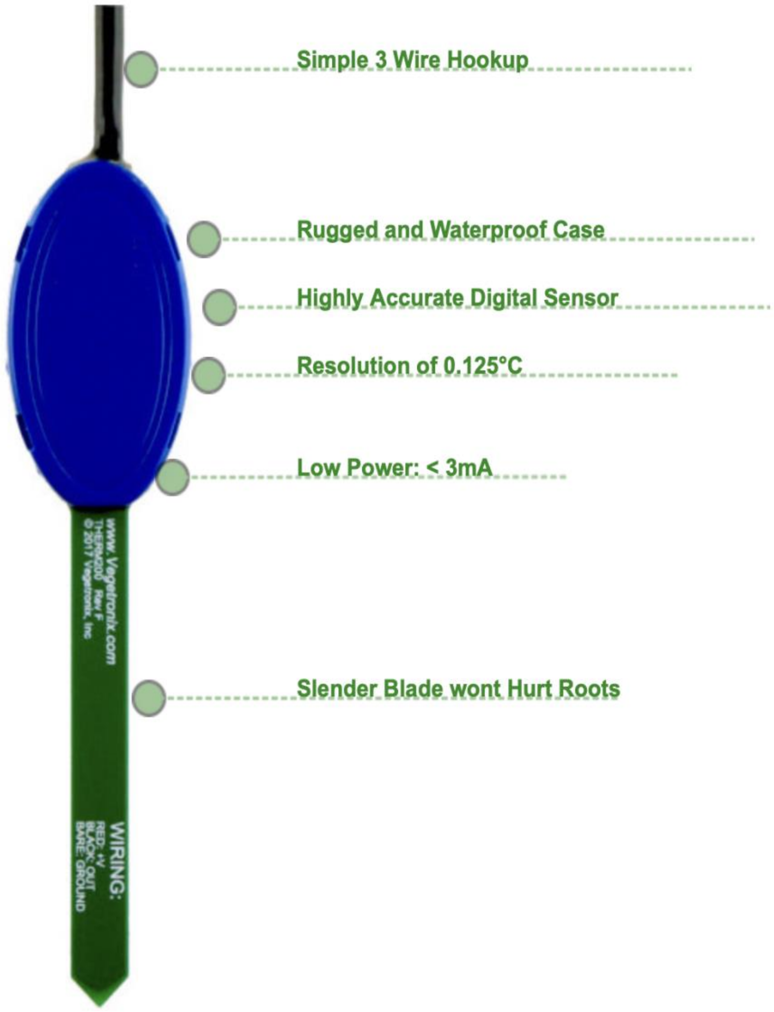


Figure 19. TERM200-2M Soil temperature sensor adapted from Vegetronix

3.6.1.2.3. Wi-Fi module unit

This unit is composed of a physical part (router) and the virtual part, which is a communication protocol (Wi-Fi). A router used for prototyping is already being used at home for internet connection.

3.6.1.2.4. Power supply unit

The power supply unit is a battery composed of 6 AA batteries. A battery holder has been used to regroup the batteries together. We chose this option because the technical specifications of the Wi-Fi sensor hub indicate a supply voltage that range between 5.5 and 12V. For normal use, another power supply source can be used provided that the final inlet power voltage to the sensor hub is between 5.5 and 12V.

Figure 20. Power supplying batteries: 6 x 1.5 V AA

3.6.1.2.5. Actuator unit

The bi-directional communication is ensured by the actuator. The pump is used to demonstrate the irrigation process in the system. Below are the characteristics of the VG-PERISTALTIC pump used in this study (see **Figure *21*** and **Table *12***).

- Flow rate is settable by turning a thumb wheel.
- Low cost.
- Compact attractive design.
- 15 Failsafe timed outputs, or continuous operation.
- Changeable flow direction
- Settable flow rate between 19 and 100 mL/ mi

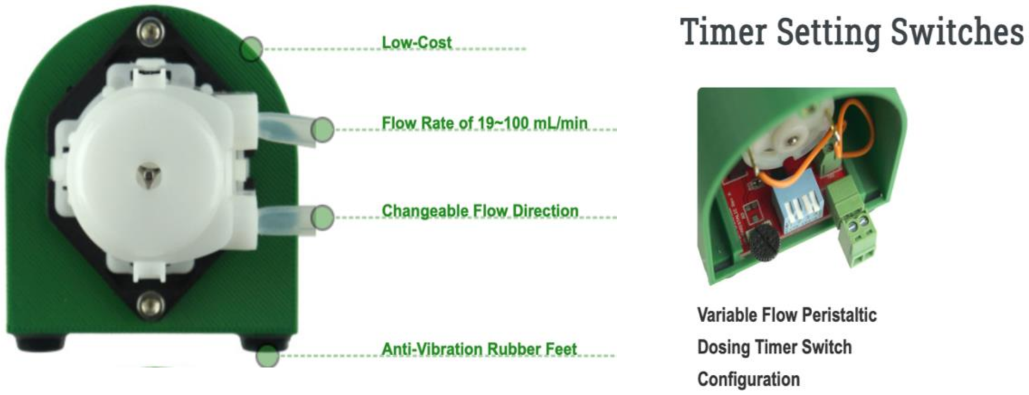
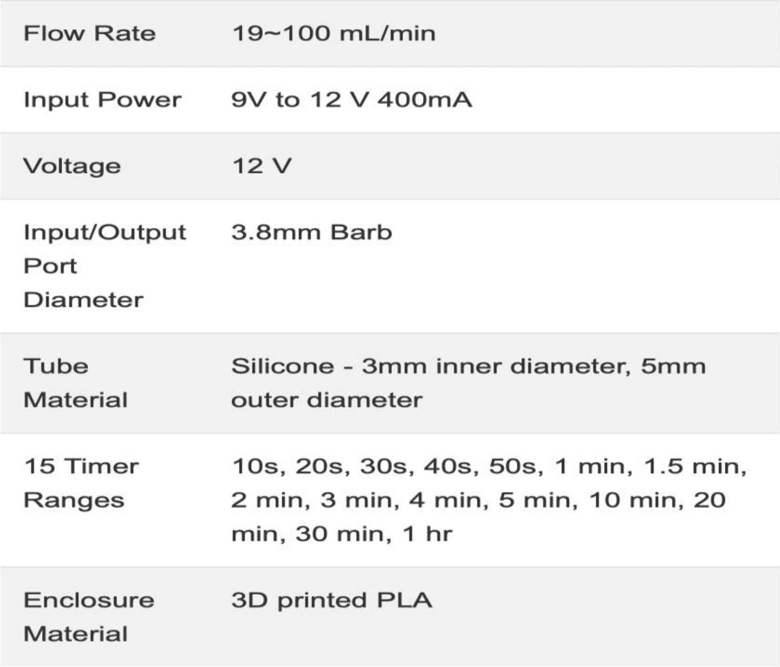


Figure 21. VG-PERISTALTIC pump adapted from Vegetronix

Table 12. VG-PERISTALTIC pump specifications adapted from Vegetronix



Flow Rate	19~100 mL/min
Input Power	9V to 12 V 400mA
Voltage	12 V
Input/Output Port Diameter	3.8mm Barb
Tube Material	Silicone - 3mm inner diameter, 5mm outer diameter
15 Timer Ranges	10s, 20s, 30s, 40s, 50s, 1 min, 1.5 min, 2 min, 3 min, 4 min, 5 min, 10 min, 20 min, 30 min, 1 hr
Enclosure Material	3D printed PLA

3.6.1.2.6. User interface Unit

The hardware of the user interface unit can be any device capable of using an internet browser such as a mobile phone, a computer, or a tablet. In this study we have used a computer to access the URL of Vegecloud. As illustrated on the **Figure 16**, multiple users can access and control the system remotely. This unit constitute the monitoring unit where user can visualize, analyze and take decisions based on data and graphs provided on Vegecloud.

3.6.1.3. Wi-fi communication protocol

After carefully reviewing the literature on different communication protocols used in IoT (see **Table 5**), we have chosen the Wi-Fi to link different component because of various reasons. To start with, Wi-Fi communication is widely used in the world compared to new communication protocols such as LoRa, Zigbee, etc. Moreover, Wi-Fi communication protocol is more convenient as it allows users to access network resources from any location (home, office, …). Wi-fi also offers a mobility advantages like mobility and expandability. Except a high-power consumption, Wi-Fi offers an acceptable communication range of 100m and data rate of 11-54 and 150 Mbps. Finally, considering the case study, choosing a newly founded communication protocols like Sigfox or Lora-Wan can create extra difficulty to farmers who are not quite familiar with advanced technology.

3.6.1.4.VegeCloud

It is an opensource platform that offer services such as data collection and visualization and device management. Vegecloud helps in collecting and managing data using sensors. Collected data can be processed and presented in form of graph for an easy decision making using VegeCloud. Using the platform, a user can receive texts and alerts when sensors reach a set threshold. Relays, pumps, and valves can also be controlled using VegeCloud. In brief, data collected from the field using sensors can be posted on https://vegecloud.com.

4. RESULTS AND DISCUSSION

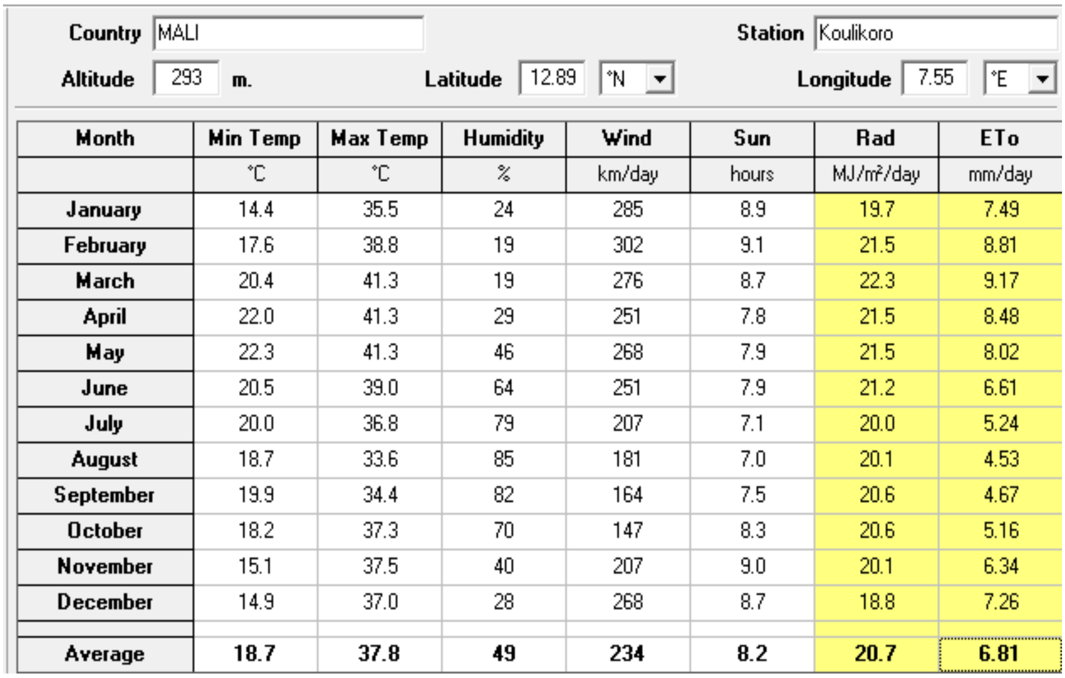
4.1. Introduction

This chapter is composed of details about the different results from CROPWAT 8.0, the details about the technical performance of the proposed protype. In the discussion, a relation between the irrigation schedule established through CROPWAT 8.0 and the water monitoring prototype based on personal observations has been established.

4.2. CROPWAT 8.0 simulation results

4.2.1. Reference crop evapotranspiration

The CROWAT 8.0 was used to calculate the ETo through the Penman-Monteith method. Compared to others approaches the FAO Penman-Monteith approach gives consistent results according to FAO. The **Figure 22** below shows the meteorological data collected from Koulikoro for ETo calculation.



Country MALI
Station Koulikoro
Altitude 293 **m.**
Latitude 12.89 °N
Longitude 7.55 °E

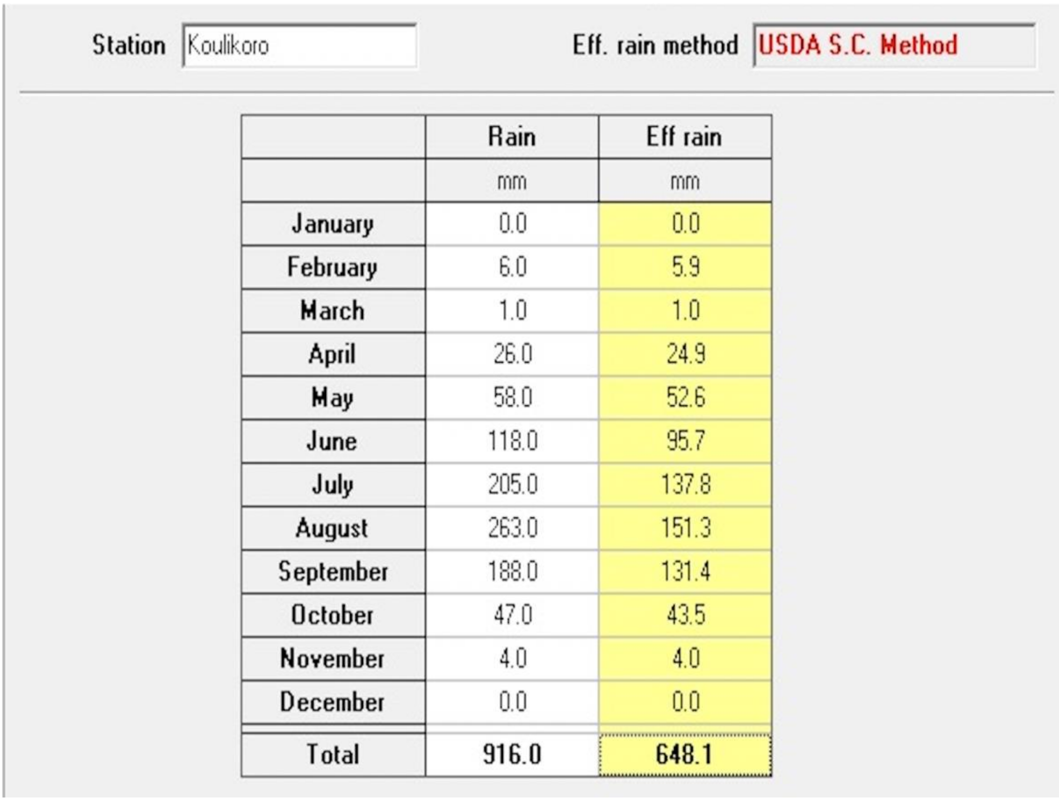
Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	14.4	35.5	24	285	8.9	19.7	7.49
February	17.6	38.8	19	302	9.1	21.5	8.81
March	20.4	41.3	19	276	8.7	22.3	9.17
April	22.0	41.3	29	251	7.8	21.5	8.48
May	22.3	41.3	46	268	7.9	21.5	8.02
June	20.5	39.0	64	251	7.9	21.2	6.61
July	20.0	36.8	79	207	7.1	20.0	5.24
August	18.7	33.6	85	181	7.0	20.1	4.53
September	19.9	34.4	82	164	7.5	20.6	4.67
October	18.2	37.3	70	147	8.3	20.6	5.16
November	15.1	37.5	40	207	9.0	20.1	6.34
December	14.9	37.0	28	268	8.7	18.8	7.26
Average	**18.7**	**37.8**	**49**	**234**	**8.2**	**20.7**	**6.81**

Figure 22. Monthly weather parameters and ETO

With a mean daily reference evapotranspiration of 6.81 mm, Koulikoro (Katibougou) present high values of ETo from January to May and December. This may be due to a relatively high monthly radiation, low humidity and high temperature observed in these months. August and September present low ETo due to the low radiation and sunshine duration coupled with high humidity rate and relatively low temperature values. From June to November the ETO is lower than 7.00 mm and decreases from 8.02 mm in May to 4.67 mm in September. Essentially, wo main seasons can be identified, the cool season August to December and the dry season from January to July.

4.2.2. Rainfall

Monthly rainfall data is primordial for determining the P_e. By Observing the **Figure 24** below, we can notice that rainfall is highly irregular in the region of Katibougou. While January, March, and December are months with practically no precipitation, the amount of rainfall in August is up to 263 mm. As a result of our observation of the **Figure *23*** below, the rain season in Katibougou can be said to begin in April and end in October. The dry season starts in November and ends in March. The results of the P_e obtained through the USDA S.C. Method show very low if not 0 values. These values are not surprising as the low Rainfall leads naturally to a lower P_e (see Equation (20) and (21)).



Station: Koulikoro

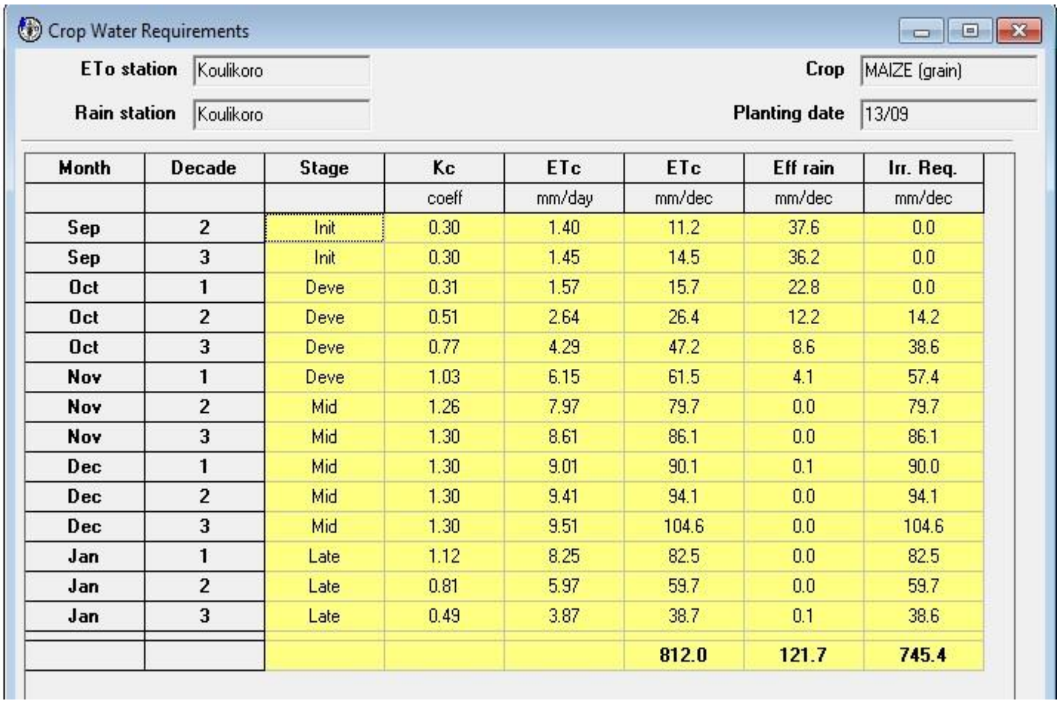
Eff. rain method: USDA S.C. Method

	Rain	Eff rain
	mm	mm
January	0.0	0.0
February	6.0	5.9
March	1.0	1.0
April	26.0	24.9
May	58.0	52.6
June	118.0	95.7
July	205.0	137.8
August	263.0	151.3
September	188.0	131.4
October	47.0	43.5
November	4.0	4.0
December	0.0	0.0
Total	916.0	648.1

Figure 23. Monthly rainfall and effective rainfall

4.2.3. Actual crop evapotranspiration

The seasonal ET_C was evaluated at 810.0 mm. During the season, it can be observed that the September and October have low actual evapotranspiration. On the opposite, November, December, and January have high ET_C values. The value of ETC is high in dry season and low in rainy season because of crops need more water in dry season due to high radiation and evapotranspiration phenomenon that occurs in this season. Contrarily, in the rain season the evapotranspiration is low, therefore low ET_C September and October are both months of rainy season while from November to December we are still in dry season in Katibougou.



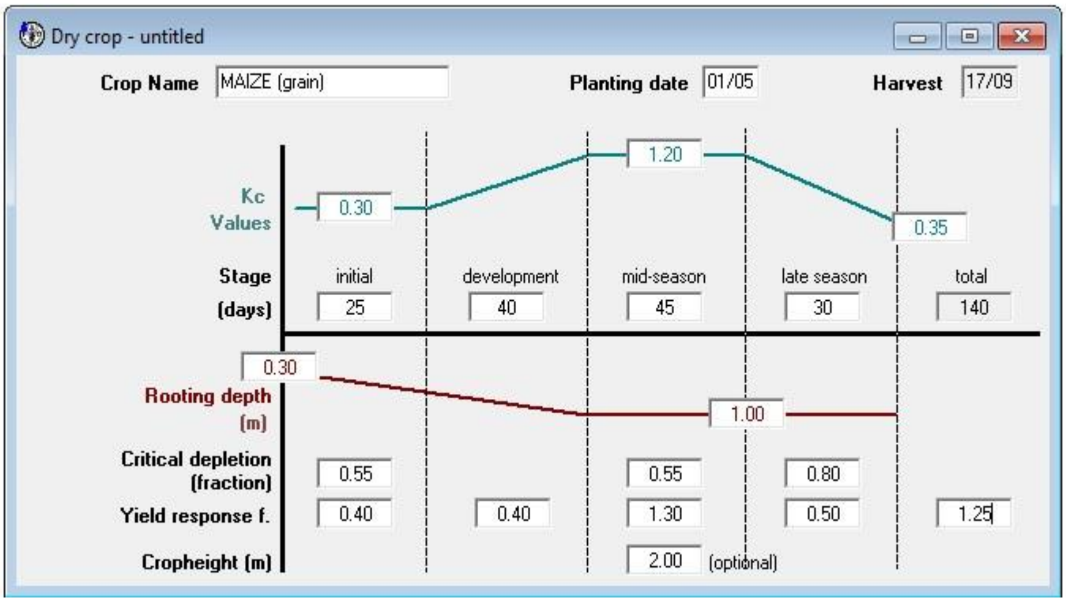
ETo station Koulikoro
Rain station Koulikoro
Crop MAIZE (grain)
Planting date 13/09

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Sep	2	Init	0.30	1.40	11.2	37.6	0.0
Sep	3	Init	0.30	1.45	14.5	36.2	0.0
Oct	1	Deve	0.31	1.57	15.7	22.8	0.0
Oct	2	Deve	0.51	2.64	26.4	12.2	14.2
Oct	3	Deve	0.77	4.29	47.2	8.6	38.6
Nov	1	Deve	1.03	6.15	61.5	4.1	57.4
Nov	2	Mid	1.26	7.97	79.7	0.0	79.7
Nov	3	Mid	1.30	8.61	86.1	0.0	86.1
Dec	1	Mid	1.30	9.01	90.1	0.1	90.0
Dec	2	Mid	1.30	9.41	94.1	0.0	94.1
Dec	3	Mid	1.30	9.51	104.6	0.0	104.6
Jan	1	Late	1.12	8.25	82.5	0.0	82.5
Jan	2	Late	0.81	5.97	59.7	0.0	59.7
Jan	3	Late	0.49	3.87	38.7	0.1	38.6
					812.0	**121.7**	**745.4**

Figure 24. Monthly actual crop evapotranspiration and irrigation requirement

4.2.4. Crop data determination

Crop related data such as allowable depletion, KC, plant growth stages, planting date and rooting depth were determined based on collected data. The KC varies not only according to the crop type but also the growth stages of the crop. The crop coefficients are obtained from **Table 2**. Crop data for maize are illustrated on the **Figure 26** below.

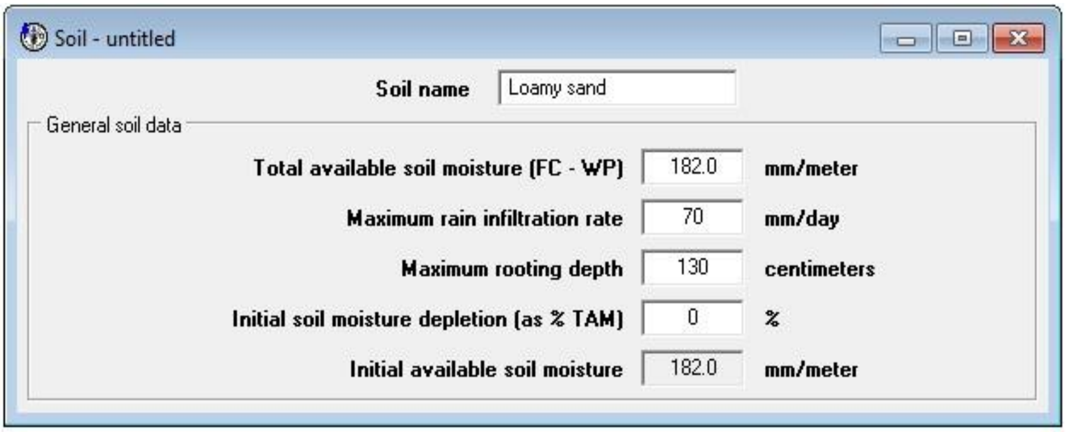


Crop Name: MAIZE (grain)
Planting date: 01/05
Harvest: 17/09

	initial	development	mid-season	late season	total
Kc Values	0.30		1.20	0.35	
Stage (days)	25	40	45	30	140
Rooting depth (m)	0.30		1.00		
Critical depletion (fraction)	0.55		0.55	0.80	
Yield response f.	0.40	0.40	1.30	0.50	1.25
Cropheight (m)			2.00 (optional)		

Figure 25. Maize crop data

4.2.5. Soil data computing



Soil name: Loamy sand

Total available soil moisture (FC - WP): 182.0 mm/meter
Maximum rain infiltration rate: 70 mm/day
Maximum rooting depth: 130 centimeters
Initial soil moisture depletion (as % TAM): 0 %
Initial available soil moisture: 182.0 mm/meter

Figure 26. Soil data for the case study area

According to the data obtained from the Laboratory SEP-IER in Mali, the texture of the soil in the study area is as follow:

Sand: 72%
Silt: 26%
Clay: 2%

Using the below, we can classify the soil as Loamy sand.

To consider the initial irrigation requirement for soil preparation, the soil moisture at the start of crop growth is assumed to be zero. The available water capacity of the soil (AWC) can be found. The rooting depth of maize from is between 1-1.7m (Richard G. Allen et al., 1998). We have chosen the average value 1.3m (FAO, 1989) for the calculation. The available soil content of loamy silt is assumed to be 140mm/m, an approximate average of the interval given by (FAO, 1985). Depletion factor of maize is 55%. Therefore, from the Equation (25); TAW = AWC * Rd

= 140mm/m *1.3m
= 182mm

From the Equation (26), $RAW = p \times TAW$

= 0.55*182

= 100.1mm

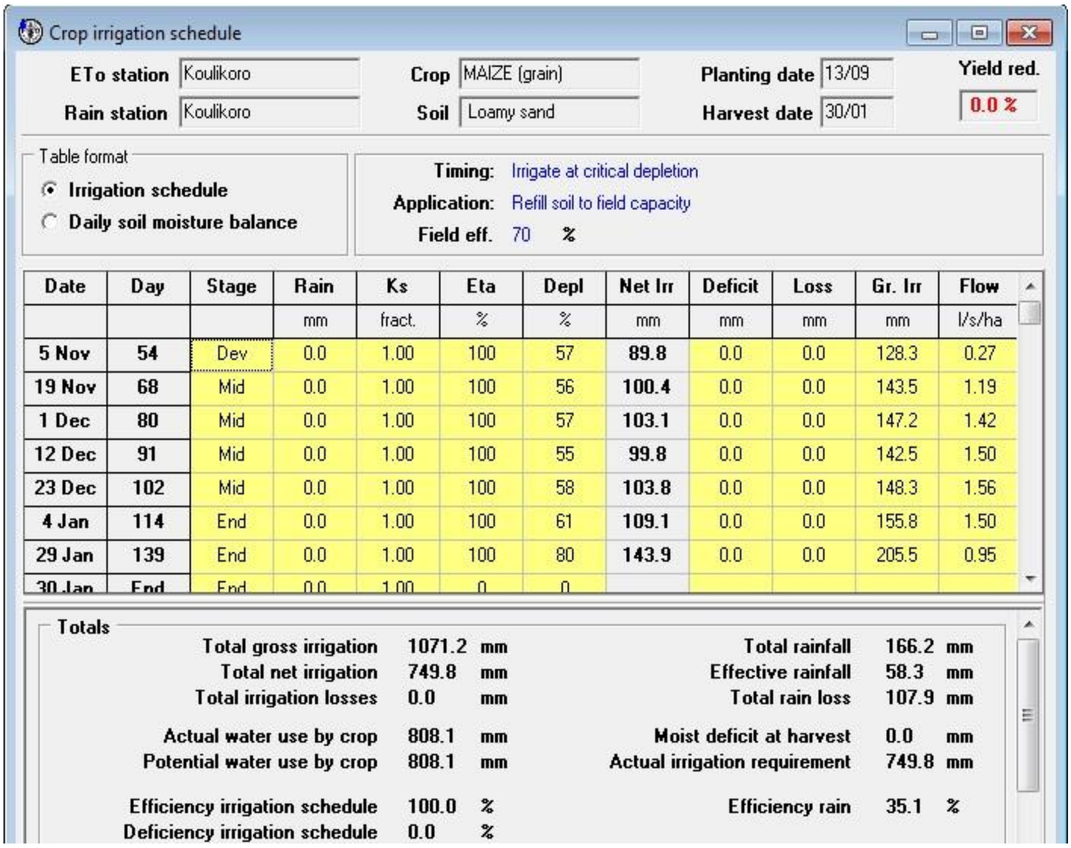
The values calculated above was then fed into CROPWAT 8.0. The above results are input in the CROPWAT 8.0 (see **Figure** *27*).

Table 13. USDA textural classes of soils (FAO, n.d.-a)

Common names of soils (General texture)	Sand	Silt	Clay	Textural class
Sandy soils (Coarse texture)	86-100	0-14	0-10	Sand
	70-86	0-30	0-15	Loamy sand
Loamy soils (Moderately coarse texture)	50-70	0-50	0-20	Sandy loam
Loamy soils (Medium texture)	23-52	28-50	7-27	Loam
	20-50	74-88	0-27	Silty loam
	0-20	88-100	0-12	Silt
Loamy soils (Moderately fine texture)	20-45	15-52	27-40	Clay loam
	45-80	0-28	20-35	Sandy clay loam
	0-20	40-73	27-40	Silty clay loam
Clayey soils (Fine texture)	45-65	0-20	35-55	Sandy clay
	0-20	40-60	40-60	Silty clay
	0-45	0-40	40-100	Clay

4.2.6. Irrigation Scheduling for maize considering case study area factors

The preparation of an irrigation schedule requires data such as planting date, harvest date, field depletion ration, etc. The planting and harvesting date are obtain from (FAO, n.d.). The wilting point was considered during the irrigation scheduling. The obtained total gross irrigation is 1071.2 mm, and the total rainfall value is 166.2 mm. The actual crop water use is estimated at 808.1 mm and the effective rainfall is 58.3 mm. From the **Figure** *27* below, the irrigation loss is 0.0 mm, and the efficiency is 100%. The actual irrigation requirement is 749.8 mm.



ETo station Koulikoro
Rain station Koulikoro
Crop MAIZE (grain)
Soil Loamy sand
Planting date 13/09
Harvest date 30/01
Yield red. 0.0 %

Table format
● Irrigation schedule
○ Daily soil moisture balance

Timing: Irrigate at critical depletion
Application: Refill soil to field capacity
Field eff. 70 %

Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	fract.	%	%	mm	mm	mm	mm	l/s/ha
5 Nov	54	Dev	0.0	1.00	100	57	89.8	0.0	0.0	128.3	0.27
19 Nov	68	Mid	0.0	1.00	100	56	100.4	0.0	0.0	143.5	1.19
1 Dec	80	Mid	0.0	1.00	100	57	103.1	0.0	0.0	147.2	1.42
12 Dec	91	Mid	0.0	1.00	100	55	99.8	0.0	0.0	142.5	1.50
23 Dec	102	Mid	0.0	1.00	100	58	103.8	0.0	0.0	148.3	1.56
4 Jan	114	End	0.0	1.00	100	61	109.1	0.0	0.0	155.8	1.50
29 Jan	139	End	0.0	1.00	100	80	143.9	0.0	0.0	205.5	0.95
30 Jan	End	End	0.0	1.00	0	0					

Totals

Total gross irrigation	1071.2	mm	Total rainfall	166.2	mm
Total net irrigation	749.8	mm	Effective rainfall	58.3	mm
Total irrigation losses	0.0	mm	Total rain loss	107.9	mm
Actual water use by crop	808.1	mm	Moist deficit at harvest	0.0	mm
Potential water use by crop	808.1	mm	Actual irrigation requirement	749.8	mm
Efficiency irrigation schedule	100.0	%	Efficiency rain	35.1	%
Deficiency irrigation schedule	0.0	%			

Figure 27. Irrigation scheduling results for maize

4.3. Designed real-time crop water monitoring prototype

4.3.1. Prototype building

The **Figure** *28* below illustrate the developed prototype. All the components where connected together. The relay is integrated into the Wi-Fi hub. The two sensors, and the pump are connected to the hub.

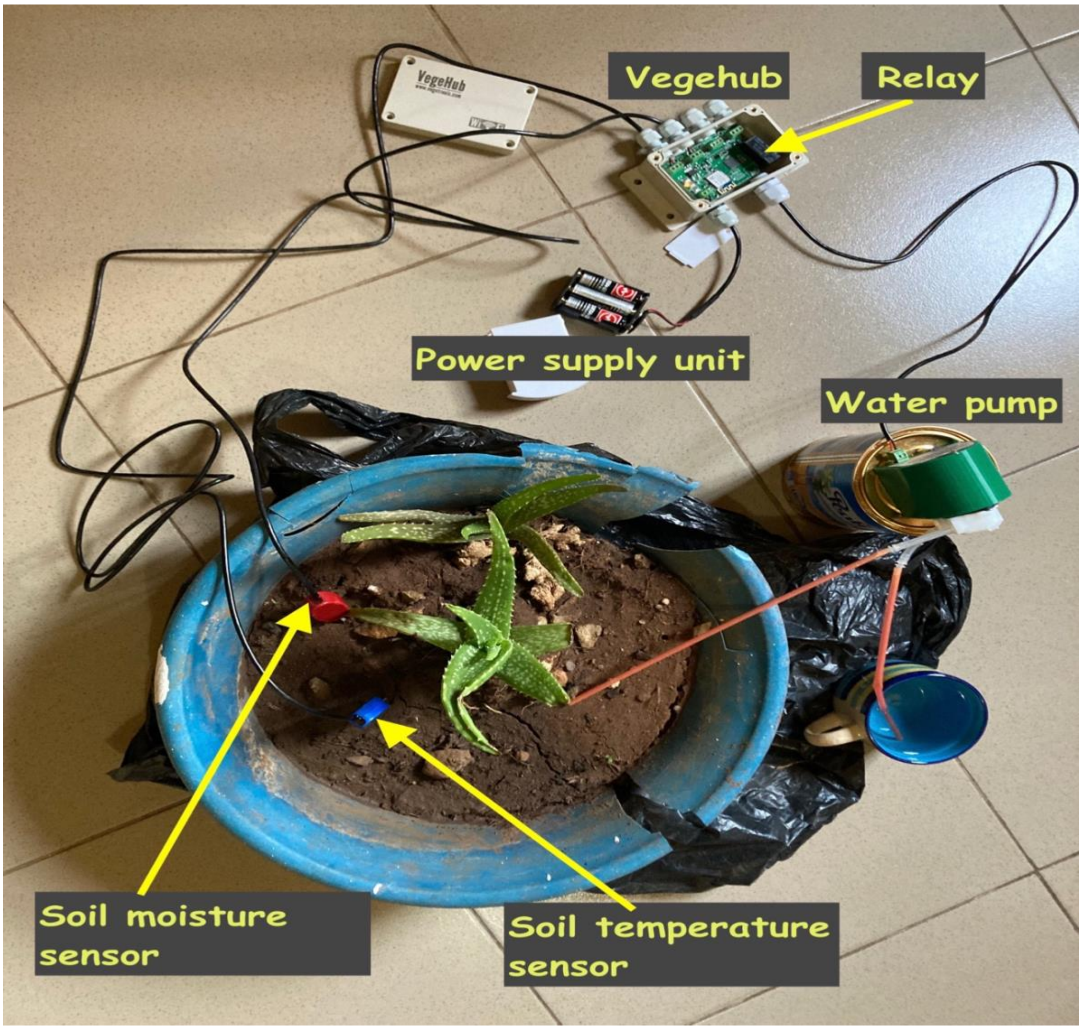


Figure 28. Prototype: Hardware components

4.3.1.1. Connecting Vegehub to the Wi-Fi network

Firstly, the power supplying system composed of 6 x 1.5 V batteries is connected to the Vegehub. The Wi-Fi setup is the pressed to find and connect a mobile phone to the Wi-Fi Vegehub. The next step is to find the IP address of the Wi-Fi hub by inserting a USB drive into the hub. The removed USB is then inserted to the computer to obtain the hub’s IP address recorded in the file named “ipaddress.txt”. The following step is the configuration of the hub. This is fulfilled by copying and pasting the IP address of the hub in a browser to go to the VegeHub’s configuration (see **Figure** *29*). After entering the Write API Key into the server setup tab of the configuration page. The Write API Key is obtained by adding new hub to the Vegecloud after creating an account. The configuration is completed by validating with the “Apply key”.

4.3.1.2. Setting up and operation of the Vegecloud

After visiting the www.vegecloud.com (see **Figure** *29*), the “Sin Up’ button in the upper right conner of the website is used to create the Vegecloud account by entering several information related to the login data. Another important information to add at the account creation is the location, describing where the sensors will be. A new hub can be added by adding clicking on “hubs” situated on the “Devices and Data” in the “DASHBOARD”. The name and model of the hub must be accurate to achieve a correct configuration of sensors. Sensors are added automatically but they can be reconfigured.

The most important part of Vegecloud.com is data representation. This is done by creating “views” on Vegecloud. On the “DASHBOARD”. View provide data in forms of graphs for a specific parameter like soil moisture or temperature. The Vegecloud also provides the possibility of adding recipients and actions to receive notifications when the value of a particular parameter (sensor reading) is higher or lower than a threshold.

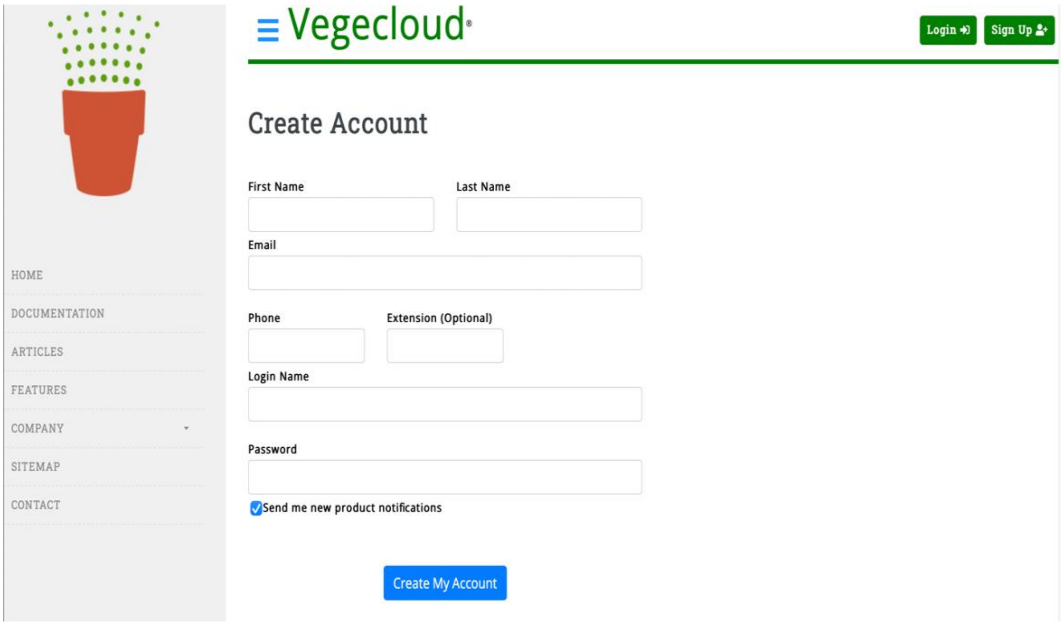


Figure 29. Vegecloud registration and login page

4.3.2. System operating principle

As it can be noticed on the **Figure *30*** below, after the power supply is on, the Vegehub establishes the connection with other components and facilitates the display of initial data on www.vegecloud.com. If the sensor reading is not done there will be a retransmission. Each sensors read separately the data of assigned parameter. After the connection is established, the sensors (soil moisture sensor and temperature sensor) read values and send them to the server though the data processing and transferring unit, the (VG-HUB4-RELAY) Vegehub. The data received and stored in the server is monitored and compared with the soil moisture and temperature values set by the user (monitor or controller). If the received values are inferior to the thresholds, the pump will be turned on, on the opposite if the sensors values are superior the threshold, the water pump will be turn off. The data received from the sensors and stored in the server is displayed on www.vegecloud.com in the form of charts. The user can make decision about new thresholds based on the graphics displayed.

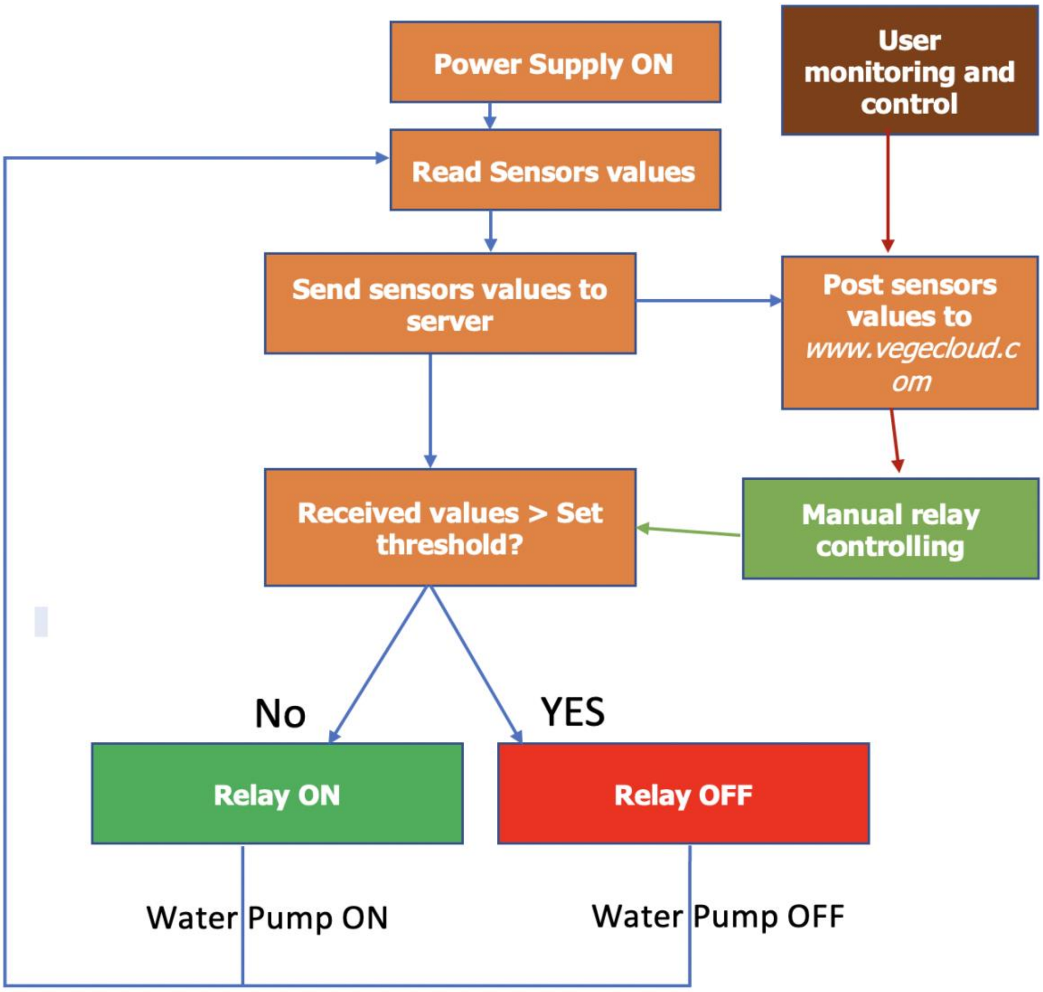


Figure 30. Real-time crop water demand monitoring system flowchart

4.3.3. Sensor data logging

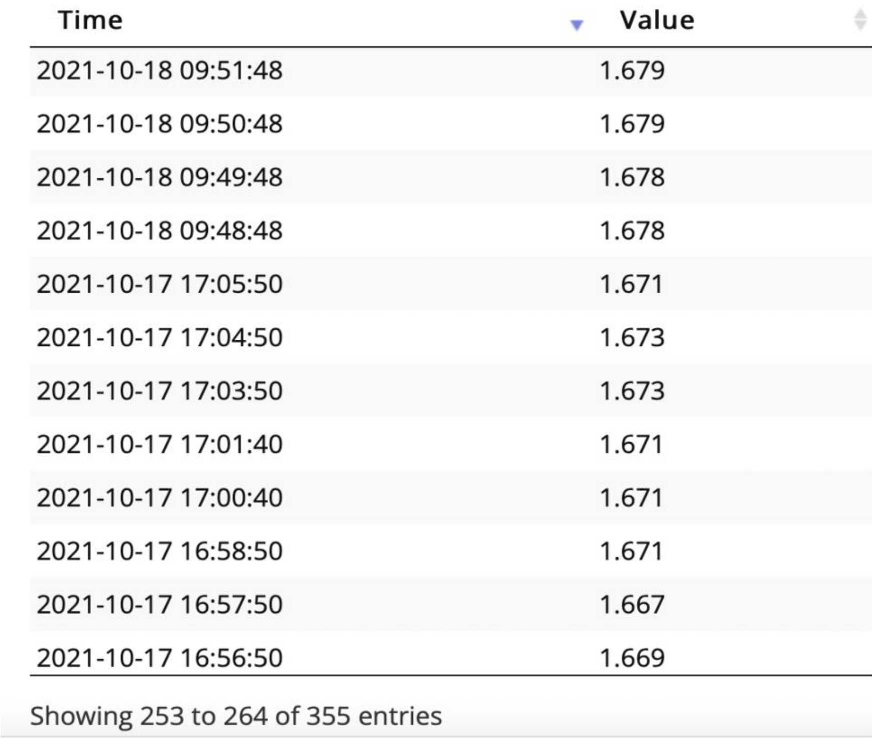
4.3.3.1. Raw sensor data

The raw sensor data is first collected by sensors and then calibrated to represent a chosen parameter such as soil moisture and soil temperature in our case. The **Figure 31** and **Figure 32** below illustrate a sample of raw (voltage) soil moisture and soil temperature data taken from Vegecloud. The data represented below can also be download in CSV form.

Time	Value
2021-10-18 09:51:48	0.055
2021-10-18 09:50:48	0.056
2021-10-18 09:49:48	0.056
2021-10-18 09:48:48	0.056
2021-10-17 17:05:50	1.783
2021-10-17 17:04:50	1.774
2021-10-17 17:03:50	1.771
2021-10-17 17:01:40	1.784
2021-10-17 17:00:40	1.809
2021-10-17 16:58:50	1.798
2021-10-17 16:57:50	0.653
2021-10-17 16:56:50	1.797

Showing 253 to 264 of 355 entries

Figure 31. Sensor data logging from soil moisture sensor



Time	Value
2021-10-18 09:51:48	1.679
2021-10-18 09:50:48	1.679
2021-10-18 09:49:48	1.678
2021-10-18 09:48:48	1.678
2021-10-17 17:05:50	1.671
2021-10-17 17:04:50	1.673
2021-10-17 17:03:50	1.673
2021-10-17 17:01:40	1.671
2021-10-17 17:00:40	1.671
2021-10-17 16:58:50	1.671
2021-10-17 16:57:50	1.667
2021-10-17 16:56:50	1.669

Showing 253 to 264 of 355 entries

Figure 32. Sensor data logging from soil temperature sensor

4.3.3.2. Calibrated soil moisture data

The raw data is transferred to the server through the Vegehub then displayed in the view section of vegecloud.com. It must be noted that the data is converted from sensor voltage to real parameter unit through a data transformation process provided by the vegecloud platform. The graphical representation facilitates data analysis and allows quicker monitoring and control. In the **Figure 33** below, the soil moisture value went from 1.5% (very dry) when the sensors where on the floor to 25% when they were put in the soil. The value has reached 42% when plants were waters. This shows that the real-time water need monitoring system is highly responding to the changing environment of the crop. The temperature illustrated on the **Figure 34** has decreased from 32 to 29°C. This can be due to the relatively cold soil environment in which the sensor was placed. This seems to be more correct hypothesis because the temperature at the beginning, when sensors were not placed in the soil was around 32. When the sensor was placed the temperature has decreased up to 30.3 and when the plant was watered, the temperature has dropped up to 29°C.

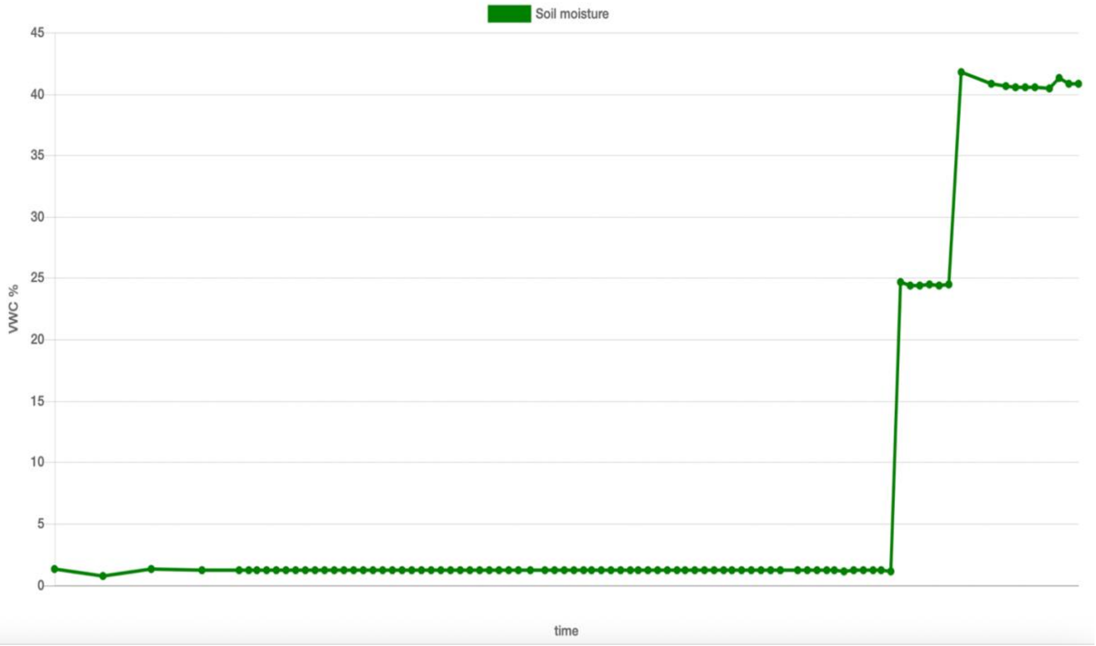


Figure 33. Soil moisture against time obtained from vegecloud.com

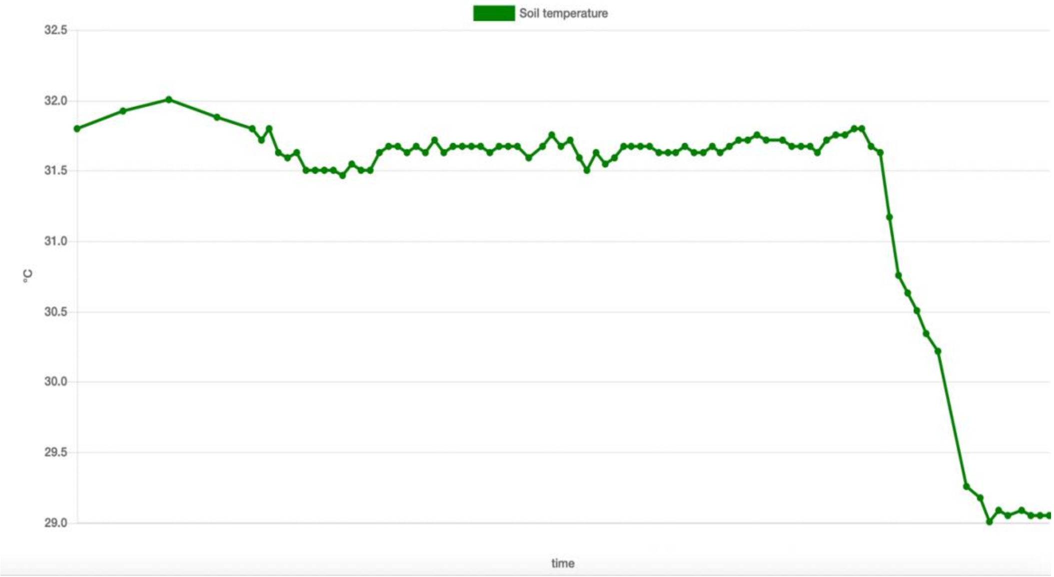


Figure 34. Soil temperature against time obtained from vegecloud.com

4.3.4. Relay control

In case user want to control the farm watering period automatically, we have placed a relay in the prototype that allows the control of the peristaltic pump. Let’s consider this graphic in the **Figure 35** below. Both soil moisture and soil temperature were plotted against time to better understand how to integrate all the parameters involve in real water demand monitoring. As it can be seen an increase in water content is translated by a decrease in soil temperature, which indicates that the water used for irrigation was relatively cold. The opposite can happen especially in hot and arid regions like Mali. The increase in soil moisture can also provoke an increase of soil temperature. This scenario can happen during the hot season. In this context the user can set up the relay on the VegeHub configuration platform to turn On and Off according to certain values of soil moisture or soil temperature. A combination of both can also be considered. For instance, the user can decide to start the pump when the soil temperature is higher than 32°C and if the soil moisture content is less than 45%.

The user can manually control the relay from his smartphone or computer by just switching it Off or On based on the monitoring results from the graphics and data logged from sensors. The decision on when to start and stop the pump is based on the set values of soil moisture and soil temperature. Therefore, it will be reasonable to use the weather data of the case study field as reference while setting the thresholds at which the pump will start or stop pumping water.

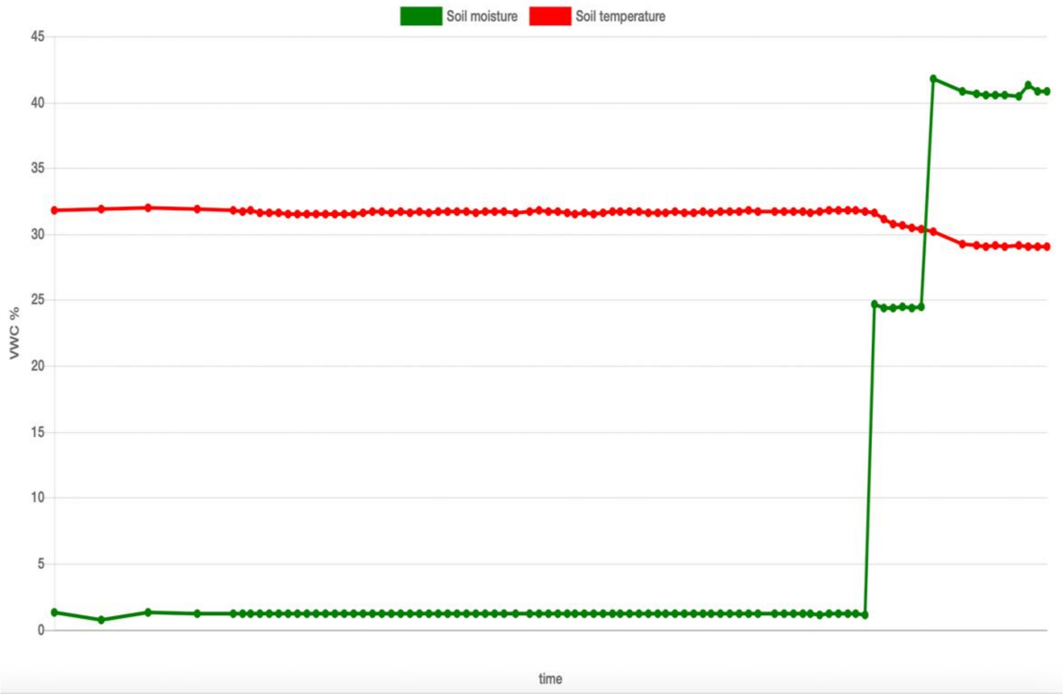


Figure 35. Soil moisture and soil temperature against time obtained from vegecloud

4.4. Evaluation of the real-time crop water monitoring system based on the irrigation scheduling obtained from FAO-CROPWAT 8.0

The designed prototype was not tested on the field of case study as a field trip was not conducted because of various reasons. Also, the evaluation of the protype require collection of data for a long period of time. Nevertheless, if the developed prototype was to be tested in Koulikoro, the soil moisture and temperature values obtained from the **Figure 35** will be compared to their equivalent meteorological data from input in CROPWAT or collected from a weather station. In case the difference between the values is high, it will be concluded that the design system is not working appropriately. On the other hand, if both values are close, it will be concluded that the prototype functions well. The same applies to the total irrigation requirement (IN), the value of IN obtained from the

Figure *27* is 749.8mm. This value will be compared with the total amount of water pumped by the actuator (in our case the VG-PERISTALTIC pump) all along the growing period.

Knowing that the decision on when to ON and OFF the pump is based on the set values of soil moisture and soil temperature, a difference between the IN obtained from FAO-CROPWAT 8.0 and the total water volume of water pumped from the developed system will automatically mean that there is a problem with the sensor readings, or the set thresholds are not reasonable. Therefore, it will be practical to consider the weather data of the case study field before setting the thresholds at which the pump will start or stop pumping water. For instance, from the **Figure 22**, when the average temperature of November is 26.3°C, the IN value was 57.3 mm in the first decade and 79.7 mm in the second decade of the month (see **Figure *24***). These results show that while setting the thresholds to automatically irrigate the crops, in the month of November in Koulikoro, the threshold of the temperature must set to be a value inferior to 26.3°C because at that temperature there IN is not equal to 0, there is still a need for irrigation.

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The aim of this study was to develop an integrated management system that will reduce the interaction rate of farmers on the fields and ensure appropriate and real-time crop water demand monitoring and water allocation in the farm through irrigation for optimal crop production. The objective was fulfilled by reviewing current irrigation water management methods and monitored parameters, proposing a convenient irrigation schedule to ensure precise water allocation, proposing a system architecture design and selecting the most suitable and appropriate components for prototype building.

The designed irrigation scheduling using CROPWAT 8.0 was able to:

- Highlight the estimate actual crop evapotranspiration
- Calculate the total gross and actual irrigation requirement
- Output a convenient irrigation schedule for the case study field

It should be noted that an evaluation of the developed irrigation schedule require a study of the data that will collected from the case study field, where the obtained irrigation schedule must be implemented for at least a crop growing season.

The developed prototype was able to:

- Read sensor data on time and in a consistent way
- Forward the data to the server instantaneously
- Process data for visualization on Vegecloud.com and storage in the server.
- Allow an easy crop water demand monitoring by providing graphs and other view types, assessing two major parameters (soil moisture and soil temperature), and providing alerts to the recipient (user) based on set thresholds
- Ensure a real-time crop water allocation through a relay controller

The prototype was built considering the conditions in Mali however it can be used in any environment due to the resistance of the selected components against a variety of climatic conditions.

The major issue faced while developing this prototype is the long duration of shipment process as well as the expensiveness of components. Another issue is lack of documentation relevant to smart agriculture in the case study country and Africa in general.

5.2. Recommendations

An incorporation of the produced prototype with a weather station can enhance the performance of the real-time monitoring system. This can also be implemented using a weather API, which will send weather data directly to the server of Vegecloud. Such application involved the redevelopment of the vegecloud.com or developing of a new web application.

To achieve further automation of the system, the use of more advanced data representation platform such as thingspeak.com. A work aiming to study the results of the incorporation of thingspeak.com and the VegeHub will be a plus to the world of smart agriculture and digital agriculture.

A broad study aiming to evaluate the prototype in the case study field can be considered by other researchers. This will be done by collecting, processing and analyzing data form the prototype during a long period of time.

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