UNIVERSITE JOSEPH KI-ZERBO

ECOLE DOCTORALE INFORMATIQUE
ET CHANGEMENTS CLIMATIQUES

BURKINA FASO

Unité-Progrès-Justice

MASTER RESEARCH PROGRAM

SPECIALITY: INFORMATICS FOR CLIMATE CHANGE (ICC)

MASTER THESIS

Design and implementation of a smart irrigation system for a sustainable water management in Niger

Presented by:

KOKOYE L. F. Glory A.

Major Supervisor

Pr NAROUA Harouna
Professeur Titulaire

Co-Supervisor

Dr SIDI ZAKARI Ibrahim
Maître Assistant

Academic year 2020-2021

DECLARATION

I hereby declare that the research reported in this thesis, except where otherwise indicated, is my original work. This thesis has not been submitted for any degree or examination at any other university. This thesis does not contain other persons' data, pictures, graphs or other information unless expressly acknowledged as being sourced from other persons.

“*Someday men will learn to irrigate and spread fertilizer instead of praying for fertility.*”

Warren Eyste (1957)

DEDICATION

To God almighty.

This work is also dedicated to all those who believed in my abilities:

- My parents **Mrs Lucien Jeannette and Mr Lucien KOKOYE**;
- My dear brothers **Elie** and **Jean-Luce**;
- My sister **Grace**.

I love you.

ACKNOWLEDGEMENTS

This project was funded by the German Ministry of Education and Research **BMBF** through the West African Science Service Centre on Climate Change and Adapted Land Use (**WASCAL**)

- I'm thankful to **Pr ZOUNGRANA Pierre Tanga,** the Director and his deputy Director **Dr COULIBALY Ousmane** of EDICC "Ecole Doctorale Informatique et Changement Climatique" (MRP Climate Change and Informatics) for their availability and dedication to the program.
- My heartly thanks to my Major Supervisor **Pr NAROUA Harouna** for his encouragement, support and all he did during my work.
- My sincere thanks to my Co-Supervisor **Dr SIDI ZAKARI Ibrahim** for his good supervision, encouragement, and all he did for the achievement of this work.
- Thanks to the Director of Tech-Innov, **Mr MAMANE KANE Abdou** for the five months of internship that he has granted me.
- My deep and sincere thanks to **Mr GARBA Rabani** of the ministry of agriculture for his kind assistance, availability, support, and adequate help during this work.
- My thanks to **Dr SALACK Seyni** Senior Climate Scientist at WASCAL for his availability.
- Thanks to **Mr ADAMOU OTTO Younoussa** and **Mr FAVI Geraldo** for their help.
- I also acknowledge WASCAL PhD students, **Mr GUIDIGAN Gildas**, **Mr RAGATOA David** and **Mr ODOU Thierry** for their help, assistance and advice.
- Thanks to my colleagues of **MRP ICC first batch** for the good time we shared together in Ouagadougou; special thanks to my friend **Mr Simon Pierre KITEGI** for his help, and **Mr KIRIBOU Razak** for his availability and support.

ACRONYMS AND ABBREVIATIONS

CIWR	:	Crop Irrigation Water Requirements
COVID-19	:	Coronavirus Disease 2019
CWR	:	Crop Water Requirement
DMN	:	Direction de la Météorologie Nationale du Niger
DSS	:	Decision Support Systems
FAO	:	Food and Agriculture Organization
GHG	:	greenhouse gas emission
IoT	:	Internet of Things
PoU	:	Prevalence of Undernourishment
SDGs	:	Sustainable Development Goals

Table of contents

Figures

Tables

Formulae

ABSTRACT

A smart irrigation system with less human intervention has been designed and implemented. A statistical data analysis was conducted on the evolution of climate factors that affect the irrigation in Niamey such as temperature, relative humidity, wind speed and rainfall. This analysis has revealed an increasing temperature from 1986 to 2020. But during the same period, the other parameters are decreasing with a high variation of rainfall. As a result, a growing need of irrigation in the area of study has been observed. To develop the proposed irrigation system, we made use of an Arduino microcontroller, a relay, a temperature and humidity sensors, a soil moisture sensor, a motor pump with three drip irrigation pipes and a breadboard. The system has been experimented on tomato nurseries.

Key words: ***Smart irrigation, Climate data analysis, Low-cost sensors, Tele-irrigation, Arduino microcontroller***

RESUME

Un système intelligent d’irrigation avec une faible intervention de l’homme a été conçu et expérimenté. Une analyse statistique des données a été menée sur l’évolution des paramètres du climat qui influencent l’irrigation à Niamey comme la température, l’humidité relative, la vitesse du vent et les précipitations. L’analyse a révélé que la température est croissante sur la période de l’étude qui est de 1986 à 2020. Par contre, les autres paramètres décroissent sur la même période avec une grande variabilité de la pluviométrie. Ceci explique le besoin d’irrigation dans la zone. Pour développer le système d’irrigation proposé, nous avons utilisé un microcontrôleur de type Arduino, des capteurs de température et d’humidité ambiante, un relais, un capteur d’humidité du sol, une moto pompe avec trois tuyaux d’irrigation et une platine d’expérimentation. Le système a été expérimenté pendant quelques jours sur des plants de tomate.

Mots clés : ***Irrigation intelligente, analyse des données climatiques, capteurs à bas prix, télé-irrigation, microcontrôleur Arduino.***

INTRODUCTION

FAO (2020) estimated the number of undernourished people to nearly 690 million in 2019, corresponding to 8.9% of the world population. The number has increased up by nearly 60 million between 2014 and 2019 and the COVID-19 pandemic could add an additional 83 to 132 million more people in 2020. In the same report, it was stated that the prevalence of undernourishment (PoU) in Africa was 19.1 percent of the population in 2019 corresponding to more than 250 million people which is more than twice the world average and the highest among all world regions. Therefore, feeding a world population of 9.1 billion people in 2050 would require raising overall food production by some 70 percent (Otto and Sorensen, 2018). According to the world resource institute (WRI), agriculture has contributed to the global greenhouse gas emission (GHG) from 14% in 2000 to 17% in 2020[1]. This reveals that the world is facing a double challenge: feeding the growing population in quantity and quality while mitigating GHG emission.

To overcome this situation; precision agriculture has been found as one of the best solutions. Precision agriculture is the term given to crop management methods which recognise and manage within-paddock spatial and temporal variations of the soil–plant–atmosphere system (Cook 1998). Smart irrigation has been practiced in many countries around the world as a technological process to manage water to meet the precision agriculture principles. Aman (2017) defined the smart irrigation system as an Internet of Things (IoT) based device which can automate the irrigation process by analysing the moisture of soil and the climate condition. It provides water supply at the right time, in the right quantity and at the right place, in the field. It uses sensors for soil moisture, temperature and humidity to easily manage water supply for irrigation by analysing the condition of soil, plant and climate. The sensors send the data to the control unit and based on that data the field is irrigated automatically or not.

To contribute to the United Nations' Sustainable Development Goals (SDGs) #2, which stands for food for all, in Niger, there has been a wider implementation of smart irrigation with tele-irrigation concept developed by Tech-Innov. Although the tele-irrigation is currently used in several rural and peri urban areas of Niger, the challenges associated to

[1] https://ourworldindata.org/ghg-emissions-by-sector

this technology include the dependency of farmers to a third party centralized digital system for irrigation of their perimeter, the initial investment costs for the materials and skills needed by farmers for the choice and the monitoring of irrigation parameters.

Research Questions

How can we design and implement a smart irrigation system without internet and with less human being intervention?

Specific questions

- How is evolution of climate factors affecting the irrigation in Niamey?
- What are the existing smart irrigation systems and which ones are locally relevant and accessible at low cost?
- What are the low cost equipments that are available for implementing the proposed smart irrigation system?

Hypothesis

It is possible to have an automated smart irrigation system without internet with less human being intervention.

Specific hypothesis

- Climate factors are affecting irrigation in Niamey and its peri urban areas
- It is possible to design a smart irrigation system that will work without internet and with less human being intervention
- Low-cost equipments are available to implement the proposed smart irrigation system

Objectives

In order to contribute to this emerging area of research and innovation, we have settled the following general objective which is to:
build a low-cost irrigation system that requires little human intervention.

Specific objectives

- Analyse the evolution of climate factors that affect irrigation in Niamey
- Design a smart irrigation system
- Implement a prototype of the proposed smart irrigation system

The remaining part of this document will be structured in three chapters. The first one will be on the definitions and literature review on emerging irrigation systems and technologies, the second chapter will be on the methodology and the last one will be dedicated to the results and discussion. We will end the document with a conclusion followed by some perspectives to upscale this work.

CHAPTER ONE

DEFINITIONS AND LITERATURE REVIEW ON EMERGING IRRIGATION SYSTEMS AND TECHNOLOGIES

1.1 Definitions

Irrigation

"Irrigation is the supply of water to agricultural crops by artificial means, designed to permit farming in arid regions and to offset the effect of drought in semi-arid regions. Even in areas where the total seasonal rainfall is adequate on average, it may be poorly distributed during the same year and may vary from one year to another. Where the traditional rain-fed farming is a high-risk enterprise, irrigation can help to ensure stable agricultural production." (FAO, 1997).

Smart Irrigation

It is the application of water to a plant on the basis of its water requirement at different stages, soil type, and climate, with the help of micro irrigation sensors and controllers (Hwang, 2017). Tazhina and Parker (2020) defined smart-irrigation as a system of automatically started/interrupted irrigation associated with the use of soil moisture sensors. It can also be defined as the use of IoT sensors to enable the monitoring of the soil moisture levels around plants, as well as monitoring weather conditions, to make the water use more efficient and effective[2].

Drip irrigation

In this type of irrigation, water is distributed directly to the roots of plants through pipes with small openings called drippers. This allows farmers to significantly reduce evaporation and runoff. It is also defined as a system of crop irrigation involving the controlled delivery of water directly to individual plants through a network of tubes or pipes[3].

---

[2] https://www.aeris.com/news/post/introduction-to-smart-irrigation/

[3] https://www.dictionary.com/browse/drip-irrigation/

1.2 Literature Review

1.2.1 Traditional irrigation systems

Farmers practice irrigation through the manual control in which they irrigate the land at regular intervals. This process consumes more water and results in water wastage (Rajkumar et al., 2017). The first used irrigation methods include: Sub-surface irrigation, Surface irrigation, Trickle irrigation, Sprinkler irrigation. All these techniques are not efficient as they result in wastage of water and can also propagate disease such as fungal formation due to over-moisture in the soil (Kshirod Kumar et al., 2018). In the case of furrow irrigation, Hassen (2004) concluded his study by saying that the water application was excessive and much higher than the crop water requirements. The application efficiency was also considered as poor and huge amount of money have been invested to construct the structures. Maupoux (2010) also found that the water application efficiency for furrow system is low, ranging from 50% to 60%. To respond to all the different problems facing farmers and to help in the achievement of the United Nations' Sustainable Development Goals number two ((SDG #2, namely *End hunger, achieve food security and improved nutrition and promote sustainable agriculture*), many works have been conducted to improve the performance of the agriculture using IoT.

1.2.2. Smart irrigation systems

One of the recent works was done by Pathak et al. (2019) on a smart system based on IoT environment using Arduino open-source platform as head of the system. In their system (Figure 1.1), datasets have been used to calculate the prediction of crop planning using hardware sensors like temperature sensor and soil moisture sensor. The pH sensor was also used in that system for the measurement of the pH in the soil.

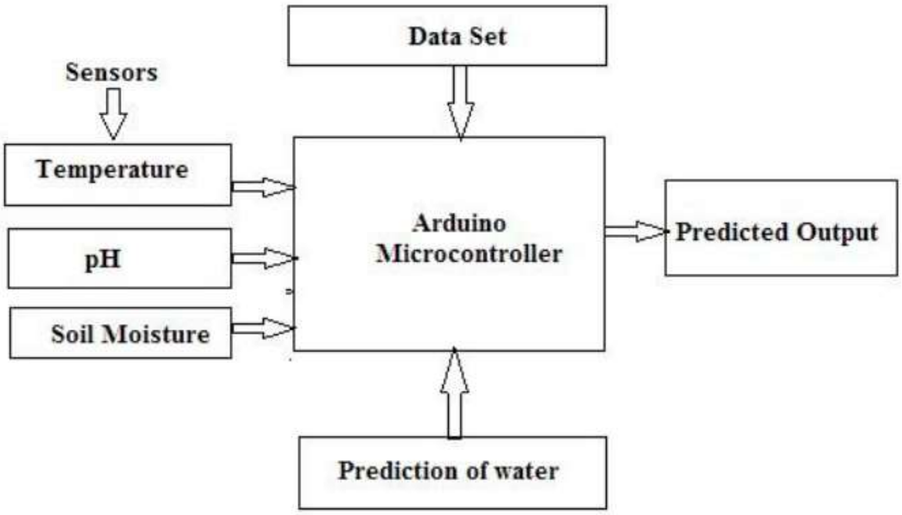

Figure 1.1: Block diagram of the system Architecture (Pathak et al., 2019)

For this architecture, datasets are collected by sensors (like temperature, pH and soil moisture) and sent as input to the Arduino microcontroller where they are compared with the actual sensors data to determine when there is a need for irrigation. The algorithm was programmed in the microcontroller and the result is a predicted output. The authors have also analysed some kinds of soil from different places. They noticed that when the value of soil moisture is above 700, the soil is dry, so they coded the program to start the pump automatically when the moisture value rises above 700. The temperature value is displayed on LCD and sent to the cloud for further analysis. Another investigation was carried out by Rajkumar et al. (2017) in which they used a system composed of a microcontroller, sensors for soil moisture, humidity and temperature together with a GSM module (Figure 1.2).

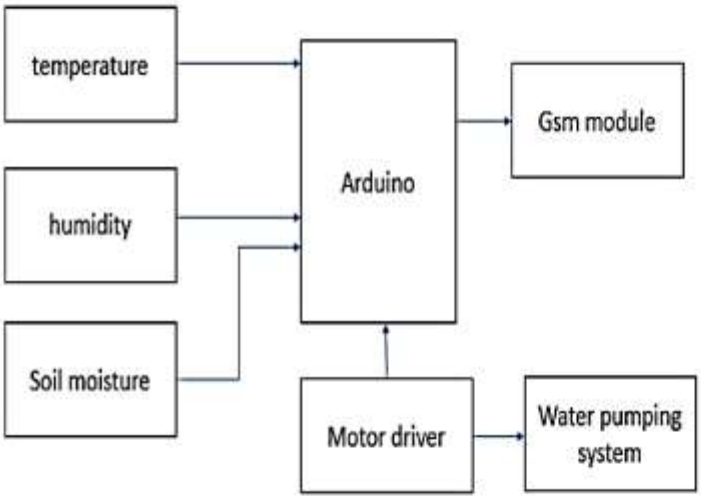

Figure 1.2: System architecture (Rajkumar et al., 2017)

The above architecture (Figure 1.2) is centred over of a microcontroller (ATmega328) which is the brain of the overall system. Both moisture and temperature sensors are combined to the input pins of the controller. The water pump and the servo motor are coupled with the output pins. If the sensors depart from the pre-ordinated range, the controller turns on the pump. The servo motor is used to control the angular point of the pipe, which ensures equal diffusion of water to the soil. The entire system is observed and controlled by a micro-controller Arduino. Basic DC motors are used for automatic water supply. The power is supplied by a 5-volts battery. All sensors values are displayed on the monitor by using Arduino operating system and the connection is established via a java code. The motor automatically switches ON and OFF based on the soil moisture values. Further investigations have been performed by Jimenez et al. (2020) on intelligent agents and multi-agents for irrigation scheduling. In their paper, they explained the principal sensing technologies for estimating irrigation rates and times in agriculture and identifying control and actuation techniques used to regulate water flow in crops irrigation. Additionally, the methodologies and platforms are described for the implementation of Decision Support Systems (DSS), inference strategies and prediction mechanisms for irrigation management using artificial intelligence. The review highlights the interaction of multiple agents for the management of water resources in agriculture. It is organized into two sections: intelligent agents in crop irrigation (Figure 1.3) and multi-agents systems applied to water resource management. The first section is split into the following subsections: conceptualization, sensors systems in irrigation intelligent agents, decision support systems for irrigation management and artificial intelligence applied to irrigation.

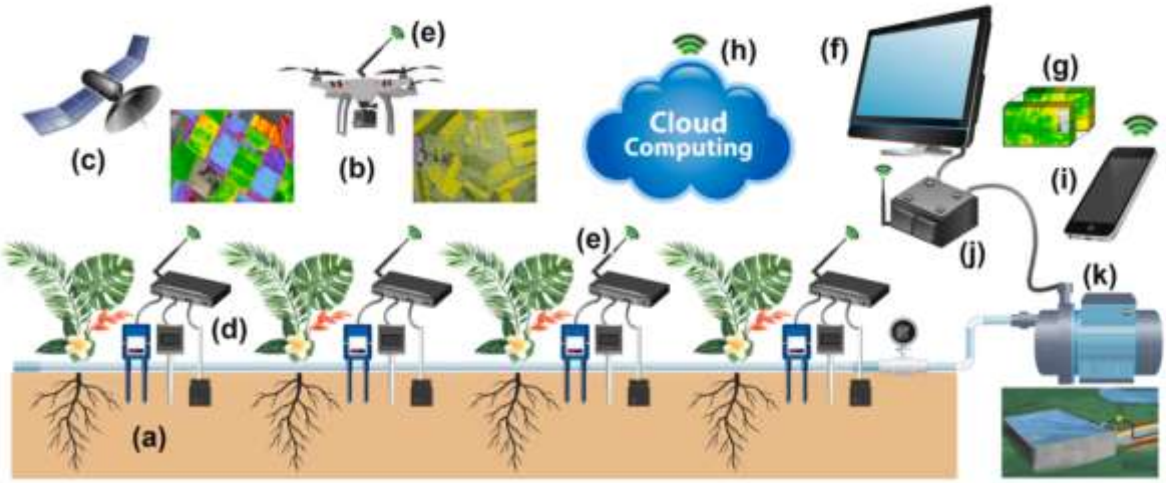

Figure 1.3: Intelligent agents for irrigation applications. (a) nodes or motes, (b) cameras installed in unmanned autonomous vehicles - UAV, (c) images from satellite platforms, (d) data acquisition systems - DAQS, (e) data transmitter units - DTUs, (f) central master control system, (g) specialized software, (h) cloud computing, (i) internet of things, (j) master control centre, (k) pumps, solenoid valves or other actuators for supplying the irrigation (Jimenez et al., 2020).

The above figure shows the basic components of an intelligent agent for irrigation applications, where the data about the hydric conditions of the crop is acquired using different kinds of sensors. These sensors are installed and grouped into nodes or motes (Figure 1.3 (a)), which measure physical variables in plants, soil or the environment (e.g., relative humidity, temperature and radiation). Additionally, data can be acquired using non-invasive sensing technologies for obtaining images from the field using different electromagnetic wavelengths (thermal, multispectral, night vision or photometric cameras). The sensors data are delivered and sent to the data acquisition systems - DAQS (Figure 1.3 (d)). The DAQS receive, transform, scale and condition the electrical signals from the sensors to give digital data stored in a numerical format to be processed or integrated. The digitized data that provide crop information are transmitted wirelessly through Data Transmitter Units (DTUs) using wireless communication protocols (ZigBee, Wi-Fi or

Bluetooth). The DTUs are composed of modems and antennas (Figure 1.3 (e)), which conform a network of wireless sensor nodes that transfer remotely the crop data by a router linked to an information collection centre or central master control system. The central master control system (Figure 1.3 (f)) is integrated by a high-performance computer or server with a specialized built-in software (Figure 1.3 (g)) that manipulates and processes the data and images collected from the crops using artificial intelligent processing techniques. The algorithms programmed in the central master control system allow displaying real-time information about the crop, interpreting and analysing the data to give support and manage the irrigation applications, making decisions to generate control signals for the actuators that dose water in the field and predict future behaviours of the crop. In Niger also there is a new irrigation system developed by Tech-Innov company named Tele-irrigation.

1.2.3 Tele-irrigation

"Tele-Irrigation" is a process of remotely controlling an irrigation system irrespective of time and space using a mobile phone. It integrates IoT sensors following an intelligent distribution of water with the possibility of real-time collection of meteorological and hydrological data, namely temperature, humidity rate, rainfall, solar radiation, air speed and quality (Patent n ° 16025 OAPI / BOPI / 07/13). This process allows:

i) a saving of time and energy;
ii) an increase in the irrigable area;
iii) an increase in the production and income;
iv) a controlled management of irrigation water.

The tele-irrigation kit of the company is composed of an Interactive voice application, GSM DRH telecom module, Electro valve 2”, 3”, 4”, 5”, 5 years car lithium battery and a solar panel (electricity) (Figure 1.4).

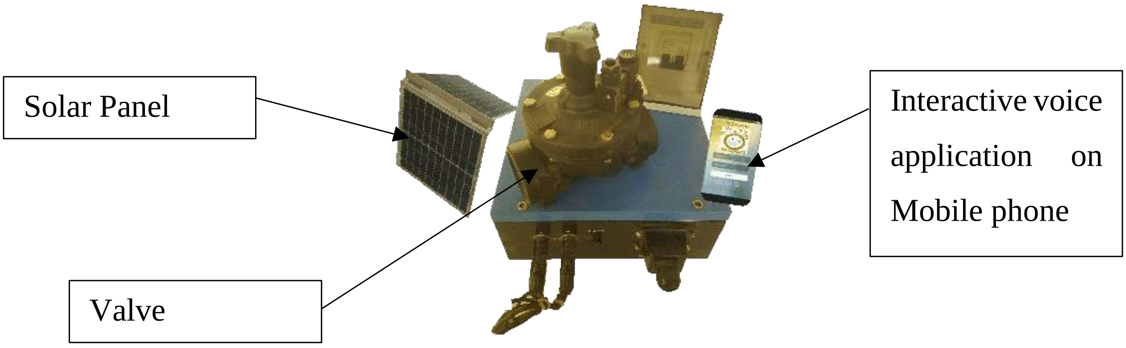

Figure 1.4: Tech-Innov Tele-irrigation kit[4]

The main smart irrigation service provider in Niger remains Tech-Innov. It has irrigated many perimeters and is solicited in different countries across Africa. The process of tele-irrigation is proposed to farmers in two ways:

i) the farmer can switch the moto pump ON or OFF;

ii) The farmer can interactively discuss with the virtual assistant of the company on the soil parameters, the irrigation perimeter, the amount of water to provide and the cost of the service.

This process has many challenges: the system is dependent to the farmer; and the farmer needs to have a domain skill to manage the system.

1.2.4 Identification of climate factors that influence irrigation

Most of the existing smart irrigation systems that we studied in the literature review use sensors for monitoring key climate factors. After investigation, we have identified the following five major climate factors: Air Temperature, Humidity, Wind Speed, Sunshine and Soil moisture. They directly affect the plant respiration: humidity influences the germination and plant growth, Wind Speed has an impact on plant growth, Sunshine influences the photosynthesis, air Temperature has an influence on the growth of shoots, soil moisture is essential for the physiology of the crops. These climate factors have an influence on the availability of water and agricultural yield as they are linked to rainfall as illustrated in Figure 1.5.

[4] http://www.tele-irrigation.net/nos-innovations-solu/systeme-tele-irriga/

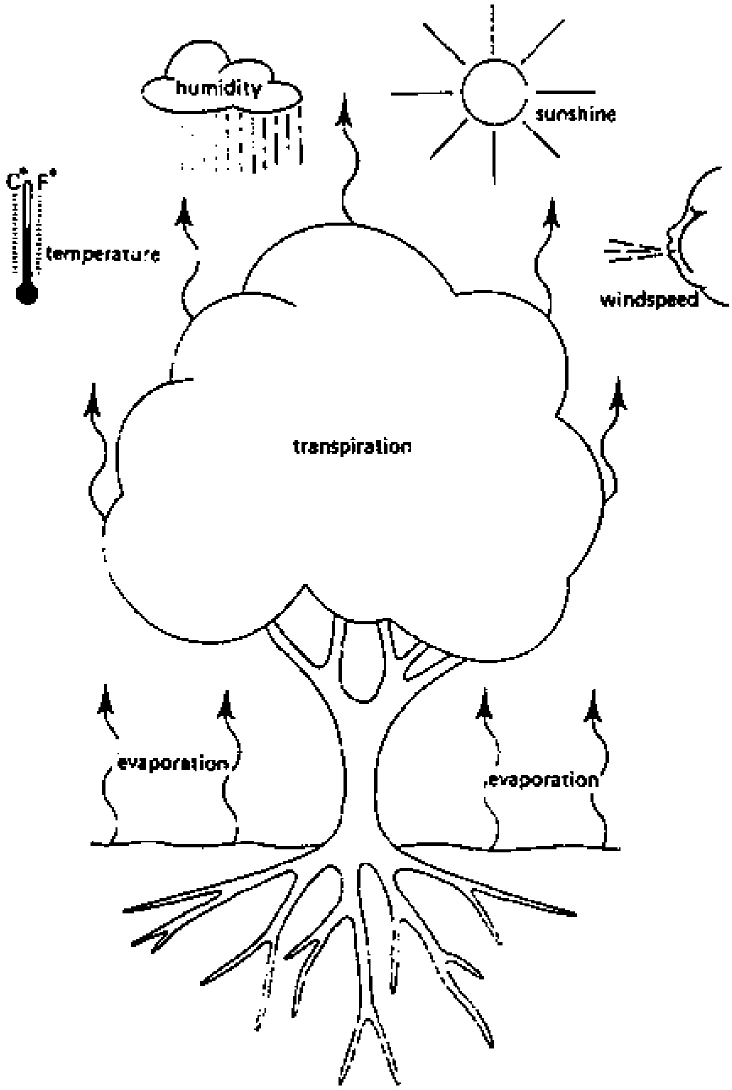

Figure 1.5: Major climatic factors influencing crop water needs[5]

The effects of temperature, humidity, wind speed and sunshine on crop water need are given in Table 1.1. We can see that the highest need of water remains in hot, dry, windy and sunny areas. The lowest need is for cool areas, humid, with little wind and no sun.

[5] http://www.fao.org/3/s2022e/s2022e07.htm

Table 1.1: Effects of the major climatic factors on crop water needs.[6]

Climatic Factor	Crop water need	
	High	**Low**
Temperature	Hot	Cool
Humidity	low (dry)	high (humid)
Windspeed	Windy	little wind
Sunshine	sunny (no clouds)	cloudy (no sun)

The data used for the analysis was obtained from nooa.gov[7]. They are daily data which contain rainfall, mean temperature, max temperature, relative humidity and wind speed from 1986 to 2020. We used this range of period because we need a minimum of 30 years to analyze to expect a good result from the analysis. The data quality control was done by checking the presence of missing values (NA) and the analysis of the range of each observation. The NA values were not taken into consideration during the analysis.

For the data analysis, the Standard Precipitation Index (SPI) as indicator of the rainfall variation was computed. This indicator is used to describe extremely dry or wet climate situations. The World Meteorological Organization (WMO) recommends this approach for the monitoring of dry spells[8]. Besides we computed the monthly rainfall trend, the temperature evolution, the monthly temperature trend, the humidity and the wind speed evolutions from 1986 to 2020. Two different softwares were used for the data analysis namely Excel and R version 4.0.4 with packages like: readxl, tidyr, ggplot2, dplyr. Excel was used for the computation of the potential evapotranspiration ETo (see equation 3) while R was used for the analysis of the local climate factors that impact irrigation. We choose them because Excel is a simple, fast and easy to use software for small data while R is a

6 http://www.fao.org/3/s2022e/s2022e07.htm

7 https://www.ncei.noaa.gov/data/global-hourly/access/

8 https://www.preventionweb.net/news/view/12077

programming language that can help to compute big data and draw good graphs with simple scripts.

1.2.5 Assessment of crop irrigation water requirements

"*Crop irrigation water requirements (CIWR) is the quantity of water necessary for crop growth.*"[9]. Generally expressed in mm/day, mm/month or mm/season, two parameters are used when estimating it (CIWR): the Crop Water Requirement (CWR) and the effective precipitation (Pef) that is the part of the total precipitation that replaces, or potentially reduces, a corresponding net quantity of required irrigation water[10].

The formula used to calculate the CIWR is:

$$\mathrm{CIWR} = \mathrm{CWR} - \mathrm{Pef} \qquad (1)$$

Our study area is in the Sahel (that has a long dry season); so, in our case we will study the off-season CIWR and at that time the effective precipitation is neglected. Therefore, the Equation reduces to:

$$\mathrm{CIWR} = \mathrm{CWR} \qquad (2)$$

The CWR is the amount of water needed by a crop to grow optimally. The concept of crop water requirements is intimately linked with the crop evapotranspiration since both refer to the same amount of water. Nevertheless, there is a difference between them. Crop evapotranspiration is defined as the water losses that effectively occur (hydrological term). In contrast, the crop water requirement indicates the amount of water that should be supplied accounting to these losses (irrigation management term) (Todorovic, 2006).

The CWR estimation can be done with the crop coefficient (Kc) and the potential evapotranspiration (ET0) data (Equation3).

[9] http://www.fao.org/3/w4347e/w4347e0c.htm#calculation%20of%20irrigation%20water%20requirements

[10] https://link.springer.com/chapter/10.1007%2F978-1-4020-8948-0_3

$$\mathrm{CWR} = \mathrm{Kc} \times \mathrm{ET0} \qquad (3)$$

a. Crop coefficient (Kc) data

Kc is a parameter used in the estimation of CWR, in which the effect of crop transpiration and soil evaporation are integrates[11]. The K_c coefficient incorporates crop characteristics and average effects of evaporation from the soil. Its values change depending on the different growth stages of the crop. In general, there are four growing stages (initial, development, mid-season and late-season) with a given number of days for each. In this study, the Kc used is collected from the software (CROPWAT/ FAO database).

The crop water requirement largely depends on the growth stage. The FAO Irrigation and Drainage Paper No. 24 (Doorenbos and Pruitt, 1977) provides general lengths for the four distinct growth stages and the total growing period for various types of climate and locations.

1. The initial stage: This is the period from sowing or transplanting until the crop covers about 10% of the ground.

2. The crop development stage: This period starts at the end of the initial stage and lasts until the full ground cover has been reached (ground cover 70%–80%); it does not necessarily mean that the crop is at its maximum height.

3. The midseason stage: This period starts at the end of the crop development stage and lasts until maturity; it includes flowering and grain setting.

4. The late season stage: This period starts at the end of the midseason stage and lasts until the last day of the harvest; it includes ripening.

[11] http://www.fao.org/3/x0490e/x0490e0b.htm#chapter%206%20%20%20etc%20%20%20single%20crop%20coefficient%20(kc)

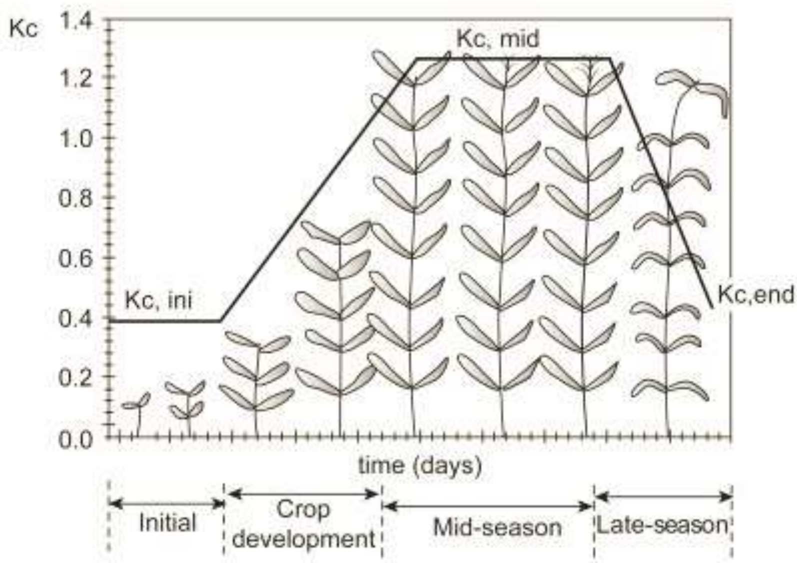

Figure 1.6: Crop growth stages

Source: Simonneaux, 2008

b. Potential evapotranspiration (ETo) data

The potential evapotranspiration (ETo) is a crucial component in determining water requirements for crop irrigation. In this study, the potential evapotranspiration data used was collected from the National Meteorological agency of Niger (DMN). The data collected is 10 years data from 2002 to 2011. We use this period because it was the one that was accessible for us.

CHAPTER TWO

MATERIALS AND METHODS

2.1. The study area

This study was carried out in Niamey, the capital city of Niger. Niger is a Sahelian country, with three-fourths of the area (1,267,000 km2) situated in the desert zone, which makes it highly exposed to climate risks, with highly variable rainfall during the year. Four climatic zones can be distinguished in Niger. The Saharan zone (65% of the national territory) receives less than 100 mm of rainfall per year; the Sahelo-Saharan zone (12.2% of the national territory) receives between 100 and 300 mm of rainfall per year; the Sahelo-Sudanian zone (21.9% of the national territory), where rainfall varies from 300 to 600 mm; and the Sudanian zone (0.9% of the national territory) the most rainy zone with more than 600 mm of rainfall per year (Kosmowski, 2015). The country experiment three different seasons in the year: cool-dry season, rainy season and worm-dry season. To deal with drought and rainfall issues, irrigation is practiced in the country.

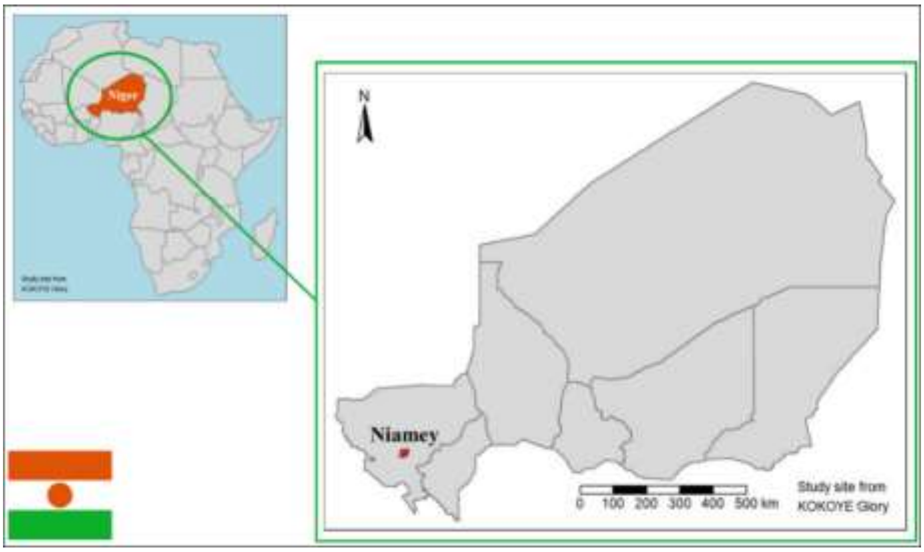

Figure 2.1: Position of Niamey on the map

2.2 The equipment of the system

The idea is to have an automated system that stand alone without human intervention for its management. The equipment used for our system is composed of an Arduino microcontroller, a soil moisture sensor, a breadboard, a humidity sensor, a temperature sensor, a relay and a motor pump as described below:

- **The Arduino microcontroller**

  Arduino is an open-source electronics platform based on an easy-to-use hardware (Figure 2.2) and software. Arduino boards are able to read inputs (sensors data) and turn them into an output (activating a motor). Through the USB cable, the written code (a set of instructions) is sent to the microcontroller to tell it what to do. For our system we used Arduino UNO V3 because it is easy to use, accessible and low cost.

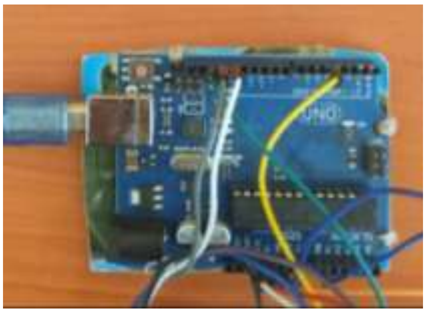

Figure 2.2: Arduino microcontroller

- **DHT11 Temperature and Humidity sensor**

  DHT11 is an inexpensive sensor that provides calibrated digital outputs for ambient temperature and relative humidity. It comes in a single row 4-pin package and operates from 3 to 5.5V power supply. It can measure temperature from 0-50 °C with an accuracy of ±2°C and relative humidity ranging from 20-95% with an accuracy of ±5%.

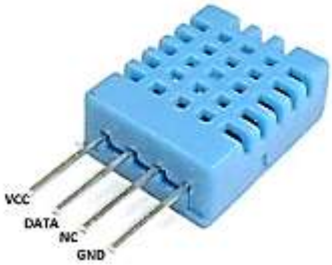

Figure 2.3: DHT11 humidity and temperature sensor[12]

Capacitive Soil Moisture Sensor v1.2

Capacitive moisture sensor is a sensor which senses the moisture in the soil. The moisture in the soil can be measured using two methods namely resistive and capacitive. This v1.2 sensor uses the capacitive method instead of the resistive one. An analogue capacitive soil moisture sensor measures the volumetric amount of moisture levels present in the soil. Unlike other moisture sensors which use two metallic electrodes printed on the silicon board which cause the electroplating activity on one electrode and the metals corrode by damaging the sensor permanently within one month; the capacitive one is the best moisture sensor (Figure 2.4) made of non-corrosive materials. With capacitive sensor, the analogue signals and the metallic parts are not exposed to water which tends to ensure long time run of the sensor. The sensor works from 3.3v to 5.5v with an output analogue Voltage going from 0 ~ 3.0 V DC.

Figure 2.4: Capacitive Soil Moisture Sensor v1.2

[12] https://www.indiamart.com/proddetail/dht11-temperature-and-humidity-sensor-19237198597.html

This soil moisture sensor is provided with a connector which is clearly labelled as GND, VCC, and AOUT. The VCC pin connect to 3.3V of the Arduino and GND to GND. Similarly, connect the Analog output pin to A0 pin of Arduino.

- **Breadboard**

The breadboard is used to make quick electrical connections between the sensors and the Arduino.

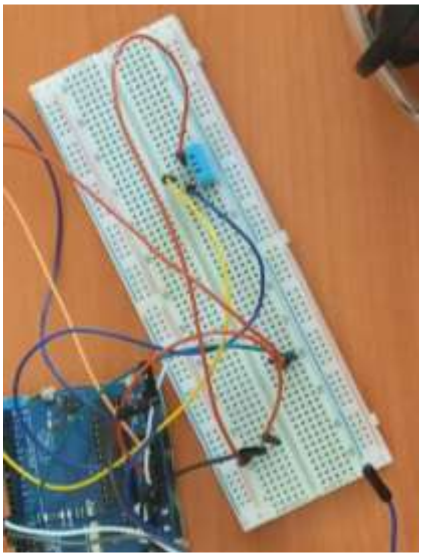

Figure 2.5: Breadboard

- **Motor Pump and Relay**

The motor pump LIFETECH Aquarium is a water pump of 220V. Aquarium Pump is a Submersible Pump Garden Fountain Pump AP1300 (Figure 2.6). In our system, it is used to send the water in the pipe when the Arduino sends a request.

Figure 2.6: Motor Pump

The motor pump has 2 pins: (+) positive pin and (-) negative pin. To control the motor pump, we used a relay in between Arduino and the motor pump. Arduino can control the pump via the relay.

Figure 2.7: Relay and pump Architecture

The relay has two groups of pins (Figure 2.7): low voltage group and high voltage group.

Pins in the low voltage group are connected to Arduino, including three pins:

- ✧ GND pin: needs to be connected to GND (0v)
- ✧ VCC pin: needs to be connected to VCC (5v)

✧ IN pin: receives the control signal from Arduino

Pins in the high voltage group are connected to high voltage, the motor pump and the electrical cable. The pins include three pins:

✧ COM pin: is the common pin. It is used in both normally open mode and normally closed mode

✧ NO pin: is normally open pin. It is used in the normally open mode

✧ NC pin: It is used in the normally closed mode

In our system, the relay works on the normally open mode, then at the high voltage level we use the COM and the NO pins, that receives the positive pin of the motor pump. The "normally open mode" means that "if the IN pin is connected to LOW (0V), the switch is open, the motor pump is OFF (or inactive); if the IN pin is connected to HIGH (5v), the switch is closed, the pump is ON (or active)".

The drip irrigation pipe is a canal used to provide water to crops. For our system we use two types of pipes. The first pipe is the connector pipe that links the motor pump to the second pipe that passes through the plant root to the end of the soil (Figure 2.8). At every 8 mm there is one hole where the water escapes from the pipe to the plant root, drop by drop (Figure 2.9). If the motor pump is switched on for one hour, the plant receives 1.6 liters of water through the hole.

Figure 2.8: Pipe architecture

Figure 2.9: Drop by drop pipe

2.3 The system diagram

The system (Figure 2.10) is a smart irrigation system that works automatically without the intervention of human being to switch it ON or OFF. This system is based on soil moisture data and have Arduino microcontroller that controls and manages the system with two additional data (temperature and relative humidity).

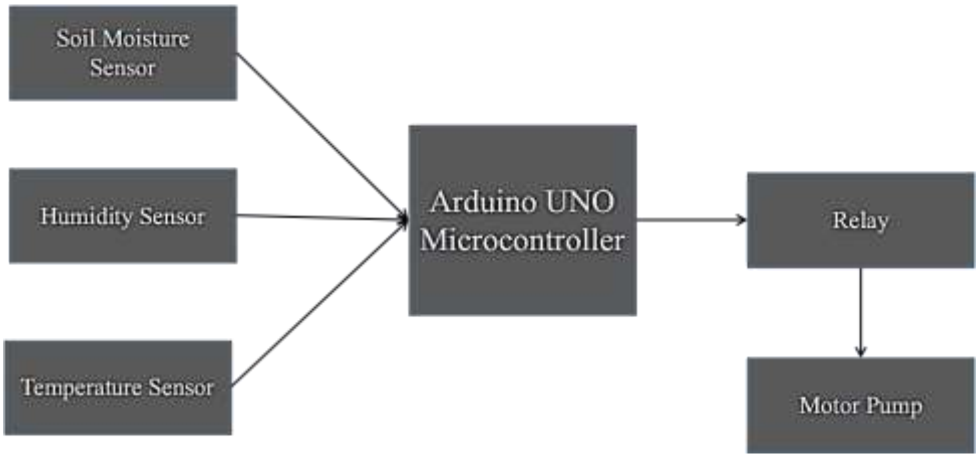

Figure 2.10: System diagram

The sensors record the data and send them to the Arduino microcontroller that decides according to the given thresholds. When the soil is dry, the motor pump is activated, and when the soil is sufficiently wet the motor pump stops.

2.4 Implementation

To implement the system, we used the Arduino programming language (based on Wiring), and the Arduino Integrated Development Environment (IDE), based on Processing. Wiring is an open-source programming framework for microcontrollers. The idea of the language is to write a few lines of code to connect a few electronic components to the hardware of choice and manage them. The language process is based on sketching with hardware. The IDE (Figure 2.11) is a cross-platform application that is written in functions from C and C++. It is used to write and upload programs to the Arduino board. The IDE version 1.8.13 was used on Linux for our work. The software is easy to understand and could be installed in any operating system (Windows, macOS, Linux).

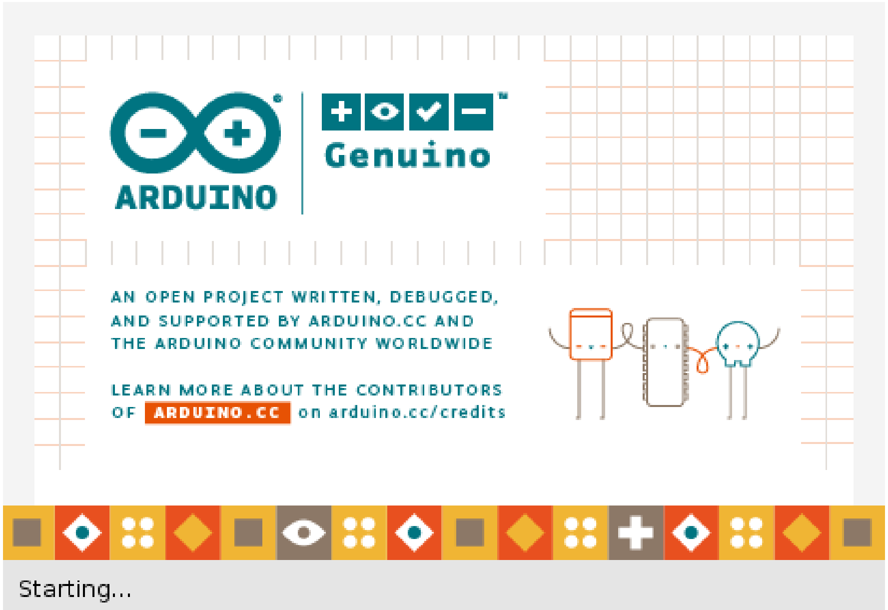

Figure 2.11: Arduino IDE

For the implementation of the system, we followed the following steps:

- ✓ Connect the devices to the Arduino board

First, we connected the humidity and temperature sensors to the Arduino board through the breadboard. Besides, we connected the soil moisture sensor. We connect the relay to the motor pump. The relay is also connected to the Arduino board in order to get the signal from it to activate the motor pump. The motor pump is alimented with a 220V, however the Arduino board voltage recommended is 7-12V. For this work, the Arduino was connected to our laptop and the motor pump to a direct plug.

- ✓ The calibration of the sensors

The calibration of the sensors is the next step. It is feasible by creating a specific sketch to each sensor on the Arduino IDE in order to test the sensor and to set the values to start the system.

The developed system has 6 components (Figure 2.12). The Arduino microcontroller which is the heart of the system, has to manage the computer program in order to turn the system ON or OFF. It gets the data to be analysed from sensors to integrate the soil moisture and temperature which will help it to activate or not the moto pump with the amount of water needed. This helps to give to the plant the needed amount of water at the right time without human intervention. Figure 2.13 represents the flowchart of the algorithm used by the system to work.

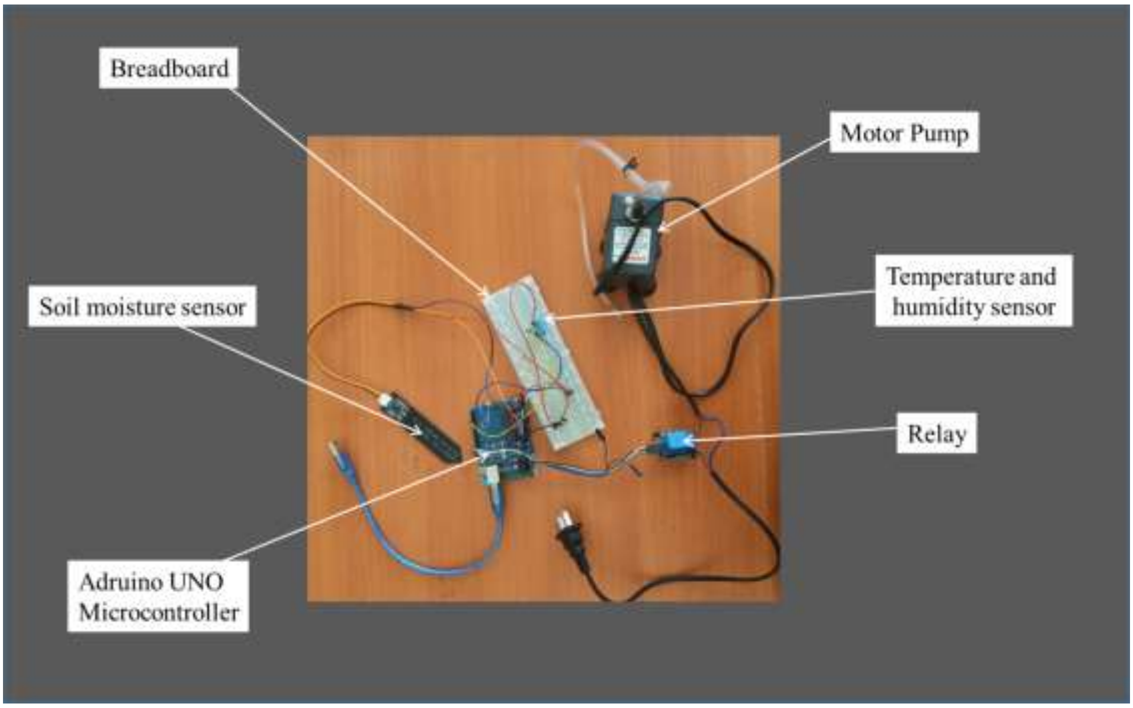

Figure 2.12: System overview

Figure 2.13 explains how the system works to enable automatic irrigation of the soil. First, the Arduino microcontroller gets the data from the soil moisture sensor to check the level of soil moisture, from the temperature sensor and the relative humidity sensors. These data have to be analysed by the Arduino which is the master control unit. It decides according to the soil moisture, the temperature and the relative humidity threshold that are already in the script. The microcontroller compares the values and determines if there is any need of water or not. If there is need of water, a signal is sent to the relay that also sends a signal to the motor pump to turn it ON. When the scheduled time is out, the sensors send new data to the Arduino which follows again the process to check if the conditions are now good for the plant. If yes, the motor pump is OFF, else the motor pump continues to provide water to the field until the condition becomes yes. It is a continuous process that will stop only when the farmer stops it at the harvesting phase.

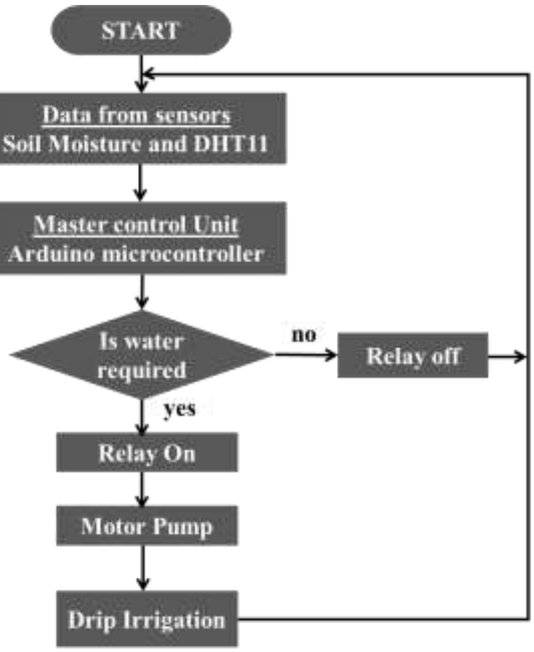

Figure 2.13: Flowchart diagram

The following figure (Figure 2.14) shows a portion of the code used by the Arduino for the management of the system.

```
Serial.println();
Serial.print(soilMoistureValue);
Serial.print("\t Soil Moisture (%): ");
Serial.print(soilmoisturepercent);
Serial.print("\t");
Serial.print("Humidité (%): ");
Serial.print((float)DHT11.humidity, 2);
Serial.print("\t");
Serial.print("Température (°C): ");
Serial.println((float)DHT11.temperature, 2);
Serial.println();
```

Figure 2.14: Portion of the code

CHAPTER THREE

RESULTS AND DISCUSSION

3.1 Analysis of climate parameters influencing irrigation in Niamey

The rainfall anomalies in Niamey are shown in Figure 3.1 from which we can see that the precipitation is highly variable. The anomaly is dominant with negative anomalies from 1986 to 2011 and positive anomalies from 2012 to 2020 except 2019 that experienced a negative anomaly. However, the highest negative index was in 1999 and the highest positive index was in 2017; facts that show respectively the severe drought and heavy flood experienced in Niamey. This is in agreement with Bigi (2018) who has stated that Niger will experience an increase of rainfall with high risk of flooding and drought in the future. The high variability of the rainfall will continue also in the future due to climate change. This experience of instability of rainfall insinuates the need of irrigation to ensure a constant production that will contribute to food security in the area.

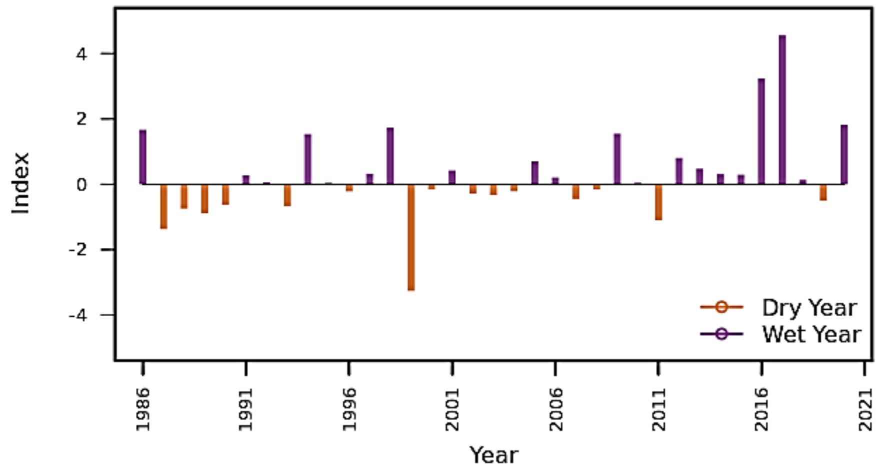

Figure 3.1: Rainfall anomaly in Niamey

Figure 3.2 presents the monthly rainfall variation. It shows that from 1986 to 2020 the main rainy months are from June to September; and the critical period when the irrigation is really needed is from April to May and from October to December.

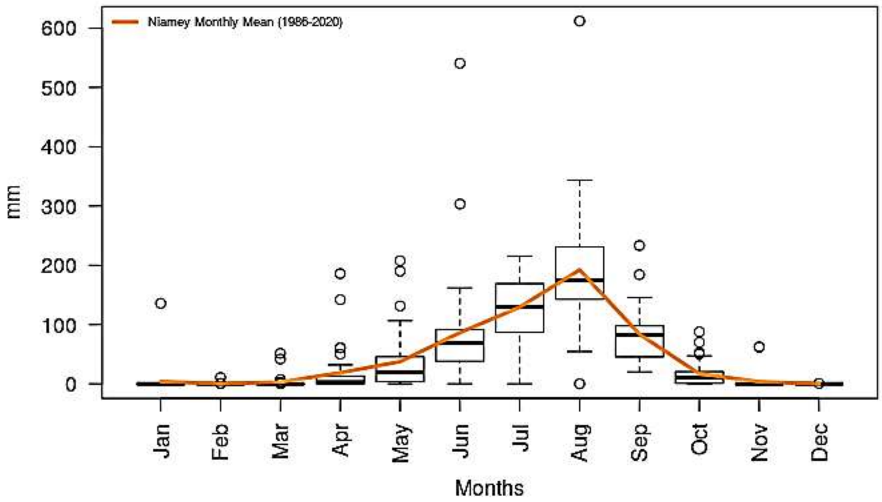

Figure 3.2: rainfall seasonal cycle in Niamey

Figure 3.3 reveals the evolution of the mean temperature from 1986 to 2020. The range of the temperature during the period is between 29 and 30.5 degree Celsius. The highest temperatures were registered at the end of the last years of the study period. The trend line shows an increase of the temperature along the period with and R squared of 41%. This increase of the temperature is not seen to decrease in the coming years. This result is similar to the one obtained by Ndiaye et al. (2017). For their analysis, they used the data from 1976 to 2011 and they have found that the temperature and the number of hot days is increasing.

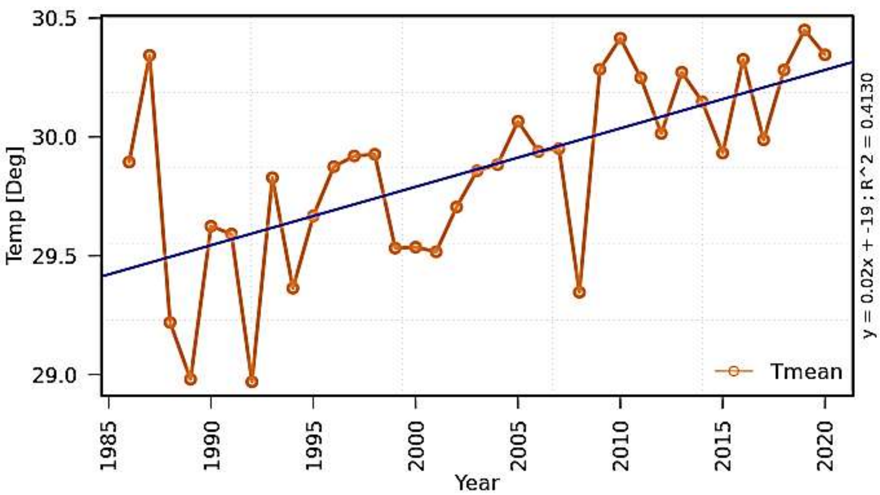

Figure 3.3: Mean temperature evolution in Niamey

Figure 3.4 gives the trend of wind speed in Niamey from 1986 to 2020. The highest speed is 4.25 meters per second and the lowest is closer to 3 meters per second. The trend shows a high decrease of the wind speed from 1996 to 2009 and seems to increase from 2009 to 2020. But the trend line shows a decrease of the wind speed from 1986 to 2020. This decrease of the wind speed has also been observed by Garba and Ozer (2014) who used the 3-hourly wind speed datasets of the Niamey airport from 1990 to 2005.

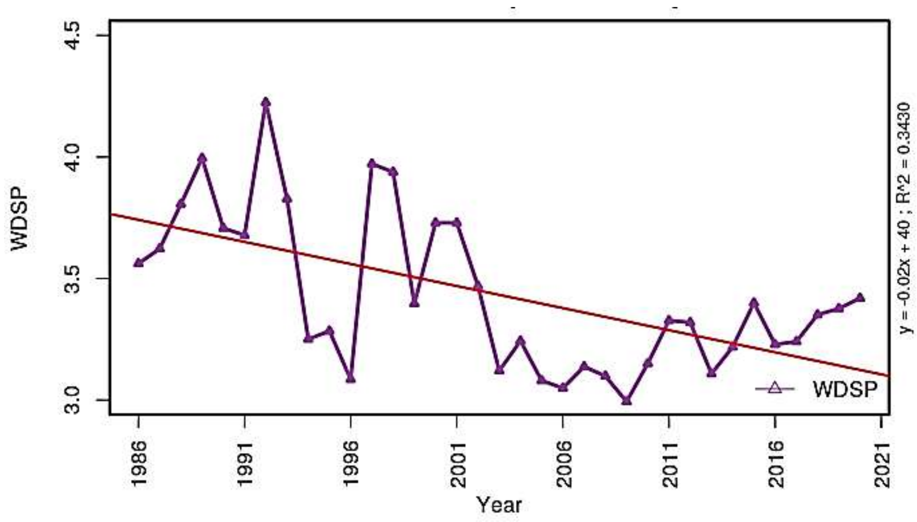

Figure 3.4: Wind speed evolution in Niamey

The relative humidity (Figure 3.5) trend line from 1986 to 2020 depicts a decrease. The highest decrease could be seen from 2005 to 2006 and can be explain by the change of equipment. But since 2006 it attempts to increase slowly. The huge variation of the relative humidity along this period also explains the need of irrigation.

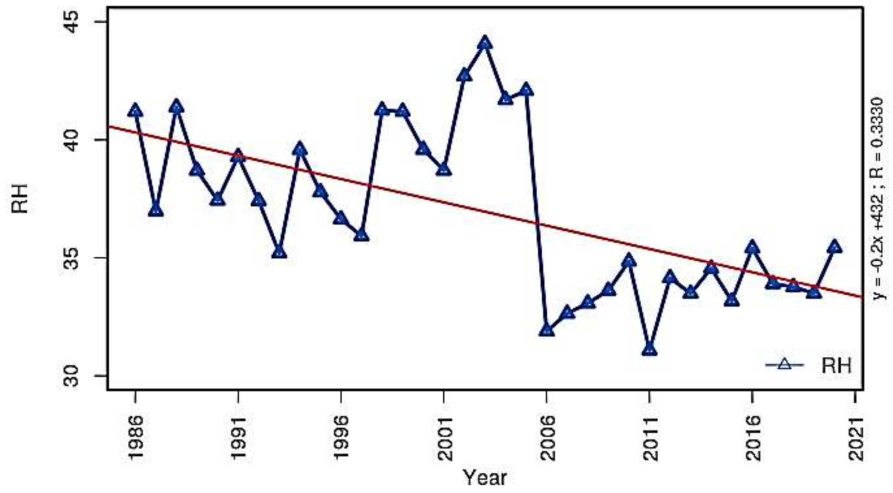

Figure 3.5: Relative humidity evolution in Niamey

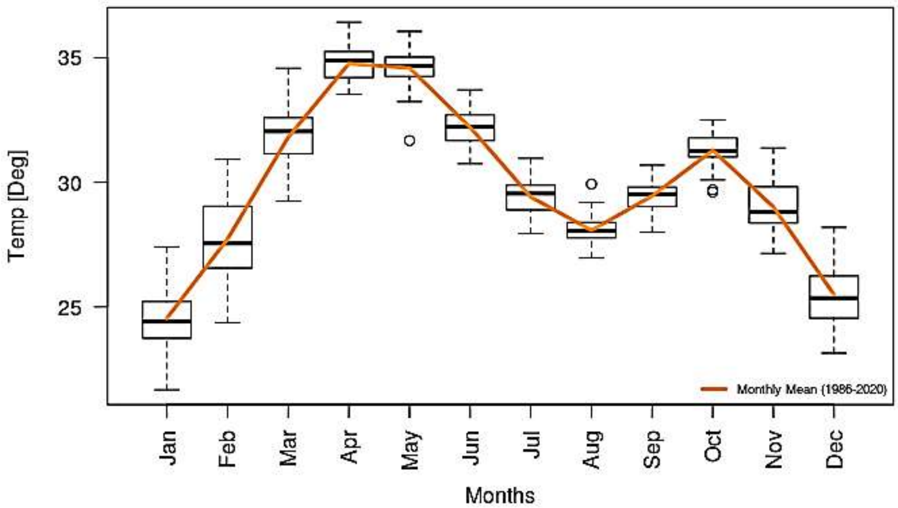

Figure 3.6: Temperature seasonal cycle in Niamey

From all the parameters analysed during the period from 1986 to 2020, the results pointed out the need of irrigation. For the rest of our analysis, we consider the hottest months as there is a high need of irrigation during these periods (according to Table 2.1).

3.2 Crops calendar

The irrigation calendar (see Table 3.1) is used for the estimation of the total water need in order to help the farmers in the choice of the suitable pump needed for smart irrigation. The months taken into consideration were March, May, April, June and July and represent the months with high need of water as they are the hottest ones. Favi (2020) in his thesis found that 61% of the used water was lost, only 39% was needed by the crops due to the bad choice of motor pumps. The computation of the plant water need is important to design the system, especially for the choice of the motor pump.

Table 3.1: Tomato plant irrigation water need calendar

<table>
<tr><th></th><th>1 to 30 Mar</th><th>31 Mar</th><th>01 to 30 Apr</th><th>1 to 9 May</th><th>10 to 31 May</th><th>1 to 24 Jun</th><th>25 to 30 Jun</th><th>1 to 25 July</th><th>Total</th></tr>
<tr><td rowspan="2">Number of days</td><td rowspan="2">30</td><td colspan="3">40</td><td colspan="2">45</td><td colspan="2">30</td><td rowspan="2">145</td></tr>
<tr><td>1</td><td>30</td><td>9</td><td>21</td><td>24</td><td>5</td><td>25</td></tr>
<tr><td>Kc</td><td>0.6</td><td colspan="3">0.875</td><td colspan="2">1.15</td><td colspan="2">0.975</td><td></td></tr>
<tr><td>Eto</td><td>8.3</td><td>8.3</td><td>8.2</td><td>8.6</td><td>8.6</td><td>8</td><td>8</td><td>7.2</td><td></td></tr>
<tr><td>CWR (mm)</td><td>4.98</td><td>7</td><td>7.175</td><td>7.525</td><td>9.89</td><td>9.2</td><td>7.8</td><td>7.02</td><td>60.59</td></tr>
</table>

3.3 The smart irrigation system

For the experimentation, if the soil moisture is less than 30% (first case) or if the soil moisture is less than 50% (second case), and the temperature is greater than 30°C, the motor pump is activated automatically (the relay will switch on the motor pump that will feed the soil in water with drip irrigation process due to the type of pipe we have used). The system will display "***irrigation on***" when it is on and "***irrigation off***" when it is off. (Figure 3.7). The system will continue to irrigate (Figure 3.8) until the sensors send again the data on the humidity, soil moisture and temperature and the soil moisture is equal or greater than 30 in the first case and equal or greater than 50 in the second one.

The precision of the soil moisture sensor used is not stable. It will be good for further study to use more precise sensors for a better result.

```
Soil Moisture (%): 11  Humidité (%): 69.00    Température (°C): 34.00
 irrigation on
Soil Moisture (%): 42  Humidité (%): 69.00    Température (°C): 34.00
 irrigation on
Soil Moisture (%): 56  Humidité (%): 69.00    Température (°C): 34.00

Soil Moisture (%): 29  Humidité (%): 69.00    Température (°C): 34.00
 irrigation on
```

Figure 3.7: System output

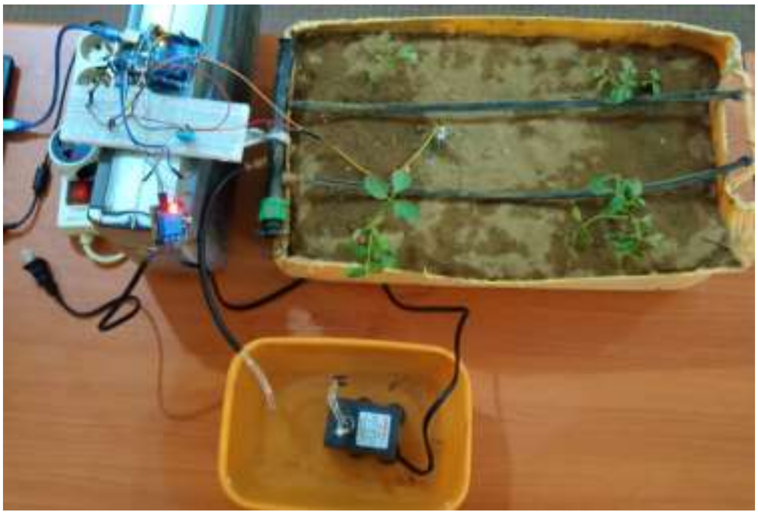

Figure 3.8: Experimentation overview

Figure 3.8 gives an overview of the experimentation. The experimentation was done on four tomatoes nurseries with soil moisture sensor, temperature and humidity sensor, motor pump, relay, Arduino microcontroller, breadboard and pipes. To scale up this system, we can consider a farm of 1 hectare minimum. Figure 3.9 illustrates a plan of the smart system with the optimum number of sensors based on the x transect model. The soil moisture sensors will be five on the ground at each intersection as proposed on the mentioned figure. There will be a unique air temperature sensor that will be placed at the centre of the farm. The Arduino microcontroller will take into account the mean of the humidity data coming from all the sensors before starting the system.

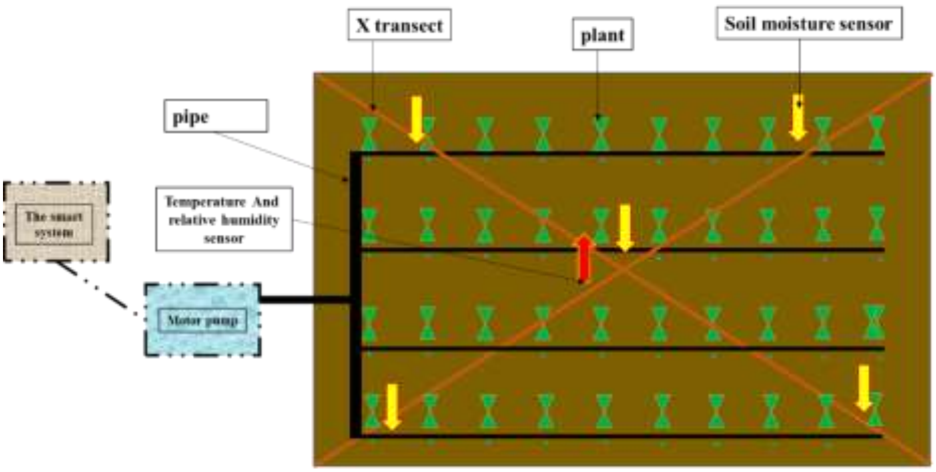

Figure 3.9: The system on a farm of 1 hectare

The Figure 3.10 shows an optimum plan to irrigate a large farm with many plots of different crops which have different water needs. Here the developed system can help to monitor all the plots. The smart system will be connected to each motor pump of each plot.

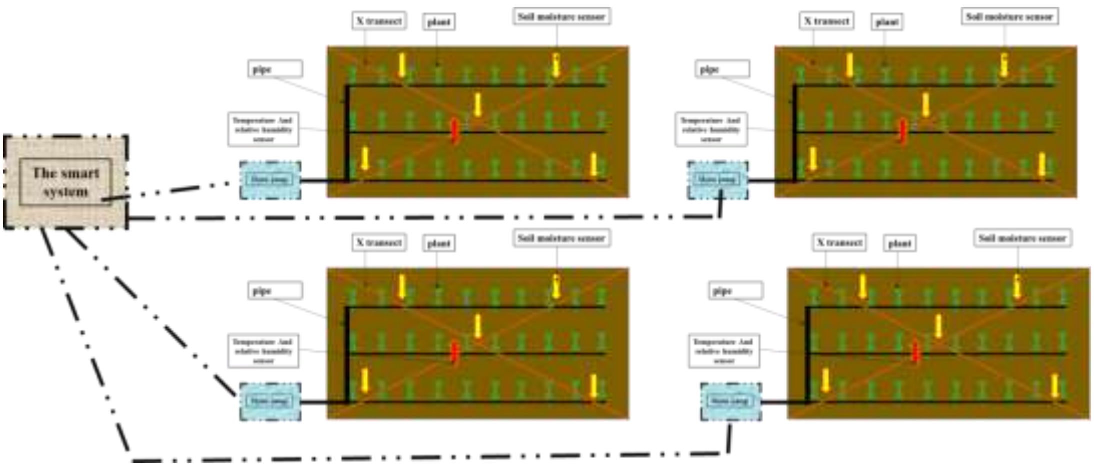

Figure 3.10. The system on a farm of 4 plots with an area of 2 hectares per plot

CONCLUSION AND PERSPECTIVES

A smart irrigation system adapted to farmers local conditions and realities is important for improving food security in Niger and in West Africa. Throughout our study, we have analyzed the evolution of climate factors that are affecting the irrigation in Niamey and its peri urban areas where technologies such as tele-irrigation are currently being experimented. We observed that the temperature is increasing while humidity and wind speed are decreasing from 1986 to 2020. Besides, the rainfall during the same period was highly unpredictable because of its high variability. The Arduino microcontroller and low-cost sensors-based irrigation system that we have developed is standalone as it does not need the human intervention except for maintenance. This system can help to reduce the waste of water in irrigation; it is cost effective; not farmer dependent; can help to irrigate large perimeters without human intervention and it saves time.

In order to improve the system, further works can be done such as:

- Experimentation of the smart irrigation system during the three different seasons of Sahelian region (cool-dry season, rainy season and worm-dry season);
- Analysis and comparison of the evolution of the different climate factors that influence irrigation during the different dry seasons of sahelian region;
- Analysis of the willingness of the population to adopt the new technology;
- Use of GSM techniques to send the data (on when the irrigation starts and how it stops) to the farmer to help him monitor the system wherever he is;
- Use of more precise sensors for better results.

BIBLIOGRAPHY

Abdullah A., Enazi S. Al, Damaj I., AgriSys: A Smart and Ubiquitous Controlled-Environment Agriculture System. (2019) doi:10.1109/ICBDSC.2016.7460386.

Aman K., Ajit K., Praveen K. S., Smart Irrigation System using iot: sis, international journal of engineering research & technology (ijert) Volume 06, Issue 06 (2017), http://dx.doi.org/10.17577/IJERTV6IS060067

Bhattacharya M., Roy A., Pal J., Smart irrigation system using internet of things. Lect. Notes Networks Syst. **137**, 119–129 (2021).

Bigi V., Pezzoli A., Rosso M., Past and Future Precipitation Trend Analysis for the City of Niamey (Niger): An Overview. (2018) Climate. 6. 73. 10.3390/cli6030073.

Chikankar P. B., Mehetre D., Das S., An automatic irrigation system using ZigBee in wireless sensor network, 2015 International Conference on Pervasive Computing (ICPC), Pune, 2015, pp. 1-5.

Cook S. E., Bramley R. G. V., Precision agriculture — opportunities, benefits and pitfalls of site-specific crop management in Australia. **(1998)** Australian Journal of Experimental Agriculture **38**, 753-763.

Doorenbos J., Pruitt W.O., Crop Water Requirements. (1977) FAO Irrigation and Drainage. Paper 24, FAO, Rome, 144 p.

FAO (Food and Agriculture Organization). Small-Scale Irrigation for Arid Zones: Principles and options. (1997) FAO, Rome

FAO, 22 Water reports: Deficit Irrigation Practices, Rome, 2002, pp. 79-87

FAO, Agriculture, food and water. A contribution to the World Water Development Report, 2003, pp.64

FAO, ECA and AUC. 2020. Africa Regional Overview of Food Security and Nutrition 2019. Accra. https://doi.org/10.4060/CA7343EN

FAO, Guidelines for water management and irrigation development, International Commission on Irrigation and Drainage, 2008

FAO, IFAD, UNICEF, WFP and WHO. 2020**.** In Brief to The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets. Rome, FAO. pp.320. https://doi.org/10.4060/ca9699EN

Favi G. S., Efficiency evaluation of photovoltaic water pumping system for Suitable exploitation: A Case study of Bonkoukou in Niger. Master's thesis at Université Abdou Moumouni, in integrated master program sustainable rural transformation (imp-srt), 2020, 97 pages.

Garba Abdou M., Ozer P., Assessment of wind energy potential in in Niamey, Niger., Submitted to the 1st International Conference on Energy, Environment And Climate Changes, **16**, 4009 (2014).

Gutiérrez J., Villa-Medina J. F., Nieto-Garibay A., Porta-Gándara M. Á., Automated Irrigation System Using a Wireless Sensor Network and GPRS Module. in IEEE Transactions on Instrumentation and Measurement, vol. 63, no. 1, pp. 166-176, Jan. 2014.

Hassen Y., Assessment of small-scale irrigation using comparative performance indicators on two selected schemes in upper awash river valley. Master's thesis, Alemaya University school of graduate studies, Ethiopia, 2004, 167 pages

Hwang S., Monitoring and Controlling System for an IoT Based Smart Home. International Journal of Control and Automation, vol 10 (2017), pp. 339-348

Jegathesh Amalraj J., Banumathi S., Jereena John J., A study on smart irrigation systems for agriculture using iot. International Journal of Scientific and Technology Research, vol 8 (2019), pp. 1935-1938

Jimenez Andres F., Cardenas P. F., Canales A., Jimenez F., Portacio A., A survey on intelligent agents and multi-agents for irrigation scheduling. Comput. Electron. Agric. **176**, 105474 (2020).

John J., Palaparthy V. S., Sarik S., Baghini M. S., Kasbekar G. S., Design and implementation of a soil moisture wireless sensor network. Twenty First National Conference on Communications (NCC), Mumbai, 2015, pp. 1-6.

Kosmowski F., Gibigaye M., Muller B., Lalou R., Innover en milieu rural ouest-africain Quels changements dans les pratiques agricoles des exploitants ? Les sociétés Rural face aux Chang. Clim. environnementaux en Afrique l'Ouest 1–19 (2015) doi:10.13140/RG.2.1.4005.1287.

Kshirod Kumar R., Samuchita M., Sivkumar M., Solar powered smart irrigation system using internet of things. In proceedings - 2nd international conference on data science and business analytics, ICDSBA, Institute of electrical and electrical and electronics engineers inc. (2018), pp. 144-149

Maupoux M. Solar (Photovoltaic). (2010) 44(871954).

Ndiaye A., Rabani A., Moussa G., Arona D., Global Warming and Heat Waves in West-Africa: Impacts on Electricity Consumption in Dakar (Senegal) and Niamey (Niger). International Journal of Energy and Environmental Science, 2.1 (2017), 16–26

Otto D., Sorensen A., Global agriculture towards 2050, Rome 2018

Pathak A., Uddin M., Jainal Abedin M., Andersson K., Mustafa R., Hossain M. S., IoT based smart system to support agricultural parameters: A case study. Procedia Computer Science, vol 155 (2019), pp. 648-653

Rajkumar M., Abinaya S., Kumar V., Intelligent irrigation system - An IOT based approach. IEEE International Conference on Innovations in Green Energy and Healthcare Technologies (ICIGEHT'17), (2017), pp. 1-5

Simonneaux V., Benoît D., Helson D., Er-Raki S., Olioso A., Chehbouni A., The use of high-resolution image time series for crop classification and evapotranspiration estimate over an irrigated area in central Morocco. (2008) International Journal of Remote Sensing. 29. 10.1080/01431160701250390.

Tazhina G., Parker J., Toward Sustainability Through Digital Technologies and Practices in the Eurasian Region. 2020, pp.294

Todorovic M. (2006). Crop Evapotranspiration. 10.1002/047147844X.aw57.

Websites

AgFunder Network Partners (AFN), https://agfundernews.com/iot-agriculture-farmers-arent-quite-sure-despite-4bn-us-opportunity.html, visited March 16, 2021

Arduino Uno Rev3 (store), https://store.arduino.cc/arduino-uno-rev3, visited June 12, 2021

Crop Water Needs (FAO), http://www.fao.org/3/s2022e/s2022e07.htm, visited June 11,2021

Dht11 Temperature And Humidity Sensor (indiaMART), https://www.indiamart.com/proddetail/dht11-temperature-and-humidity-sensor-19237198597.html, visited June 12, 2021

Drip irrigation (Dictionary.com), https://www.dictionary.com/browse/drip-irrigation, visited June 3, 2021Crop Water Requirement (CWR) FAQ, https://nwa.mah.nic.in/sdmc/faq/cwr.htm, visited June 25, 2021

Introduction to Smart Irrigation (aeris), https://www.aeris.com/news/post/introduction-to-smart-irrigation/, visited June 3, 2021

Technologies & Innovations: Tech-Innov SARL, http://www.tele-irrigation.net/nos-innovations-solu/systeme-tele-irriga/, visited June 11, 2021

Annex: Arduino Code

```
#include <dht11.h>
#define DHT11PIN 4 // broche DATA -> broche 4
   dht11 DHT11;
   const int dry = 700;   //represent the soil moisture value when the place is dry
   const int w
et = 500;  //represent the soil moisture value when the place is wet
   int soilMoistureValue = 0;
   int soilmoisturepercent=0;
   int pin_out = 13;

   void setup()
   {
             Serial.begin(9600); // open serial port, set the baud rate to 9600 bps.
             while (!Serial) {
             // wait for serial port to connect. Needed for native USB (LEONARDO)
              }
             pinMode(pin_out,OUTPUT);     //set pin no. 13 as output.
   }   void loop()
   {
    soilMoistureValue = analogRead(A0);  //put Sensor insert into soil
    if(soilMoistureValue >= 700){
      soilmoisturepercent = 0;
         }else if(soilMoistureValue < 500){
              soilmoisturepercent = 100;
             }else if(500 <= soilMoistureValue < 700){
                  soilmoisturepercent = map(soilMoistureValue, dry, wet,0, 100);
                  }

      DHT11.read(DHT11PIN);
      if (isnan(soilMoistureValue) || isnan(DHT11.humidity) || isnan(DHT11.temperature) ){
        Serial.println(F("Failed to read from DHT sensor!"));
        return;
        }

      Serial.print(soilMoistureValue);
      Serial.print("\t Soil Moisture (%): ");
      Serial.print(soilmoisturepercent);
      Serial.print("\t");
      Serial.print("Humidité (%): ");
      Serial.print((float)DHT11.humidity, 2);
      Serial.print("\t");
      Serial.print("Température (°C): ");
      Serial.println((float)DHT11.temperature, 2);
      Serial.println();

    if(DHT11.temperature > 37 && soilmoisturepercent <= 50){
     Serial.println(" \t  irrigation on  ");
      digitalWrite(pin_out,HIGH);     //set pin high (5v)
    }else if(soilmoisturepercent <= 30){
     Serial.println(" \t  irrigation on  ");
      digitalWrite(pin_out,HIGH);     //set pin high (5v)
     }else{
      Serial.println(" \t  irrigation off  ");
      digitalWrite(pin_out,LOW);    //set pin low (0v)
     }
    delay(3600000);

 }
```