UNIVERSITY OF AGDER

Water Supply in Rwanda

Use of Photovoltaic Systems for Irrigation

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Abstract

The current energy situation in the world where most of the energy needed is generated from non-renewable sources such as fossil fuels is no longer sustainable. During few years, non-renewable sources have become an interesting solution to provide energy to areas with small needs of electricity, rather than using non-renewable sources.

Therefore, this project has pursued to implement photovoltaics panels to supply energy in a rural region in central Africa, contributing to the development of the area and proving that this technology is viable to pump water for irrigation instead of the conventional electric grid.

A rural area between Kidogo Lake and Rilima town, in Bugesera district of Rwanda, has been chosen as target. This analysis has focused on typical plantations of the country, being the main crops banana, cassava and maize, each one with very similar maximum water needs; 71 m^3/ha_day, 70 m^3/ha_day and 67 m^3/ha_day, respectively.

The eastern province of Rwanda is formed by seven districts. A preliminary study was developed in order to find the target area in terms of weather conditions, high temperature and low rainfall. Therefore, parameters such as precipitation, solar irradiance and evapotranspiration, among others, have been crucial for deciding the driest zone. Indeed, the Bugesera district is an ideal candidate due to the reception of a large amount of solar irradiation, with an annual average of 5,28 kWh/m^2_day.

In order to dimension the photovoltaic and water-pumping system, a preliminary research including a large amount of background was required to determine the best structure. Indeed, knowing the water demand, we decided the water should be pumped up into a tank, letting it irrigate the field via gravitation only. A sample irrigation layout was then designed to ensure that with a number of pipes, water was conveyed to every plant.

The use of a tank not only for storing water, but also as a source of system's pressure lead us to calculate the minimum distance from the ground to the bottom. The height obtained of 2,2 meters provides the necessary pressure to distribute water and irrigate the field.

With the energy needed for the water supply, a photovoltaic pumping system, consisting of a PV generator, inverter and pump, was selected. Our main findings was that the photovoltaic system must have a rated power of 1,73 kW in order to guarantee proper functioning. For the photovoltaic system, six STP290 - 24/Vd solar modules from Suntech were chosen, for the water pumping system, a B50 Electric Drive from the company BBA Pumps. Moreover, and regarding the inverter system, model Galvo 1.5-1 from company Fronius with a nominal output power capacity of 1.500 watts was chosen.

Acknowledgements

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I, Gerard Herrero want to express my sincere gratitude to all my family, giving special thanks to my parents, Josep and Rosa, and my sister, Joana, for encouraging me to develop my master thesis abroad and for their great support throughout all my life. I would also like to thank all my friends for giving me lots of laughs and for our good friendship. In particular, Artur deserves a special mention for being always there, both in good and bad moments.

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Chapter 1. Introduction

The use of photovoltaic systems has increased in recent years. The concern of conserving our natural resources by using renewable energies has expanded more nowadays than at perhaps any other time in human history. Using fossil fuel-based energy sources has been proven to contribute to global climate change. In addition, they are finite so they will be depleted over time. Clean energy alternatives like solar energy, collected through photovoltaic systems, can be of great benefit to our environment.

1.1. Background and Motivation

Earth's climate is changing in ways that affect our whole environment. A lot of ecosystems are being damaged every day and these changes cannot be caused only by natural aspects.

Bearing in mind that more than half of the world's electric power is provided by means of fossil fuels, it is obvious that human activities are contributing to climate change. On the one hand, by releasing, every year, billions of tons of CO_2 into the atmosphere contributing to "the green-house effect" together with other heat-trapping gases. Indeed, CO_2 emissions might be affecting in a negative way by melting glaciers, therefore sea-water levels are rising every year. On the other hand, large amount of gases such as NO_2, NO and CO are also released every year harming animals, plants and causing health problems in humans. Climate changes will continue into the future unless we do not do something about it.

In an effort to find a solution, some studies have been researching several renewable energy sources in order to provide to the world's inhabitants the energy needed. These renewables include bioenergy, wind, solar, geothermal energy as well as tidal power and hydro power. However, these renewable systems have also disadvantages.

On the one hand, it is not easy to generate the same amount of electricity produced by fossil fuel generators than by using renewable systems. This may mean that a reduction of the amount of energy we use is needed or just more energy facilities have to be built. It also indicates that the best solution to our energy problems may be to have a balance between different power sources, such as hybrid systems.

On the other hand, the reliability of supply is also a problem. Renewable energy power source relies on the weather and it is highly intermittent in nature, meaning that most of them experience both periodical and seasonal variations, thus being unable to guarantee an interrupted supply of electricity. Hydro generators need precipitation to maintain the dams filled, wind turbines need wind to move their blades and solar panels need clear skies and sun irradiance to collect heat and provide electricity and, obviously, this can be unpredictable. Moreover, the current cost of renewable energy technology is also high in comparison to traditional fossil fuel generation because of its large capital cost and initial investment.

1.2. Problem Statement

Rwanda is part of a group of countries with almost no access to electricity plus high scarcity of water in rural areas.

Bugesera district is one of the driest areas within the eastern province of Rwanda. Its precipitation is the lowest in the country, with values below 900 mm per year, and its average temperature is high, with values above the 21 °C. The combination of these two factors can lead to droughts, resulting in poor harvests and famine, make Bugesera a very good candidate district to perform our study.

Nowadays, the most common way to pump water is by using electricity from the grid. Most of this grid electricity comes from non-renewable energies as renewables are not fully implemented. However, it is not always possible to connect the water pumping system with the nearest electric grid due to the high cost involved with extending the main grid. As a consequence, renewable energy systems have become a suitable cost solution for supplying remote areas with electricity.

1.3. Goal and Objectives

The main goal of this thesis is to propose an optimal photovoltaic and water pumping system, in terms of cost and efficiency, in order to pump water for irrigation instead of using the electricity directly from the grid, which is not easily available. This aim is achieved by accomplishing the following objectives:

- Analysing parameters such as precipitation and solar irradiation within the seven districts of the eastern province of Rwanda.
- Finding relevant crops in the selected area.
- Calculating water requirements for each selected crop and the energy needed.
- Proposing a basic irrigation layout.
- Studying the potential of photovoltaics and the water pumping systems in the selected area.
- Selecting the photovoltaic system by using RETscreen software database.
- Analysing the economic cost and the investment.
- Comparing the cost, advantages and disadvantages between the chosen system and the electric grid system.

1.4. Key Assumptions and Limitations

The scope of this study is limited to determine both the optimal photovoltaic system to supply electricity and the water pumping system that can provide enough water for irrigation. In addition, an economical comparison between electricity from the renewable system or the grid system will be performed. This analysis has been done by making the following assumptions.

- The source for information on the irradiance conditions, the NASA satellite-derived meteorology and solar energy data are accurately enough for gauging solar photovoltaic systems.
- The calculated water needs are considered the same throughout the project lifetime.
- Solar radiation and other parameters such as precipitation and relative humidity extracted from NASA data base are also considered the same during the project's analysis.
- While using the RETscreen software and due to the lack of meteorological stations within the chosen area, the parameters needed were extracted from Kigali station, which is the nearest one.
- Due to the guarantee of the PV panels is about 20 years, the lifetime of the project has been set as equal.

The final chosen system has the following limitations.

- The photovoltaic and water pumping systems are location specific and will not be optimal for a different location with others basic parameters' values.
- This study will not be focused on the design of the electric grid.
- The water tank does not have an integrated and automatic system controlling the general valve. Therefore, a farmer or worker with enough knowledge needs to be in charge of it.
- The transport and replacement costs have not been taken into account when calculating the first investment.

1.5. Requirements

The requirements can be divided into functional and non-functional requirements. A functional requirement specifies a function that a system must be able to perform meanwhile a non-functional requirement is a statement of how the system must behave, it is a constraint upon the systems behaviour [1].

1.5.1. Functional Requirements

<u>Energy Supply</u>

Once the photovoltaic system receives sufficient solar irradiance, it must be capable of supplying enough energy to the water-pumping system. For that reason, at nights the PV system will be not working and, throughout the day, it will be switching ON and OFF spontaneously depending on the intensity of the solar irradiance. Therefore, both the PV and the water-pumping systems must be able to support this continuous variability.

1.5.2. Non-functional Requirements

Lifetime

The reliability of every part comprising the system has to be very high. Not only must a long-life water supply be guaranteed, but maintenance must be minimized in a country where there is a lack of specialised labour force. Hence, in order to minimize the indirect costs, it is necessary to invest a larger amount of money.

Portability

Although this research has been focused on a specific area of Rwanda, it is also possible to place the designed system into another location. However, this new environment should be as similar as possible to the first one in terms of solar irradiance and sun hours. Yet, the new system location should be also near to a water resource in a non-sloped land.

Scalability

The water pumping and the photovoltaic systems have been designed to irrigate one hectare of land and, in fact, if the irrigation of a larger amount of land was required, some changes in both systems should be implemented. These changes can be the increase of the power capacity of both the PV and the water pump and increase the number of water tanks. Duplication of the basic system can also be used. Certainly, these changes come with a significant cost and, obviously, the irrigation of a larger amount of land is more expensive.

1.6. Thesis Outline

The content of this thesis pursues to find a photovoltaic and water pumping system economically viable and able to compete against the use of electricity directly from the grid. The thesis comprises 9 chapters, which are detailed below.

Chapter 2 gives an overview of the Rwanda's geography which is key factor for understanding the water need in determined areas of the country. Moreover, a brief explanation of the most important analysed parameters is developed.

Chapter 3 consists in gathering climate information about each of the provinces in Rwanda and the following analysis of that stats to obtain the most critical area in terms of irrigation.

Chapter 4 focuses on the selection of the crops that fit best in the area studied. Furthermore, it describes the water requirements for each crop during the different seasons.

Taking that values into account, Chapter 5 proposes an irrigation layout that provides the minimum elevation height to ensure water flow is conveyed to every plant in the field.

Chapter 6 explains the main components used in photovoltaic and water pumping systems. It also details the major characteristics of each of the components, costs, operation and maintenance. The software used to size the system, RETscreen, is introduced and explained.

Finally, Chapter 7 presents the results and Chapter 8 gives the discussion. Chapter 9 provides the conclusions and the future scope of the work.

The Republic of Rwanda is a state in central and east Africa. It is located a few degrees south of the Equator, being bordered by the Democratic Republic of the Congo, Uganda, Tanzania and Burundi. The country is located in the African Great Lakes region, its geography is dominated by mountains in the west and savannah in the east, with a large number of lakes throughout the country. Despite being located in the tropical belt, Rwanda experiences a temperate climate as a result of its high elevation. Hence its temperature and rainfall are more moderate than the surrounding hot and humid equatorial regions.

2.1. Overview of Rwanda

Rwanda covers an area of 26.338 km^2 with an estimated population of 12,1 million, predominantly young and rural, with a density among the highest in Africa. The present borders were drawn in 2006 with the aim of decentralizing power and removing associations with the old system and the genocide. The country is structured with five provinces based primarily on geography (Figure 2.1). These are Northern Province, Southern Province, Eastern Province, Western Province, and the Municipality of Kigali in the centre.

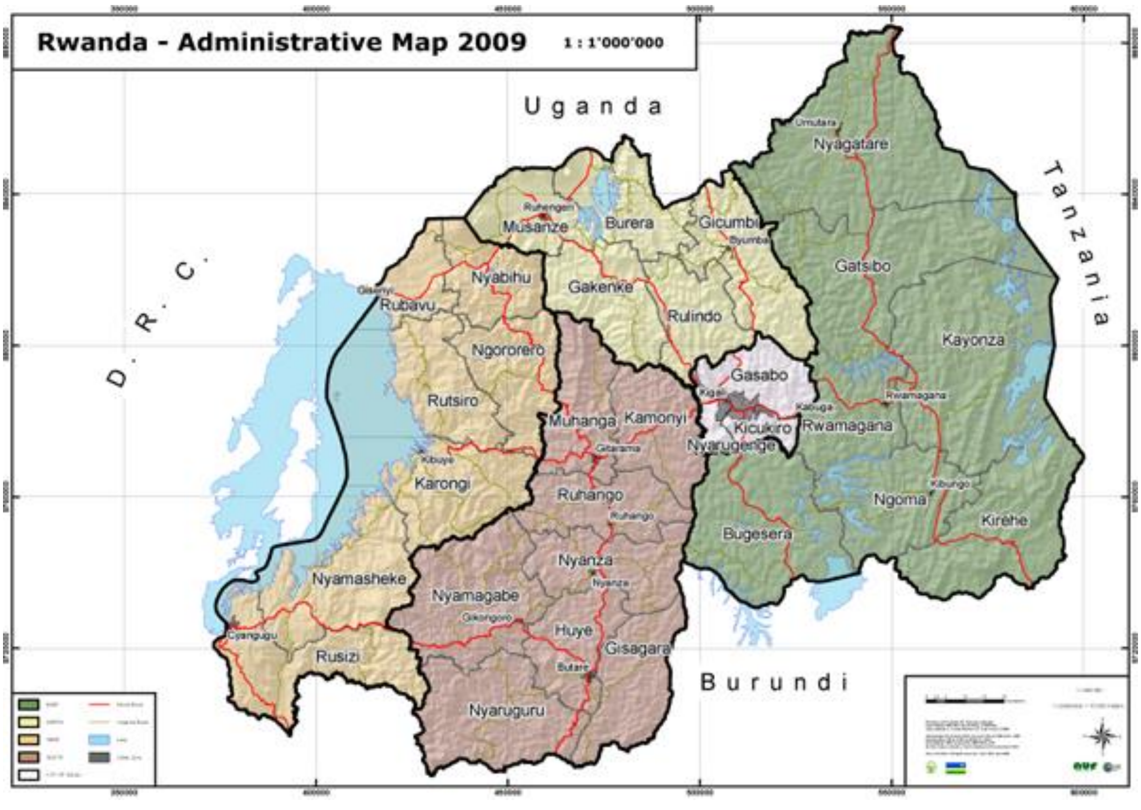


Figure 2.1: Administrative map of Rwanda (2009)
(Source: http://www.rema.gov.rw/*soe*/background.php)

To understand the actual geo-economic situation of the country, it is important to know the recent history of Rwanda. In 1899 it became under the control of Germany after being it decided in the Berlin Conference in 1884. That fact decided the beginning of the colonial era. It kept part of the German East Africa till the First World War, when Belgium invaded it. In 1961 its monarchical government was formally abolished by referendum and the first parliamentary elections were held and became independent in 1962. Fighting between the ethnic groups broke out repeatedly after independence. Finally, social tensions culminated in the 1994 genocide, in which an estimated of 500.000 to 1 million people were killed.

Since 1994, the government of Rwanda has been able to maintain overall macro stability by implementing extensive reforms. Agricultural policy is aimed at improving the production of subsistence and commercial crops. These reforms have contributed significantly to the country's strong growth performance. Still, the economy is based mostly on subsistence agriculture where coffee and tea are the major cash crops for export. Tourism is a key sector as it is growing fast and is now the country's leading foreign exchange earner. Rwanda is currently at peace and today has less corruption than the surrounding countries.

The agricultural sector is very important to the economy of Rwanda as it provides employment to nearly 90 % of the total labour force. Despite being the main source of income, it currently contributes less than 40 % of the gross domestic product. Production remains low and constraints to agricultural growth are severe, resulting in scarcity of rural infrastructure and depressed prices for the two main export commodities, coffee and tea.

2.2. Poverty Profile

Despite the large growth in Rwanda's economy over the last decade, it is still among the poorest countries in the world. According to the United Nation's Human Development Report (2011), Rwanda was ranked the 22th in terms of poverty.

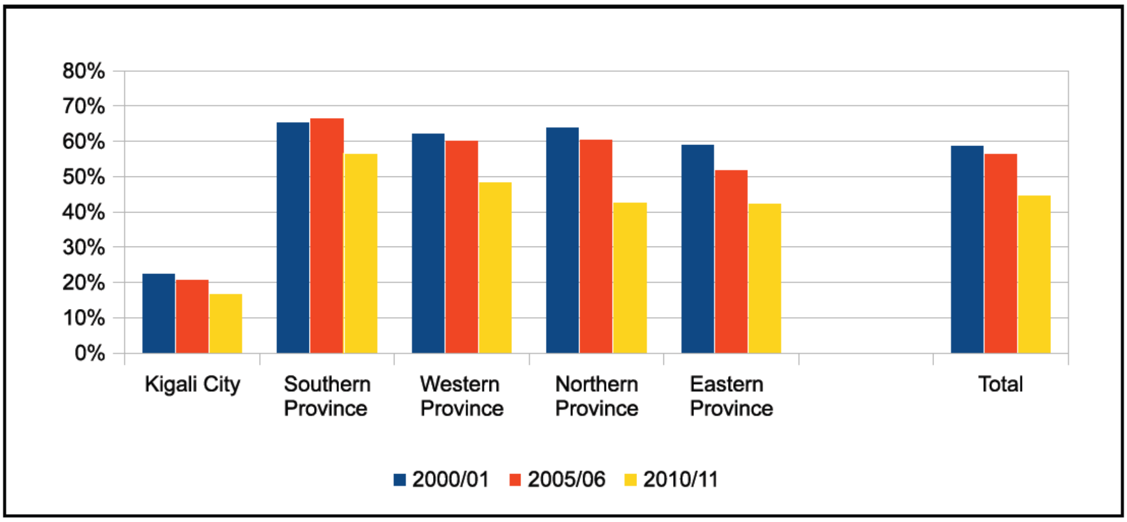


Figure 2.2: Poverty evolution in Rwanda
(Source: The evolution of poverty in Rwanda from 2000 to 2011. Republic of Rwanda. National Institute of Statistics of Rwanda)

As can be seen in Figure 2.2, in 2011 the level of poverty was almost 45 %, having a large reduction in the Northern Province. Furthermore, it is important to note the great amount of extreme poverty in every province, as detailed in the Table 2.1.

Table 2.1: Extreme poverty in Rwanda (2011)
(Source: The evolution of poverty in Rwanda from 2000 to 2011. Republic of Rwanda. National Institute of Statistics of Rwanda)

Province	Extreme poverty 2010/11 [%]
Kigali City	7,80
Southern Province	31,10
Western Province	27,40
Northern Province	23,50
Eastern Province	20,80
TOTAL	**24,10**

2.3. Water Resources

Water is a strategic natural resource for any country's economic, social and cultural development. As Rwanda is very dependent on agriculture, it increases the importance of this resource. The country has a dense hydrological network composed of numerous rivers, streams and wetlands that drain into lakes and other reservoirs.

Although water resources are abundant, they are unevenly distributed in space, category and quantities. The western region receives considerably higher amounts of rainfall compared to the east. During rainfall seasons, runoff generated in the hillsides quickly flows to the valley bottoms, marshlands, rivers or lakes creating an economic water scarcity owing to inadequate infrastructure. Thus, hillsides can support limited farming during dry seasons. On the other hand, the eastern part of the country has low rainfall but its lowlands are scattered by a good network of surface water bodies with significant flows and stock [2].

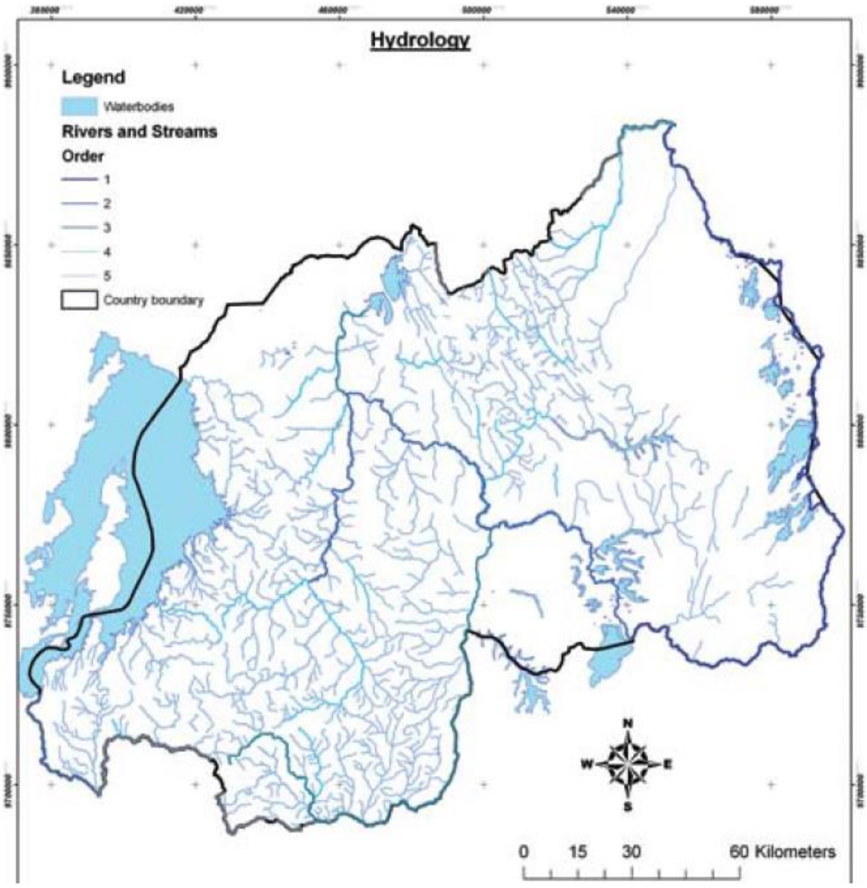


Figure 2.3: Hydrography (lakes and rivers)
(Source: The government of Rwanda, Ministry of Agriculture & Animal Resources. Rwanda Irrigation Master Plan.)

Rwanda is divided into two major drainage basins (Figure 2.3): the Nile to the east covering 67 % and delivering 90 % of the national waters and the Congo to the west, which covers 33 % and handles all national waters. How are these resources distributed is specified in Table 2.2.

Table 2.2: Water distribution in Rwanda
(Source: The government of Rwanda, Ministry of Agriculture & Animal Resources. Rwanda Irrigation Master Plan.)

Water Resources	Area [ha]	Share of Total
Runoff for small reservoirs	125.627	21,0%
Runoff for dams	31.204	5,2%
Direct river and flood water	80.974	13,6%
Lake water resources	100.153	16,8%
Groundwater resources	36.434	6,1%
Marshlands	222.418	37,3%

2.4. Climate Data

The selection of the area depends first and foremost to the particular climate conditions. Therefore, an exhaustive study of the territory is crucial for obtaining which area is the driest. Basic climatic conditions and the respective information are taken from reliable sources such as NASA website, Joint Research Centre and FAO/AGLW concerning the irrigation needs. To assess the need for irrigation, information on precipitation and evapotranspiration is needed and will be explained in this chapter.

2.4.1. Temperature

Rwanda is located just south of the equator. Because of its high altitude, its temperature and rainfall are more moderate than the surrounding hot and humid equatorial regions, despite having the same annual cycles. The temperature throughout the year is considerably constant, where the lowest registers are observed in highlands with temperatures ranging between 15 and 17 °C. On the other hand, moderate ones are generally in mid height areas temperatures can vary between 19 and 21 °C. Finally, in the east and southwest temperatures are higher due to its low height profile, being able to reach temperatures above 30 °C.

2.4.2. Precipitation

Precipitation is the main source of water for agriculture, as more than 90 % of Rwanda's agriculture is rain-fed. However, it is unevenly distributed in time and space, with about half of precipitation occurring in one quarter of the year (Table 2.3). Rainfall ranges from as low as 700 mm in the Eastern Province to about 2000 mm in the high altitude north and west.

Table 2.3: Temporal distribution of precipitation

Period	Season description	Share of Total Annual Precipitation [%]
Feb. - May.	Long rains (April being the wettest month)	48
June - Mid. Sept.	Long dry spell	Very little rains of 25-50 mm (especially in high altitudes)
Mid. Sept. - Dec.	Short rains (November being the wettest during this period)	30
Dec. - Jan.	Short rains with short dry spell	22

2.4.3. Effective Precipitation

The effective precipitation is the amount of rainfall added and stored in the soil. When raining, part of the water percolates below the root zone of the plants and part of the rain water flows away over the soil surface as run-off. This deep percolation water and run-off cannot be used by the plants. In other words, part of the rainfall is not effective. The remaining part is stored in the root zone and can be used by plants. This remaining part is called effective rainfall or precipitation. The factors which influence which part is effective and which is not, include the climate, the soil texture, the soil structure and the depth of the root zone [3].

There are several ways to calculate the effective precipitation based on real rainfall. According to Mr. Habyarimana, F., the most reliable methods to calculate the effective rainfall are by using a formula given by FAO/AGLW or the Empirical one, both equations extracted from software CROPWAT 8.0.

The effective precipitation P_{EFF} is given in mm per period of interest and is gained from the monthly precipitation using the formulas 2.1 and 2.2.

FAO/AGLW formula

$$P_{EFF} = 0{,}6 * P_{MONTH} - 10mm \qquad if\ P_{MONTH} \leq 70\ mm$$
$$P_{EFF} = 0{,}8 * P_{MONTH} - 24mm \qquad if\ P_{MONTH} > 70\ mm \qquad (2.1)$$

Empirical formula

$$P_{EFF} = 0{,}5 * P_{MONTH} - 5mm \qquad if\ P_{MONTH} \leq 50\ mm$$
$$P_{EFF} = 0{,}7 * P_{MONTH} + 20mm \qquad if\ P_{MONTH} > 50\ mm \qquad (2.2)$$

Where,

P_{EFF} is the effective precipitation (mm)

P_{MONTH} is the monthly precipitation (mm)

By using the real rainfall values, monthly effective precipitation has been calculated with these two different methods.

2.4.4. Evapotranspiration

Evapotranspiration or ET is a term describing the loss of water from the soil into the atmosphere as vapour from surfaces, including soil evaporation and transpiration from vegetation (Figure 2.4). The water generally enters the plant through the root zone, is used for various bio-physiological functions including photosynthesis, and then passes back to the atmosphere through the leaf stomata.

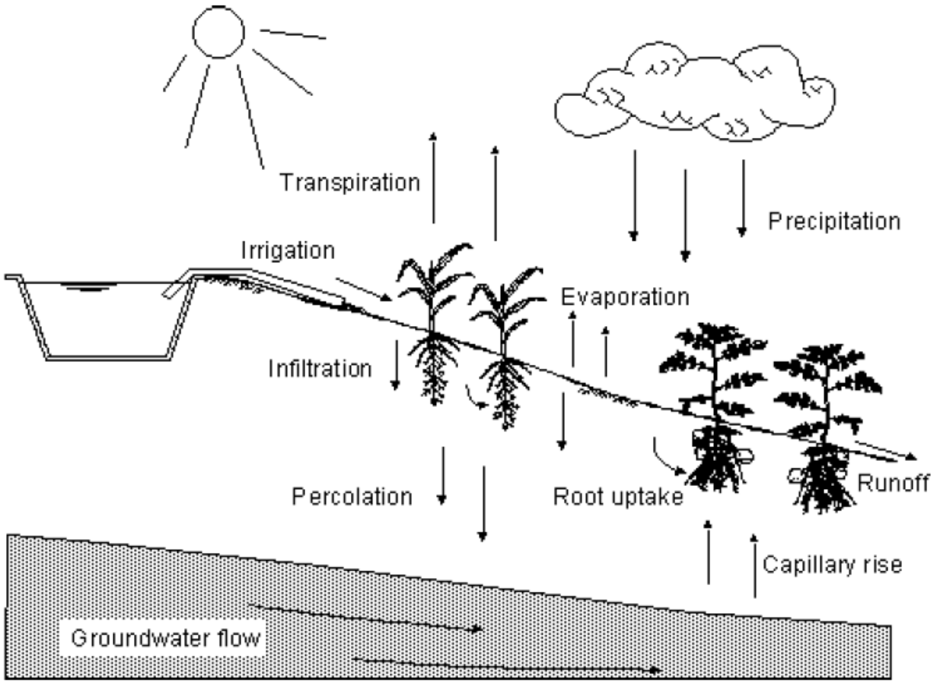


Figure 2.4: Global rainfall scheme
(Source: FAO)

There are several parameters that affect the evapotranspiration values. Temperature, relative humidity, wind and air movement are some of them.

- Temperature: When temperature rises, transpiration increases too, particularly during the growing season, when the air is warmer due to stronger sunlight and warmer air masses. Thus, the pores in stems and leaves opens and water is released whereas cold weathers produce a closure of them.

- Relative humidity: the larger the humidity, the more difficult it is for water to evaporate because the water vapour saturation. Therefore, when the humidity increases the transpiration decreases and vice versa.

- Wind and air movement: Transpiration increases whilst wind blows as the saturated air surrounding the leaf moves away and is replaced by dried air. In case the wind speed is low, the air around the leaf may not move enough which would turn into a raise of the humidity and consequently a decrease of the transpiration.

2.4.5. Solar Irradiance

Solar irradiance is a measure of how much solar power, in the form of electromagnetic radiation, a specific land area receives (power per unit area on the earth's surface). Irradiance is not a constant value, it is changing throughout the year depending on the seasons. It also varies along the day depending on the position of the sun and the weather.

As shown in Figure 2.5, not all the solar radiation reaches the earth's surface. At an average distance of 150 million kilometres from the Sun, the outer atmosphere of Earth receives approximately 1367 W/m^2 of insolation (World Meteorological Organisation). As solar irradiance passes through the earth's atmosphere, some of it is absorbed and scattered by air molecules, water vapour and clouds. Some of the radiation is reflected straight back out into space (increasing when sky is full clouds) meanwhile the rest arrives on the Earth's surface. Once the radiation arrives at the surface, some of it is immediately reflected back into the sky. This amount depends on the nature of the actual surface – fresh snow can reflect up to 95 % while desert sands reflect 35 - 45 %, grasslands 15 - 25 % and dense forest vegetation 5 - 10 % [4].

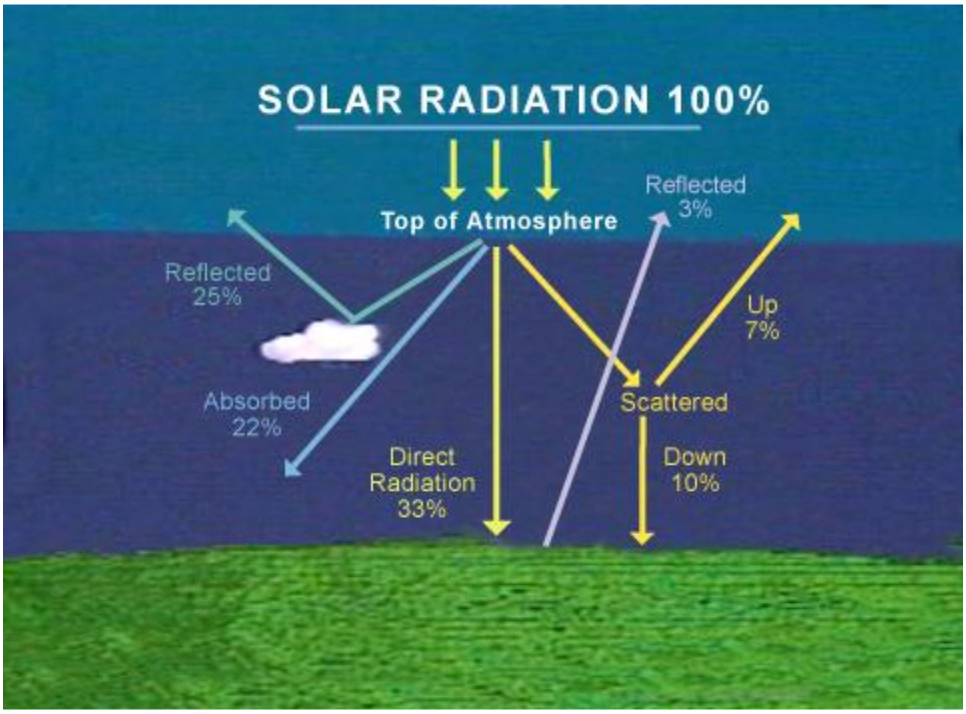


Figure 2.5: Solar radiation scheme
(Source: http://www.everredtronics.com/Solar.Download.html)

Rwanda is located in East Africa at approximately two degrees below the equator. It is characterised by Savannah climate and its geographical location and weather conditions provide enough solar irradiation intensity, approximately equal to 5 kWh/m^2_day with a peak of sun hours of also 5 hours per day.

2.5. Surface Data

2.5.1. Slope

Another important factor is the land's slope. Due to the crops chosen, banana, cassava and maize do not require large slopes for their growth and being flat lands more easily to plant, we decided to find a non-sloped crop land, or at least one with a small tilt.

As it can be seen in Figure 2.6 and focusing in the eastern part of Rwanda, there are several regions where the slope is appropriate to grow a crop. Most of the eastern province have good conditions in terms of slopes. Certainly, both the north and the southeast parts of have the best slope conditions.

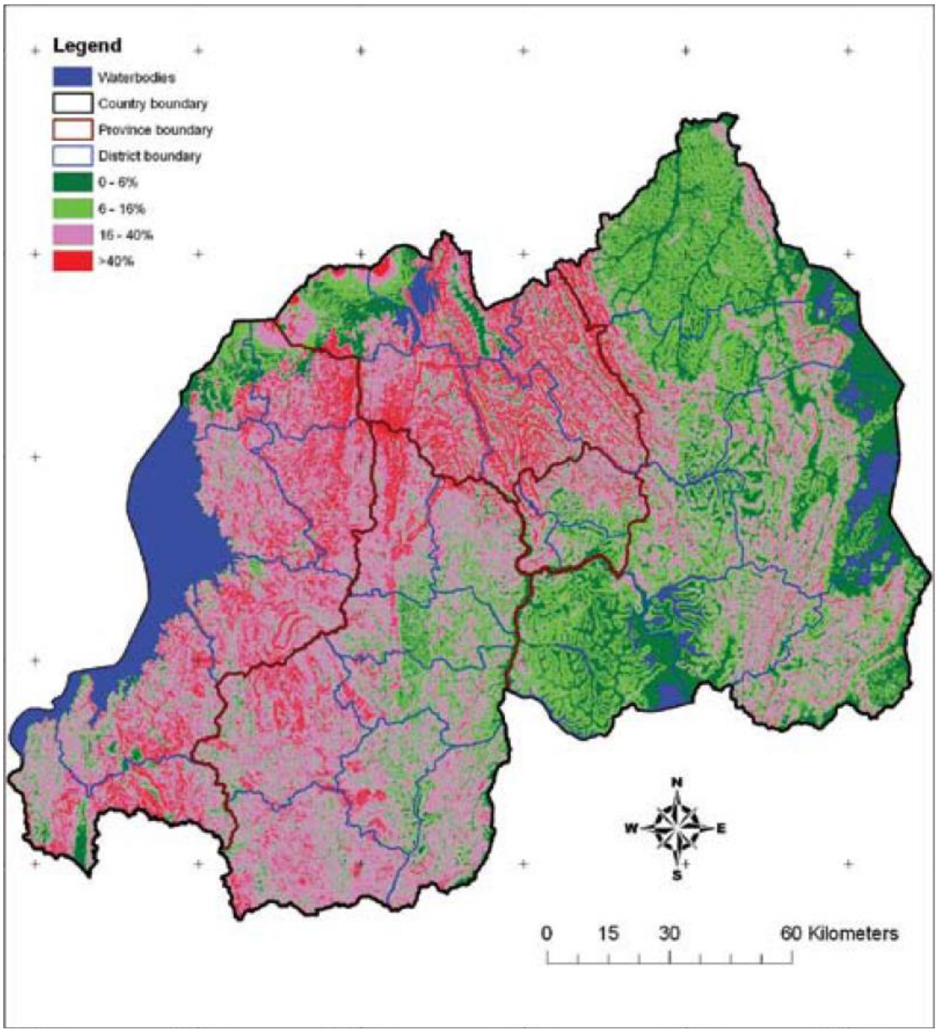


Figure 2.6: Rwanda slope percentage
(Source: The government of Rwanda, Ministry of Agriculture & Animal Resources. Rwanda Irrigation Master Plan.)

The design of photovoltaic systems require the collection of different types of data and a subsequent analyses in order to find the suitable area to maximize the PV yield. In this chapter it is explained how the data is analysed and how the studied area is chosen.

All data is obtained from reliable sources. Temperature and precipitation values are extracted from NASA website, solar irradiance values from Joint Research Centre (The European Commission's in-house science service) and evapotranspiration from CROPWAT 8.0 software, developed by FAO (Food and Agriculture Organization of the United Nations).

3.1. Introduction

In order to find the appropriate area within Rwanda for location of the proposed system, a first overview of the main parameters (temperature and precipitation) for each province has been developed to delimit the scope of the analysis. As explained in Theoretical Background, Rwanda is a country divided by five different regions: the Eastern Province, City of Kigali, Northern Province, Southern Province and Western Province (Figure 3.1).

Figure 3.1: Rwanda province map
(Source: http://www.theiguides.org/public-docs/guides/rwanda)

Once the scope have been delimited, a second analysis of different parameters throughout the chosen province has also been developed. As stated before, the parameters evaluated have been the temperature, the precipitation, the solar irradiance and the surface slope as well as the water resources.

The suitable target area must not only have a high annual average temperature but also a low annual average precipitation. In addition, it must receive a large amount of solar irradiance during the whole year and should be in a flat area or on gently slope simply to facilitate the task of planting and irrigating.

Even though Rwanda has many water resources, unfortunately they are not equally distributed. Rainfall is high in the western part of the country and low in the east. Therefore, farms in the eastern part are the most vulnerable. However, the eastern part has abundant rivers and lakes that could be used for irrigation purposes.

3.2. Main Area Selection

3.2.1. Province Selection

In order to find the most suitable province, a first overview of the annual average temperature and precipitation has been compiled. The following maps of temperature and rainfall (Figure 3.2) have been analysed and, as a result, the best region to place the system proposed is the eastern province.

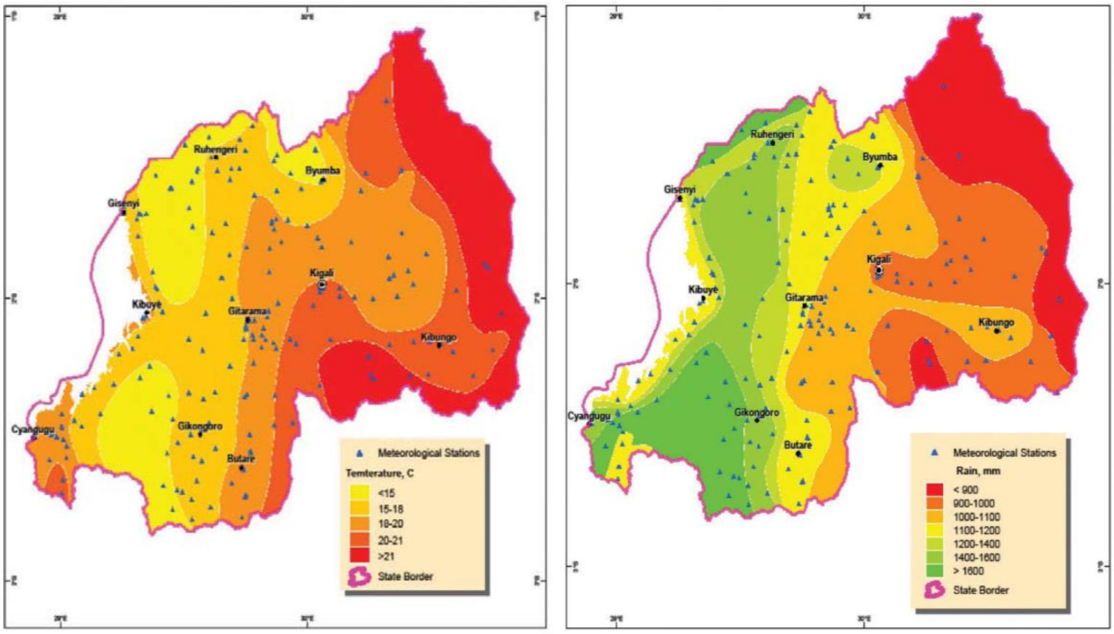


Figure 3.2: Annual average temperature and rainfall
(Source: The government of Rwanda, Ministry of Agriculture & Animal Resources. Rwanda Irrigation Master Plan.)

As it can be seen in Figure 3.2, the highest annual average temperature is focused in the eastern part of the country together with the lowest annual average precipitation. That is why all the subsequent analyses were focused within the eastern province.

3.2.2. District Selection

Once the eastern province is chosen, it is necessary to analyse the parameters of each district within this region. The eastern province is composed by seven districts: Bugesera, Gatsibo, Kayonza, Kirehe, Ngoma, Nyagatare and Rwamagana.

Within Rwanda there are only four weather stations distributed through the whole country. One station is located in Kigali, the capital of the country. There is one station in Butare and one more in Rubona-Colline, both cities in the southeast of Rwanda and the last one is located in Ruhengeri, a northeast city. As it is observed, there are no weather stations in the eastern part of the country and that is the reason why some data is the same between several districts.

In order to design both the PV and the water-pumping system with enough capacity to supply the largest water demand, it is necessary to take the lowest effective precipitation and the highest crop water need. Consequently, the highest evapotranspiration value.

Temperature

Focusing on the temperature, in Figure 3.3 it is observed a very similar trend for all the districts. However, it is also observed that both the highest maximum and minimum temperatures correspond to the district of Bugesera.

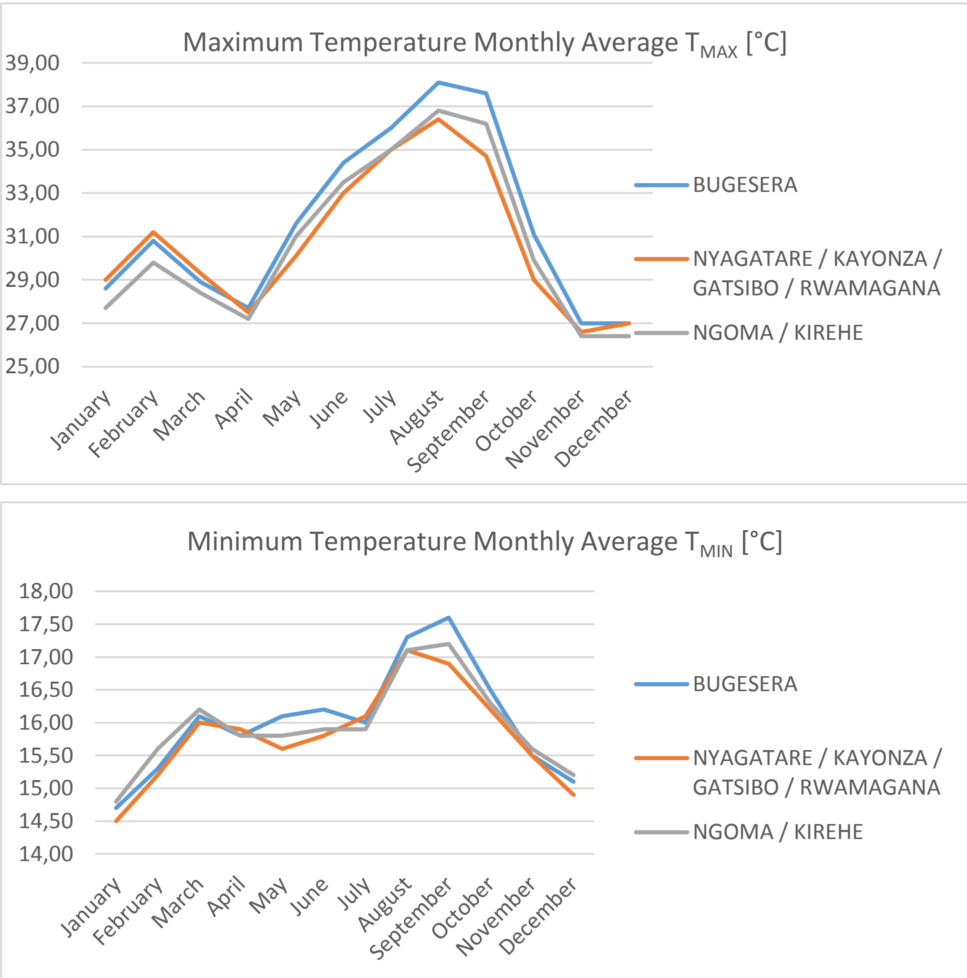


Figure 3.3: Maximum and minimum annual temperature trends per district

Effective precipitation

As stated in the section 2.3.3, the effective rainfall has been calculated by using two different methods. Table 3.1 shows the annual effective rainfall average values for each district.

Table 3.1: Annual effective rainfall values (using FAO/AGLW and Empirical formulas)

DISTRICT	Effective Precipitation using FAO/AGLW formula [mm/month]	Effective Precipitation using Empirical formula [mm/month]
BUGESERA	52,08	76,93
NYAGATARE KAYONZA GATSIBO RWAMAGANA	58,03	85,27
NGOMA KIREHE	60,01	86,91

As it is shown in Table 3.1, the lowest values appear when using FAO/AGLW formula. Therefore, in the subsequent analyses, FAO's formula is chosen due to it is more restrictive than the Empirical formula.

In addition, it is observed in Figure 3.4 that Bugesera district has the lowest effective precipitation from March until the end of the year as well as during the rainy season.

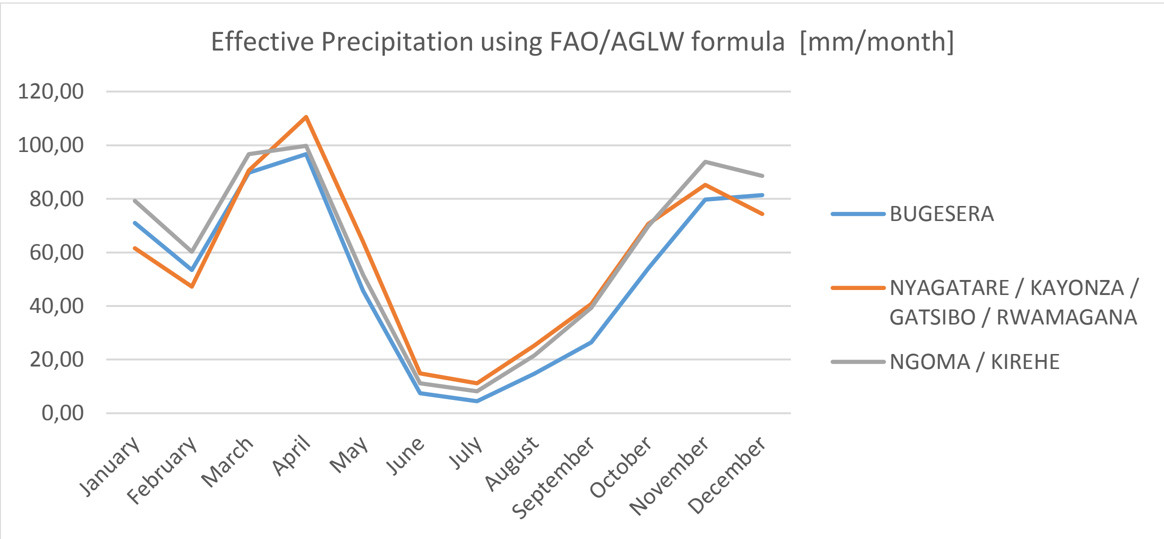


Figure 3.4: Annual effective precipitation trend per district

Evapotranspiration

As mentioned above, it is necessary to find the highest evapotranspiration value in order to design a system able to supply the highest water need. This ET_0 values are provided by CROPWAT 8.0 software and they are shown in Figure 3.5. As can be seen, the ET_0 of each district follows a similar trend as well as the temperature. Nevertheless, the ET_0 value for Bugesera is higher from April until the end of the year, coinciding with the rain season.

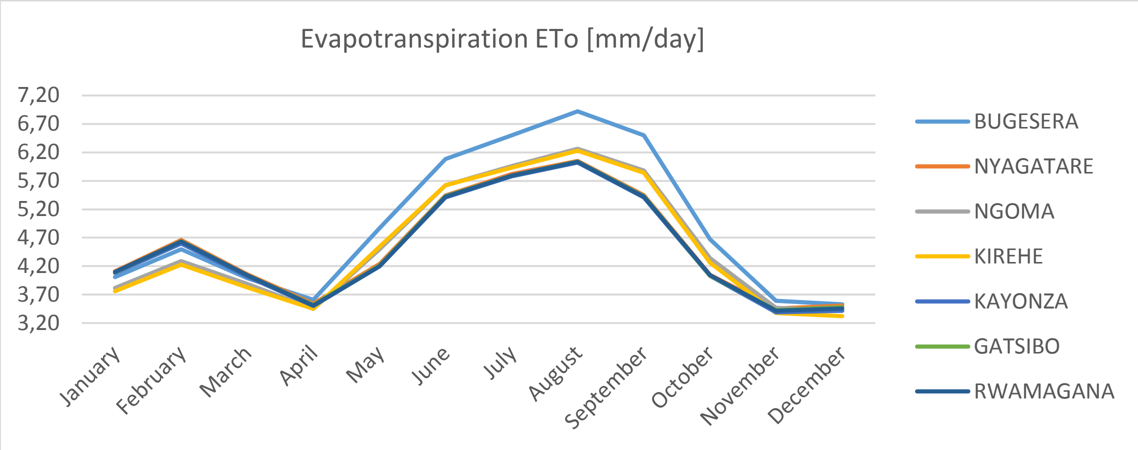


Figure 3.5: Annual evapotranspiration trend per district

Solar Irradiation

It is difficult to find out which district has the highest solar irradiation as seen in Figure 3.6 because, as expected, they also have a similar trend throughout the whole year. However, Bugesera has the highest annual average solar irradiation with 5,28 kWh/m^2_day, shown in Table 3.2.

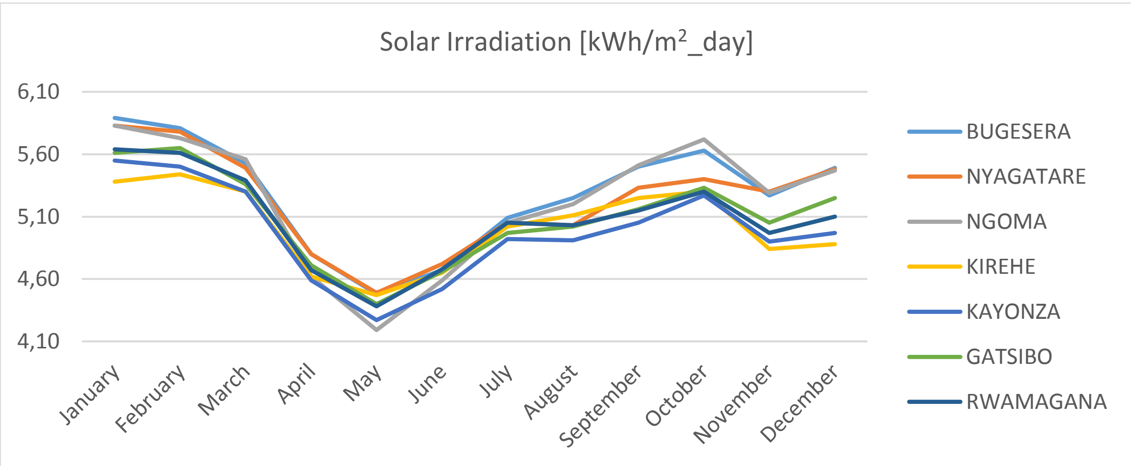


Figure 3.6: Annual solar irradiation trend per district

Table 3.2: Annual average solar irradiation per district

DISTRICT	Annual Average Solar Irradiation [kWh/m^2_day]
BUGESERA	5,28
NYAGATARE	5,23
NGOMA	5,23
KIREHE	5,02
KAYONZA	4,98
GATSIBO	5,10
RWAMAGANA	5,08

Table 3.2 above shows the annual average solar irradiation kWh/m^2_day per district. It is observed that irradiation is quite similar but Bugesera is slightly higher than the others.

Chart summary and other information

Table 3.3: Average of the analysed parameters per district

DISTRICT	Annual Irradiation [kWh/m^2_day]	Annual Effective Precipitation [mm/month]	Annual ET_0 [mm/day]	Annual T_{MIN} [°C]	Annual T_{MAX} [°C]
BUGESERA	5,28	52,08	4,90	16,02	31,57
NYAGATARE	5,23	58,03	4,53	15,81	30,73
NGOMA	5,23	60,01	4,58	15,95	30,69
KIREHE	5,02	60,01	4,53	15,95	30,69
KAYONZA	4,98	58,03	4,49	15,81	30,73
GATSIBO	5,10	58,03	4,51	15,81	30,73
RWAMAGANA	5,08	58,03	4,51	15,81	30,73

Once all the parameters have been discussed and analysed, it is observed (Table 3.3) that all districts have similar values. However, Bugesera is the one that stands out above the others due to its low effective precipitation as well as its high minimum and maximum temperatures. In addition, its annual average evapotranspiration is also the highest.

Poverty is also taken into account for deciding the district. The region of Bugesera, which has experienced long periods of droughts and low levels of rainfall, is one of the poorest regions in Rwanda with a percentage of food insecure household between 36 and 40 (Figure 3.7).

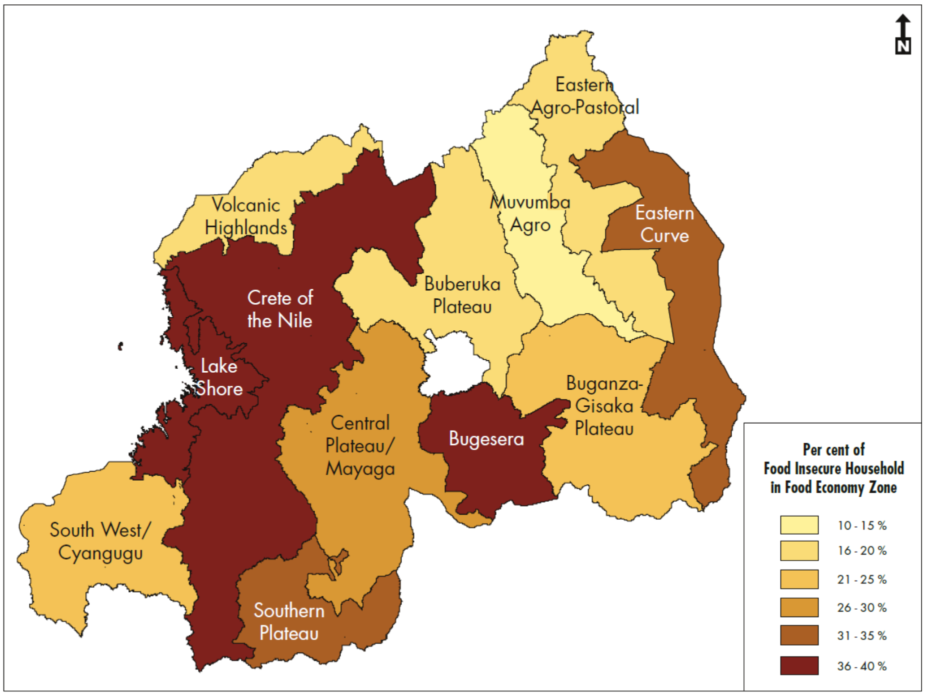


Figure 3.7: Percentage of food insecure household in food economy zone
(Source: Economic Development and Poverty Reduction Strategy, 2008-2012. The Republic of Rwanda.)

Bugesera is also one of the poorest districts in the Eastern Province in Rwanda as shown in table 3.4.

Table 3.4: Percentage of poverty in Eastern province
(Source: Economic Development and Poverty Reduction Strategy, 2008-2012. The Republic of Rwanda.)

District	Extreme poverty [%]	Poverty (excluding extreme) [%]	Total poverty [%]
Bugesera	28,3	20,1	48,4
Kirehe	25,6	22,3	47,9
Ngoma	22,3	25,3	47,6
Gatsibo	18,8	24,3	43,1
Kayonza	19,2	23,4	42,6
Nyagatare	19,1	18,7	37,8
Rwamagana	12,4	18	30,4
Rwanda's mean	**24,1**	**20,8**	**44,9**

In summary, the district that meets the requirements is Bugesera. Not only has the target weather and climate conditions but also a high level of poverty.

3.2.3. Area Selection

Bugesera is a dry and arid district located about one hour south of Kigali and, as it was mentioned before, nowadays its inhabitants live in extreme poverty due to the droughts and the unfavourable crop weather conditions.

However, Bugesera has several water resources spread all over the district in form of lakes, rivers, dams and marshlands. Even though a lot of them are protected areas, there are still enough water sources left. Indeed, riverine potential irrigation areas are located along Akanyaru and Nyabarongo rivers whilst lakes PIAs depend on Gashanga, Kidogo, Rumira, Mirayi, Kirimbi and Gaharwa lakes, located in the eastern part of the district and named from north to south, respectively (Figure 3.8). As shown in the figure below, there are many suitable areas where the system can be placed and all of them are very close to water sources [5].

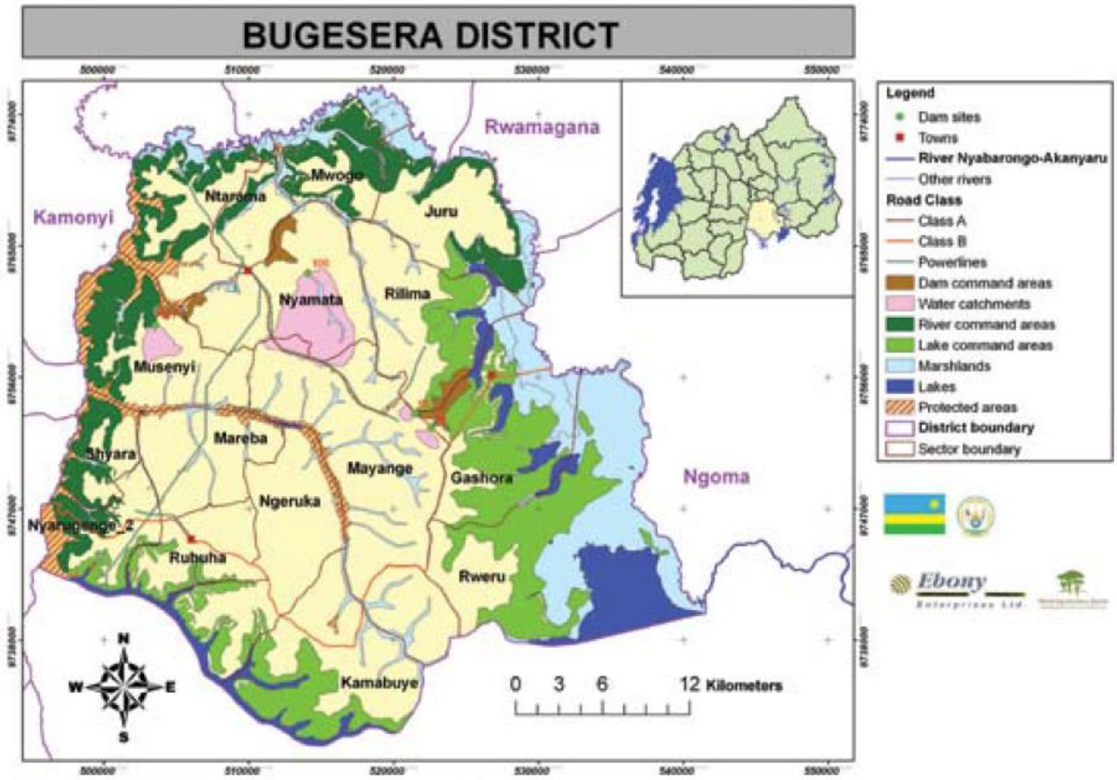


Figure 3.8: Bugesera district (rivers, lakes, marshlands and protected areas)
(Source: The government of Rwanda, Ministry of Agriculture & Animal Resources. Rwanda Irrigation Master Plan.)

Bearing in mind that this project is based on banana, cassava and maize crops and focusing on Figures 3.9, 3.10 and 3.11, which show the potential suitability of the dominant land units for the cultivation of banana, cassava and maize in Rwanda, it is found that the most appropriate zone to place the system is between the two first lakes. These are Gashanga and Kidogo.

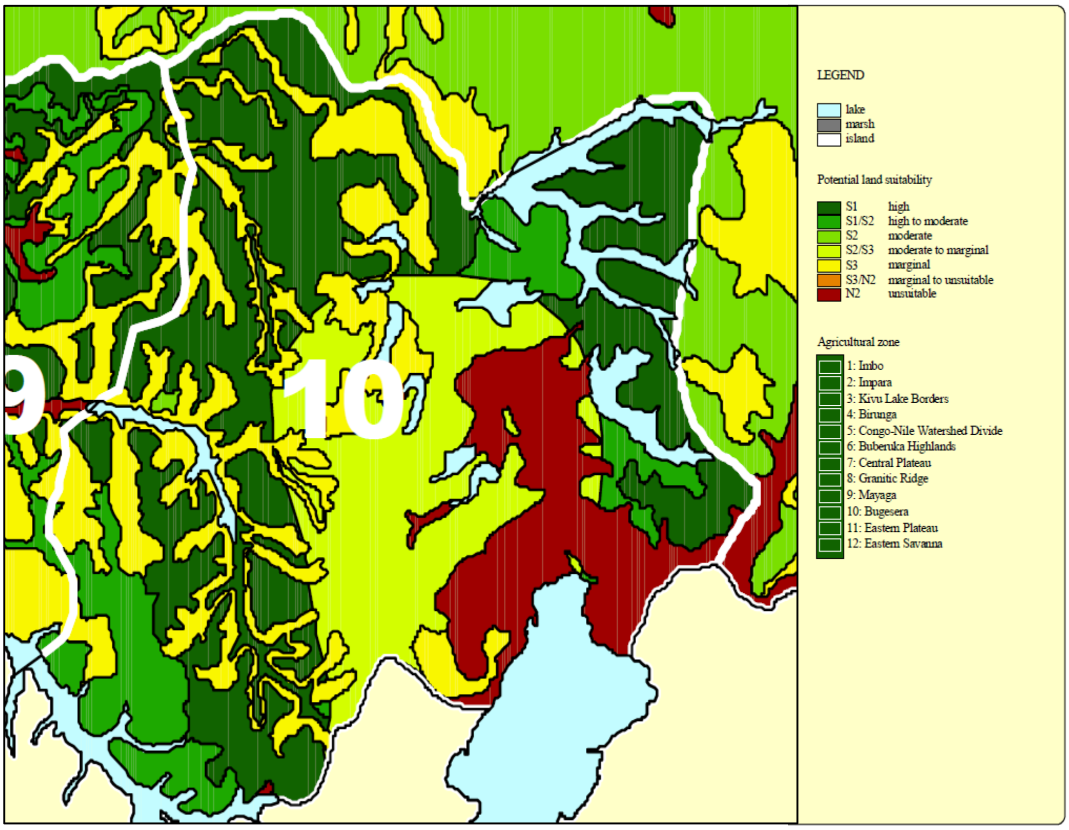


Figure 3.9: Potential suitability of the dominant lands units for the cultivation of banana in Rwanda
(Source: A Large-Scale Land Suitability Classification for Rwanda. A. Verdoodt & E. Van Ranst. Ghent University.)

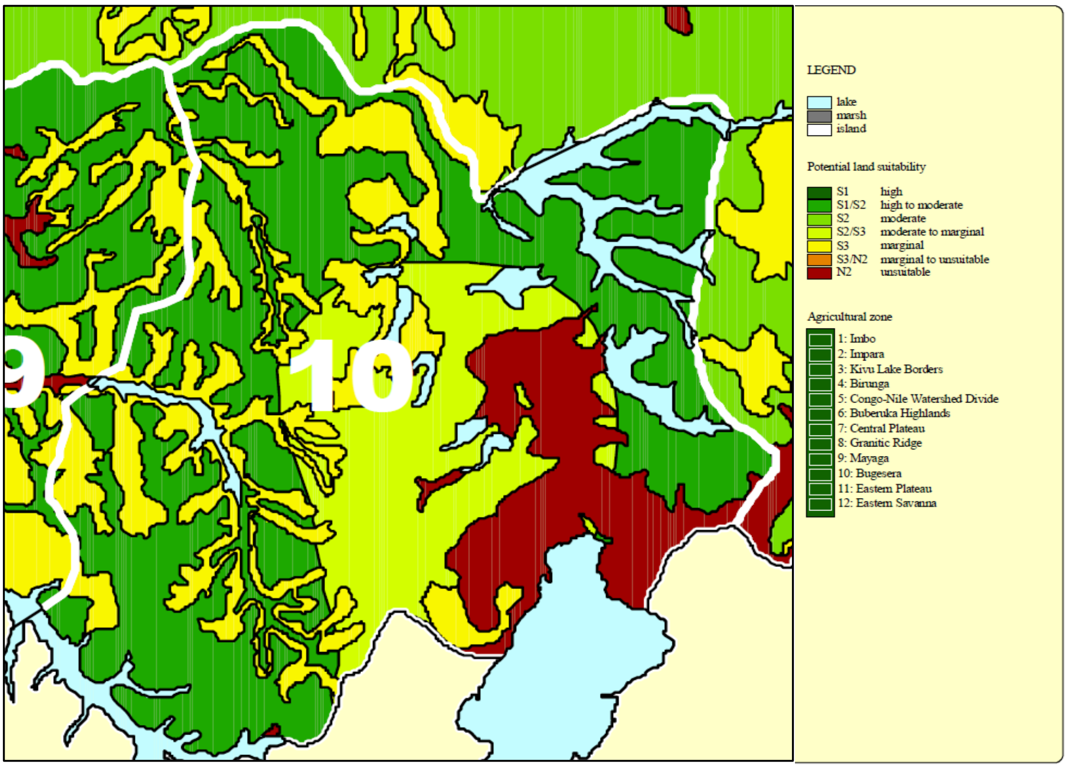


Figure 3.10: Potential suitability of the dominant lands units for the cultivation of maize in Rwanda
(Source: A Large-Scale Land Suitability Classification for Rwanda. A. Verdoodt & E. Van Ranst. Ghent University.)

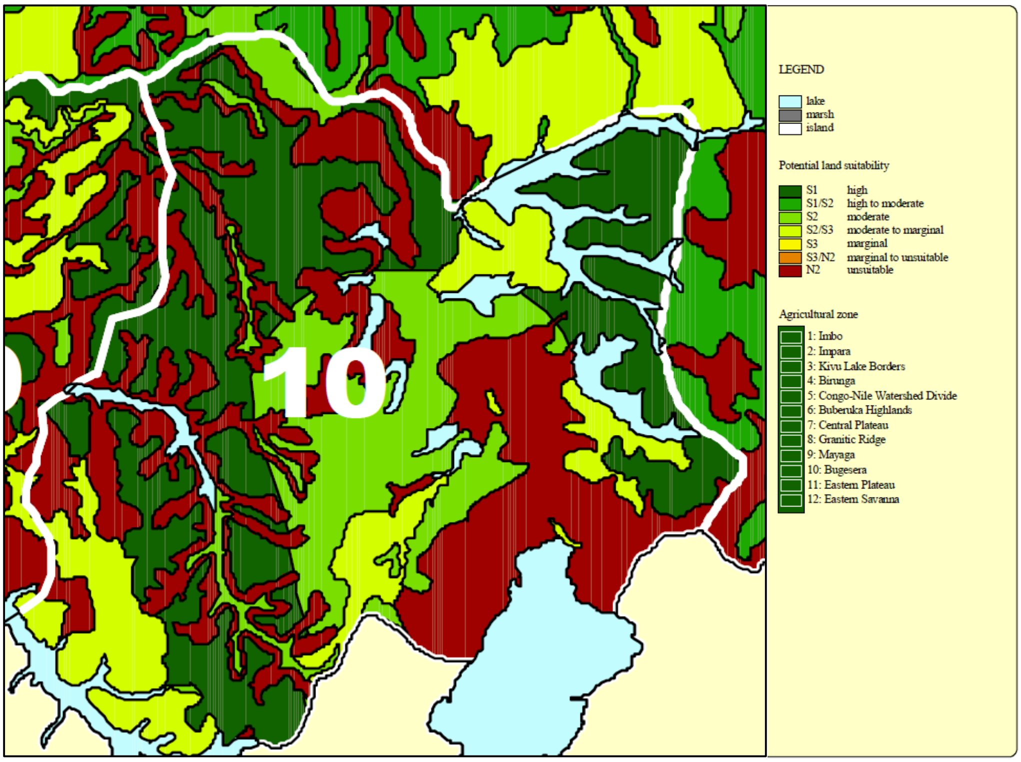


Figure 3.11: Potential suitability of the dominant lands units for the cultivation of cassava in Rwanda
(Source: A Large-Scale Land Suitability Classification for Rwanda. A. Verdoodt & E. Van Ranst. Ghent University.)

Figure 3.12: Suitable crop land
(Source: Google Maps)

Analysing figures 3.9, 3.10 and 3.11 above, it is observed that the north side of Kidogo Lake has a high potential land suitability to crop either banana, cassava or maize. Therefore, this rural area was chosen as a target (Figure 3.12).

Chapter 4. Crops and Water Needs

Agriculture in Rwanda contributes to 35 % of its GDP and employs the 80 % of the labour force. Indeed, most people in Rwanda earn their living, directly or indirectly, from agriculture. Bananas, cassava, beans, maize and sweet potato, among others, are the staple food grown for local consumption.

In this chapter we discuss and justify which are the chosen crops and the methodology used to calculate their water requirements.

4.1. Overview

Increasing Rwanda's agricultural production for a growing population was not an easy process. Since 1994, just after the civil war and the horrible genocide, almost 4 million inhabitants were living in extremely poverty and competing for scarce land resources. Fortunately, 17 years later, agricultural production was doubled, improving food security and decreasing poverty rate from 57 to nearly 40 percent.

This increase can be awarded to the expansion of several crops (especially maize crop) as well as the exportation of some final products. On the one hand, Rwanda's main high-quality crops are coffee and tea and both together make nearly four-fifths of the agricultural exports. On the other hand and focusing on local consumption, the most popular crops are bananas, cassava, maize, potatoes and beans, among others.

For local consumption, crop fields are generally small (half a hectare on average, approximately) due to each little farmer has its own plot of land. However, farmers are being encouraged by the government to grow specific crops in groups in order to improve logistics. In return, these groups receive help with improved seeds and new fertilisers. Therefore, harvests of maize, wheat, cassava and beans have increased significantly. Nevertheless, bananas also weighs heavily in local consumption and are of great importance to Rwandans as they are grown on over a third of the country's cultivated land.

4.2. Chosen Crops

Although most of the benefits are provided by tea and coffee due to their exportation, this project is focused on the local consumption in order to try to improve the lifestyle of small farmers and this is one of the reasons why banana, cassava and maize were the chosen crops.

Firstly, the main crop in Rwanda is basically banana, due to its high yield through all the year and its high production rate. Hence, as long as there are good weather conditions, bananas are the best to guarantee food security and to fight famine if other crops fail. Moreover, bananas are used in every form imaginable such as raw, fried and baked and even a type of beer is made from fermented banana pulp.

Secondly, cassava is the most important tropical root crop because its roots are a potential source of energy for a large amount of inhabitants. Cassava is known to be the highest producer of carbohydrates among staple crops and its leaves, that can be consumed, are rich in protein. Moreover, cassava can be stored under the ground for several seasons and be used as a reserve food together with bananas. According to the United Nations Food and Agriculture Organization (FAO), cassava ranks fourth as a food crop in developing countries such as Rwanda.

Last but not least, maize crop has become important in terms of production due to it ranks first among grain crop production in Rwanda. Since 2005, maize cropping production has experienced an impressive positive growth with more than 400 % of increase in 2011 (percentage value relative to 2005 production), much more than any other crop. In June 2008, maize was catalogued as a priority crop by the government of Rwanda as it played an important role in food security by reducing poverty rate.

4.3. Crop Water Needs

Once the crops were chosen and to realize a proper design of both systems, it was necessary to find the irrigation water need for each selected crop. In this stage of the project, parameters such as effective precipitation (P_{EFF}) and evapotranspiration (ET) were involved and, as stated in chapter 3, both of them were calculated by software CROPWAT 8.0.

4.3.1. Irrigation Water Need (IN)

The irrigation water need of a crop is the difference between the crop water need and that part of the rain that can be used by the crop, called effective rainfall or effective precipitation (P_{EFF}). For each of the chosen crops, the crop water need has been determined on a monthly basis, in this case millimetres per month.

For all crops and for each month of the growing season, the irrigation water need is calculated by subtracting the effective rainfall from the crop water need.

$$CROP\ WATER\ NEED - EFFECTIVE\ RAINFALL = IRRIGATION\ WATER\ NEED \tag{4.1}$$

(Source: FAO)

The values of the effective rainfall for Bugesera district are shown in Table 4.1.

Table 4.1: Monthly Effective Precipitation in Bugesera district

Month	J	F	M	A	M	J	J	A	S	O	N	D
P_{EFF} [mm/month]	71,0	53,5	89,8	96,7	45,7	7,5	4,5	14,7	26,4	54,1	79,7	81,4

4.3.2. Crop Water Need

The crop water need (ET_{CROP}) is defined as the amount of water needed to satisfy the water loss because of evapotranspiration and it always refers to crop grown under optimal conditions, i.e. a uniform crop, actively growing, free of diseases, etc. In other words, it is the depth of water needed by crops to grow optimally.

This depth of water can be provided by precipitation, by irrigation or by a combination of both if the first one is not enough. Indeed, the irrigation water supplements to the rainfall and only in desert or arid areas all water needed is supplied by irrigation.

The crop water need mainly depends on:

- The climate: As it is obvious, with hot and sunny weather, crops need more water per day.
- The crop type: By nature, some crops need more water need than other ones. For instance, crops like rice or sugarcane need more water than bean crop.
- The growth stage of the crop: Fully grown crops need more water than crop that have just been planted.

To represent the effects of both crop transpiration and soil evaporation, there exists another parameter named coefficient crop (k_C). This parameter integrates crop characteristics and averaged effects of evaporation from the soil.

To represent the effects of the weather conditions, there exist another parameter named ET_0.

Using both the ET_0 and the coefficient crop, it was possible to find, also in millimetres per month, the monthly crop water need by using the following equation.

$$ET_0 * CROP\ COEFFICIENT\ (k_C) = CROP\ WATER\ NEED \tag{4.2}$$

(Source: FAO)

4.3.2.1. Crop Coefficient (k_C)

In order to find the monthly crop coefficient it is necessary to know the crop planting date and both the days and the k_C of each crop growth stages. The agricultural year in Rwanda has three season:

- Agricultural Season A: Starts in September of one calendar year and ends in February of the following calendar year.
- Agricultural Season B: Starts in March and ends in July of the same calendar year.
- Agricultural Season C: Starts in August and ends in September of the same calendar year.

Focusing on banana crop, it is only necessary to know which its planting date is. The establishment of a new banana plantation takes approximately 6 months from planting to full ground cover. One year after planting, the first harvest takes place and the shoots that have produced are removed. Meanwhile, young shoots have fully developed and take over the production [6].

Starting in season A, the k_C values for the first 6 months after planting are indicated in Table 4.2. After 6 months, the k_C value remains constant.

Table 4.2: Banana coefficient crop values
(Source: FAO)

Months after planting	1	2	3	4	5	6	7 onward
Crop coefficient k_C	0,7	0,75	0,8	0,75	0,9	1,0	1,1

The following steps will explain how to calculate the monthly coefficient crops for cassava and maize as well as the irrigation water need for the three chosen crops. Using this method, it has to be supposed that all months have exactly 30 days.

The values of monthly standard evapotranspiration (ET_0) in Bugesera provided by CROPWAT 8.0 software are shown in Table 4.3.

Table 4.3: Monthly evapotranspiration values in Bugesera

Month	J	F	M	A	M	J	J	A	S	O	N	D
ET_0 [mm/day]	4,01	4,50	3,99	3,61	4,87	6,08	6,50	6,92	6,50	4,67	3,59	3,53

Cassava

In case of cassava, its plantation date starts on season B and lasts almost two years. Its days and k_C values per growth stages are described in Table 4.4 and are divided in two phases:

Table 4.4: Days and crop coefficient value per growth stage for cassava

	GROWTH STAGES	Days	k_C per growth stage
FIRST PHASE	Initial stage	20	0,30
	Crop development stage	40	0,80
	Middle season stage	90	0,80
	Late season stage	60	0,30
TOTAL DAYS		210	
SECOND PHASE	Initial stage	150	0,30
	Crop development stage	40	1,10
	Middle season stage	110	1,10
	Late season stage	60	0,50
TOTAL DAYS		360	

By using the k_C per growth stage, the days of each growth stage and the ET_0, it has been possible to calculate the k_C per month (Table 4.5 and 4.6) and, afterwards, the monthly irrigation water need.

Table 4.5: Coefficient crop value per month for cassava (phase one)

FIRST PHASE							
SEASON	B					C	A
Month	Mar	Apr	May	Jun	Jul	Aug	Sept
ET_0 [mm/day]	3,99	3,61	4,87	6,08	6,50	6,92	6,50
Growth Stages	Initial stage	Dev. stage	Mid. season stage			Late season	
k_C per gr. st.	0,30	0,80	0,80			0,30	
k_C per month	0,47	0,80	0,80	0,80	0,80	0,30	0,30

Table 4.6: Coefficient crop value per month for cassava (phase two)

SECOND PHASE												
SEASON	A					B					C	
Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
ET_0 [mm/day]	4,67	3,59	3,53	4,01	4,50	3,99	3,61	4,87	6,08	6,50	6,92	6,50
Growth Stages	Initial stage					Dev. stage	Mid. season stage				Late season	
k_C per gr. st.	0,30					1,10	1,10				0,50	
k_C per month	0,30	0,30	0,30	0,30	0,30	1,10	1,10	1,10	1,10	1,10	0,50	0,50

As shown in equation (4.3) and in case that during one month two different coefficients appear, the crop coefficient per growth stage is spread proportionally through the whole month.

$$k_C = \sum_{i=1}^{n} k_{C_i} * \frac{N}{30} \tag{4.3}$$

Where,

k_C: Crop coefficient of the chosen month.

k_{Ci}: Crop coefficient per growth stage *"i"*.

N: Number of days of the stage *"i"* within the month.

For instance, the k_C of March of the first phase has 20 days with a k_C of 0,30 and 10 days with a k_C of 0,8.

$$k_C\ March\ (first\ phase) = 0{,}3 * \frac{20}{30} + 0{,}8 * \frac{10}{30} = 0{,}47$$

$$k_C\ April\ (second\ phase) = 1{,}10 * \frac{10}{30} + 1{,}10 * \frac{20}{30} = 1{,}10$$

<u>Maize</u>

In case of maize, its plantation date starts on season A and lasts half a year. Its days and k_C values per growth stages are represented in Table 4.7.

Table 4.7: Days and crop coefficient value per growth stage for maize

	GROWTH STAGES	Days	k_C per growth stage
FIRST PHASE	Initial stage	30	0,40
	Crop development stage	50	0,80
	Middle season stage	60	1,15
	Late season stage	40	0,70
TOTAL DAYS		180	

By using the k_C per growth stage, the days of each growth stage and the ET_0, it has been possible to calculate the k_C per month (Table 4.8) and, afterwards, the monthly irrigation water need.

Table 4.8: Coefficient crop value per month for maize

FIRST PHASE												
SEASON	A						B					C
Month	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
ET_0 [mm/day]	6,50	4,67	3,59	3,53	4,01	4,50	3,99	3,61	4,87	6,08	6,50	6,92
Growth Stages	Initial stage	Dev. stage		Middle season		Last season	Initial stage	Dev. stage		Middle season		Last season
k_C per gr. st.	0,40	0,80		1,15		0,70	0,40	0,80		1,15		0,70
k_C per month	0,40	0,80	0,92	1,15	1,00	0,70	0,40	0,80	0,92	1,15	1,00	0,70

Calculation of the k_C:

$$k_C\ November = 0,8 * \frac{20}{30} + 1,15 * \frac{10}{30} = 0,92$$

$$k_C\ January = 1,15 * \frac{20}{30} + 0,7 * \frac{10}{30} = 1,00$$

$$k_C\ May = 0,8 * \frac{20}{30} + 1,15 * \frac{10}{30} = 0,92$$

$$k_C\ July = 1,15 * \frac{20}{30} + 0,7 * \frac{10}{30} = 1,00$$

Once each month has its coefficient crop, it is possible to calculate the crop water need in millimetres per month. The methodology is the same for each crop and month.

$$\text{CROP WATER NEED} = ET_0 * monthly\ k_C \qquad (4.4)$$

(Source: FAO)

As stated in chapter 4, the irrigation water need comes from the following formula:

$$IRRIGATION\ WATER\ NEED = CROP\ WATER\ NEED - P_{EFF} \qquad (4.5)$$

(Source: FAO)

Once the monthly irrigation values for each crop has been found, in order to calculate the water flow needed (in m^3/ha_day) from the tank to the crop, the following conversion has been applied:

$$mm = \frac{10m^3}{ha} \qquad ; \qquad month = 30\ days$$

Different parameters' values for every crop per each month are shown from Table 4.9 to Table 4.15, highlighting the values of the flow of water.

Banana

Table 4.9: Monthly irrigation water needs for banana (September – February)

Month	Sept	Oct	Nov	Dec	Jan	Feb
ET_0 [mm/day]	6,50	4,67	3,59	3,53	4,01	4,50
k_C per month	0,70	0,75	0,80	0,75	0,90	1,00
CWN [mm/day]	4,55	3,50	2,87	2,65	3,61	4,50
CWN [mm/month]	136,50	105,08	86,16	79,43	108,27	135,00
P_{EFF} [mm/month]	26,40	54,10	79,70	81,40	71,00	53,50
IN [mm/month]	110,10	50,98	6,46	0,00	37,27	81,50
Q [m^3/ha_day]	36,70	16,99	2,15	0,00	12,42	27,17

Table 4.10: Monthly irrigation water needs for banana (March - August):

Month	Mar	Apr	May	Jun	Jul	Aug
ET_0 [mm/day]	3,99	3,61	4,87	6,08	6,50	6,92
k_C per month	1,10	1,10	1,10	1,10	1,10	1,10
CWN [mm/day]	4,39	3,97	5,36	6,69	7,15	7,61
CWN [mm/month]	131,67	119,13	160,71	200,64	214,50	228,36
P_{EFF} [mm/month]	89,80	96,70	45,70	7,50	4,50	14,70
IN [mm/month]	41,87	22,43	115,01	193,14	210,00	213,66
Q [m^3/ha_day]	13,96	7,48	38,34	64,38	70,00	71,22

Cassava

Table 4.11: Monthly irrigation water needs for cassava (phase one)

FIRST PHASE							
Month	Mar	Apr	May	Jun	Jul	Aug	Sept
ET_0 [mm/day]	3,99	3,61	4,87	6,08	6,50	6,92	6,50
k_C per month	0,47	0,80	0,80	0,80	0,80	0,30	0,30
CWN [mm/day]	1,88	2,89	3,90	4,86	5,20	2,08	1,95
CWN [mm/month]	56,26	86,64	116,88	145,92	156,00	62,28	58,50
P_{EFF} [mm/month]	89,80	96,70	45,70	7,50	4,50	14,70	26,40
IN [mm/month]	0,00	0,00	71,18	138,42	151,50	47,58	32,10
Q [m^3/ha_day]	0,00	0,00	23,73	46,14	50,50	15,86	10,70

Table 4.12: Monthly irrigation water needs for cassava (phase two. October - March)

SECOND PHASE						
Month	Oct	Nov	Dec	Jan	Feb	Mar
ET_0 [mm/day]	4,67	3,59	3,53	4,01	4,50	3,99
k_C per month	0,30	0,30	0,30	0,30	0,30	1,10
CWN [mm/day]	1,40	1,08	1,06	1,20	1,35	4,39
CWN [mm/month]	42,03	32,31	31,77	36,09	40,50	131,67
P_{EFF} [mm/month]	54,10	79,70	81,40	71,00	53,50	89,80
IN [mm/month]	0,00	0,00	0,00	0,00	0,00	41,87
Q [m^3/ha_day]	0,00	0,00	0,00	0,00	0,00	13,96

Table 4.13: Monthly irrigation water needs for cassava (phase two. April - September)

SECOND PHASE						
Month	Apr	May	Jun	Jul	Aug	Sept
ET_0 [mm/day]	3,61	4,87	6,08	6,50	6,92	6,50
k_C per month	1,10	1,10	1,10	1,10	0,50	0,50
CWN [mm/day]	3,97	5,36	6,69	7,15	3,46	3,25
CWN [mm/month]	119,13	160,71	200,64	214,50	103,80	97,50
P_{EFF} [mm/month]	96,70	45,70	7,50	4,50	14,70	26,40
IN [mm/month]	22,43	115,01	193,14	210,00	89,10	71,10
Q [m^3/ha_day]	7,48	38,34	64,38	70,00	29,70	23,70

Maize

Table 4.14: Monthly irrigation water needs for maize (September – February)

Month	Sept	Oct	Nov	Dec	Jan	Feb
ET_0 [mm/day]	6,50	4,67	3,59	3,53	4,01	4,50
k_C per month	0,40	0,80	0,92	1,15	1,00	0,70
CWN [mm/day]	2,60	3,74	3,30	4,06	4,01	3,15
CWN [mm/month]	78,00	112,08	99,08	121,79	120,30	94,50
P_{EFF} [mm/month]	26,40	54,00	79,70	81,40	71,00	53,50
IN [mm/month]	51,60	57,98	19,38	40,39	49,30	41,00
Q [m^3/ha_day]	17,20	19,33	6,46	13,46	16,43	13,67

Table 4.15: Monthly irrigation water needs for maize (March - August)

Month	Mar	Apr	May	Jun	Jul	Aug
ET_0 [mm/day]	3,99	3,61	4,87	6,08	6,50	6,92
k_C per month	0,40	0,80	0,92	1,15	1,00	0,70
CWN [mm/day]	1,60	2,89	4,48	6,99	6,50	4,84
CWN [mm/month]	47,88	86,64	134,41	209,76	195,00	145,32
P_{EFF} [mm/month]	89,80	96,70	45,70	7,50	4,50	14,70
IN [mm/month]	0,00	0,00	88,71	202,26	190,50	130,62
Q [m^3/ha_day]	0,00	0,00	29,57	67,42	63,50	43,54

As it can be seen in the tables above, the maximum value of water flow Q is 71,22 m^3/ha_day in August, corresponding to banana crop (Table 4.9). However, this value has been increased by 4 % in order to guarantee the water supply. Therefore, the water-pumping system has been dimensioned with a water need of 74 m^3/ha_day.

Chapter 5. Irrigation

In the previous chapters, the most interesting crops were chosen and the water need for each of them calculated. Afterwards, and in order to dimension the photovoltaic and pumping system, it is crucial to know the pressure of water inside the pipe for irrigating the field. Pressure is the key parameter for defining the PVP, therefore the need to know the loss of it along the pipe is important. As a consequence, a standard irrigation system is proposed.

5.1. Types of Irrigation

There are different types of irrigation techniques that vary in terms of how the water is distributed on the field. What all these techniques share is the aim to supply water uniformly so that each plant has the right amount of water. The most appropriate one usually depends on the climate but above all it depends on the crop.

As seen in the previous chapter, the crops that are best suited in the studied area are banana, cassava and maize. After determining the water need for each of them, the results indicate the banana as the one with greater requirements. Hence, the irrigation system should be dimensioned according to that amount of water so that it would also work for the rest of the crops once it is designed.

The two main irrigation methods for banana are the overhead system and the drip system. In overhead irrigation or sprinkler, water is distributed through a system of pipes to one or more central locations along the field and then sprayed into the air by overhead high-pressure sprinklers or guns. This method is similar to natural rainfall as water comes out the sprinkler and breaks up into small drops which fall to the ground. This system must be always designed considering the high evaporative losses, which may exceed the 40 % of the total on hot windy days.

Drip or trickle irrigation consists of delivering small amounts of water into the soil (2-20 litres/hour) over relatively long periods from a system of small diameter plastic pipes fitted with outlets called emitters or drippers. Water is applied close to plants so that only part of the soil in which the roots grow is wetted. Unlike sprinkler irrigation, which wets the whole soil, dripping water is applied more uniformly and less water loss occurs due to evaporation or wind. Despite being the most effective system in terms of reducing water loss and improving crop yields (Figure 5.1), the cost of the system is higher than a typical sprinkler method.

Considering both systems, the drip alternative fits better for the case study in Bugesera as the climate is harsh, with low rainfall and high evapotranspiration. Therefore, it is not admissible to use sprinklers so that much water would be wasted on evaporative losses and the amount of water to be pumped would increase. In terms of costs, the higher investment in the drip system is worth it as the alternative to pump more water (sprinkle system) would signify in a larger PVP system that could supply more power and in the end that would undoubtedly be more expensive.

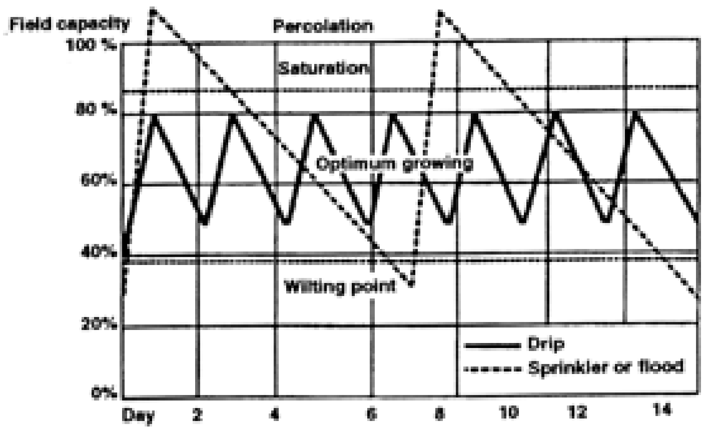


Figure 5.1: Growth of crops depending on the irrigation method
(Source: http://aggie-horticulture.tamu.edu/earthkind/drought/efficient-use-of-water-in-the-garden-and-landscape)

As can be seen in Figure 5.1, drip irrigation is more efficient in terms of the amount of water used versus the optimal growth of the crop.

5.2. Sample Layout

In order to design the irrigation system, first it is mandatory to determine the number of plants it supplies. According to FAO, the distance between each banana plant should be 2 meters. Therefore, a squared field of one hectare (both 100 meters long and width) comprises a total of 2000 plants. Moreover, the field is considered to be totally flat, with no differences of height in any part of it.

The present work has not the aim to find the most optimized layout in which losses in the pipe are minimum while the number and length of them are the adequate to diminish the price. The range of it neither contains few but important components needed in the installation such as emitters, filters (sand, gravel), valves, etc.

The decided layout has a main pipe which conveys water to 40 rows or laterals of a 100 meters with 2,5 meters separation between them (Figure 5.2). Every lateral has an emitter or dripper for each plant.

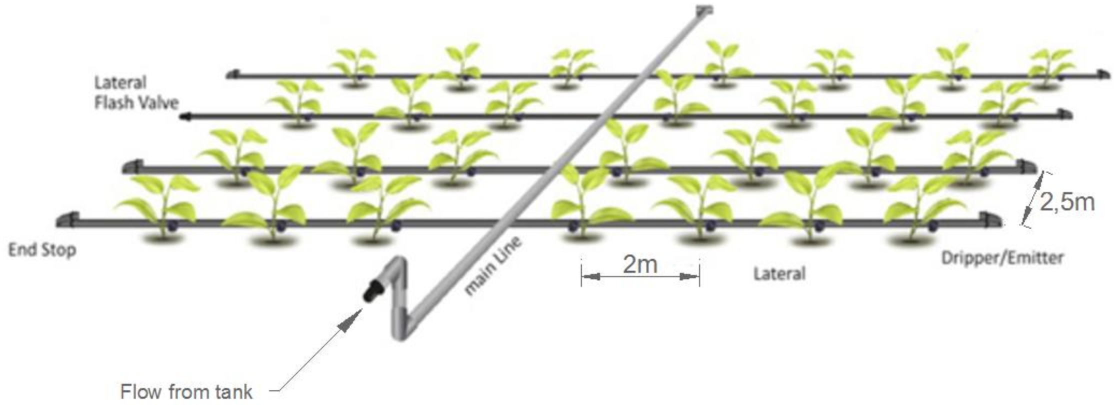


Figure 5.2: Simplified Irrigation Layout
(Source: http://www.kotharipipes.co.in/frm_DripIrrigationSystem_EmittingPipes.php)

We decided that the material of the main pipe should be Polyvinyl chloride (PVC) and laterals made of Polyethylene (PE), with a nominal diameter of 40 mm and 13,6 mm respectively. Compared to metals, not only have inner smooth surface that ensures lower friction losses but also they are easier to install and very flexible that permits to adjust the drippers to each plant.

Last but not least, the system requires a tank to storage water. The tank should be placed in an elevation point close to the field as it would minimize the energy requirement and also to get a uniform level of water in the drip irrigation. The capacity of the tank needs to meet the water requirements of the crop, about 75 m^3. Therefore, we decided that the diameter of the base is 5 m, while it is 4 meters height.

$$V_{TANK} = Area * Height = \frac{\pi Ø^2}{4} * H = 78{,}5\ m^3$$

This dimensions ensure the volume of water need, and give more stability by having a larger base to avoid overturns. In addition, it is important to provide a filter against particles due to having the tank in open air. Adding a filter that helps blocking sand, gravel and other impurities contributes to a higher reliability of the system, avoiding clogging in the emitters, pipes, etc.

The reason why a tank is fundamental is because the PVP solely works during the sun hours so the supply is not constant over time. The lack of it could produce shortages whereas if it is provided, the supply is guaranteed. Moreover, it gives the user the possibility to manage how much and when to irrigate.

Once the distribution of the pipes is clear and the main elements defined (Figure 5.3), the focus turns to the pressure needed in the system so the losses due to water flow do not affect the supply. The use of a pumping system to give pressure to the water flow from the tank is not an option as it would require electricity and increase the cost of the installation.

Hence, the only factor that can give the desired pressure is the difference of height between the tank and the ground.

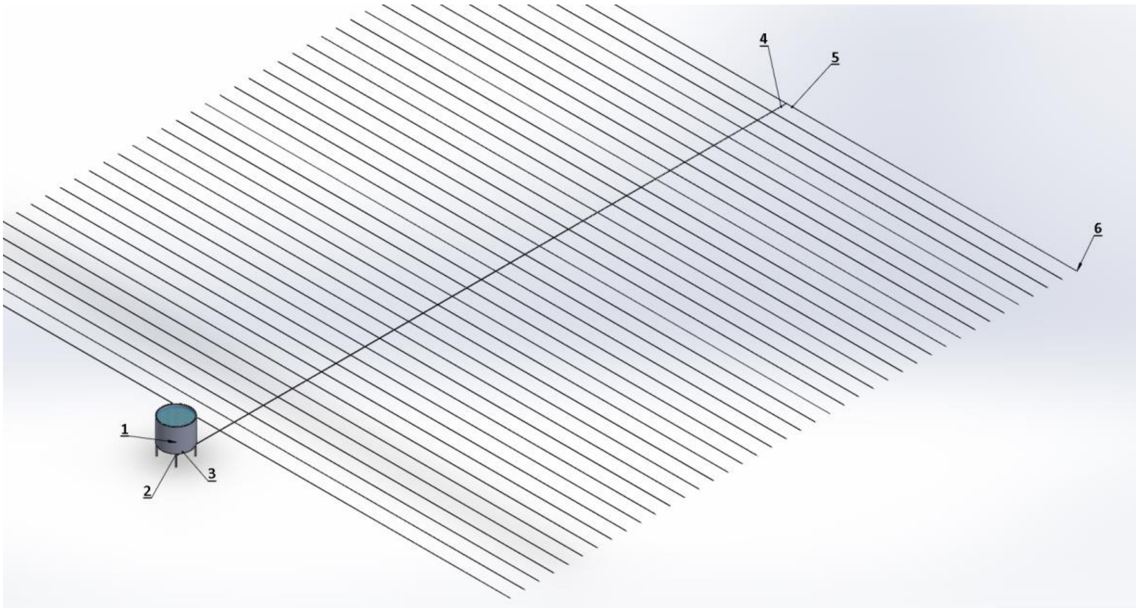


Figure 5.3: Principal parts of the irrigation scheme

To ensure that water flow is conveyed to every lateral, a study of water dynamics is required to determine the minimum working pressure of the irrigation scheme.

5.3. Fluid Characteristics

Fluid dynamics is the study of how fluids behave when they are in motion. For solving any flow problem it is required to know the physical properties of the fluid being handled and the way it flows.

Viscosity (μ): viscosity expresses the readiness with which a fluid flows when it is acted upon by an external force. The coefficient of absolute viscosity of a fluid is a measure of its resistance to internal deformation or shear. As an example, honey is a highly viscous fluid whereas water is much less viscous [7]. Also, it is important to note that a rise in temperature produces a decrease in viscosity. The viscosity of water at a temperature of 20 ºC is 1 mPascal second.

Density (ρ): the density of a substance is its mass per unit volume. The value of water density is 1000 kg/m^3. As other fluid properties, it depends on the temperature. Thus, an increase of temperature produces a decrease in density.

Fluids can be compressible or incompressible. This is the big difference between liquids and gases, because liquids are generally incompressible, meaning that they don't change volume much in response to a pressure change; gases are compressible, and will change volume in response to a change in pressure.

Regarding the flow in pipes, there are two main different types. Laminar flow is characterized by the gliding of concentric cylindrical layers past one another in orderly fashion. Velocity of the fluid is maximum at the pipe axis and decreases sharply to zero at the wall. This is valid until a certain velocity, in which the straight lines of the laminar flow break into diffused patterns. This is the critical velocity, which delimitates the laminar flow and the turbulent. Thus, at greater velocities than critical, the flow is turbulent. In this, there is an irregular random motion of fluid particles in directions transverse to the direction of the main flow. The velocity distribution is more uniform across the pipe diameter than in laminar.

Reynolds number (Re): the nature flow in pipe not only depends on the velocity but also on the pipe diameter, the density and the viscosity. The numerical value of a dimensionless combination of these four variables, the Reynolds number, may be considered to be the ratio of the dynamic forces of mass flow to the shear stress due to viscosity. Reynolds number is given by:

$$Re = \frac{\text{Ø} v \rho}{\mu} \quad (5.1)$$

Where,

ρ is the density (kg/m^3).

Ø is the inside diameter of the pipe (m).

v is the velocity of the fluid in the pipe (m/s).

μ is the viscosity (Pa*s).

Laminar flow is considered to be when Reynolds is less than 2000 and turbulent when greater than 4000. Numbers in between define a flow in a critical zone, where the flow may be either laminar or turbulent depending on several factors and meaning it is unpredictable.

Roughness (ε): the internal roughness of a pipe is also an important factor to consider when analysing the friction losses, basically in turbulent flow. Its value or range depends on the material used. For PVC it is only 0,0015 m whereas in concrete pipes the value can reach 3 m. The relative roughness (ε/d) is the ratio between roughness and diameter of a pipe, non-dimensional.

5.4. Fluid Dynamics

The laws that govern the flow of fluids, which have been also used in the thesis, are presented below.

- The equation of continuity:

The equation of continuity states that for an incompressible fluid flowing in a pipe of varying cross-section, the mass flow rate is the same everywhere in the tube. The mass flow rate is simply the rate at which mass flows past a given point, so it is the total mass flowing past divided by the time interval [8]. Therefore, the equation of continuity is expressed as:

$$\rho A_1 v_1 = \rho A_2 v_2 \quad (5.2)$$

$$Q_1 = Q_2 \quad (5.3)$$

Where,

ρ is the density, generally constant included in this study (kg/m^3).

A is the cross – sectional area (m^2).

v is the velocity of the fluid in the pipe (m/s).

- Bernoulli's Theorem:

The general energy equation in mechanic of fluids is the Bernoulli's theorem. It is the application of the law of conservation of energy to the flow of fluids in a conduit. The total energy at any point is equal to the sum of the elevation head, the pressure head and the velocity head (Figure 5.4). In addition, real systems have loses or energy variations to be taken into account. Thus, the fully developed equation is:

$$Z_1 + \frac{P_1}{\gamma} + \frac{v_1^2}{2g} = Z_2 + \frac{P_2}{\gamma} + \frac{v_2^2}{2g} + h_L \tag{5.4}$$

Where,

Z is the elevation head (m).

γ or ρg is the specific weight (N/m^3)

h_L is the head loss from point 1 to point 2 (m).

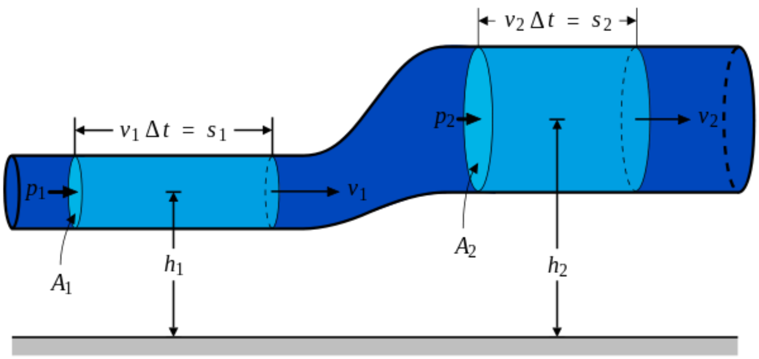


Figure 5.4: Bernoulli's theorem applied in pipe
(Source: http://en.wikipedia.org/wiki/Bernoulli%27s_principle)

- Darcy's equation

Obviously, there are losses inside the pipe due to friction of fluid particles against each other and against the pipe. This pressure drop in the direction of the flow is given by Darcy's formula which is expressed in meters of fluid:

$$h_L = f\frac{Lv^2}{2\emptyset g} \tag{5.5}$$

Where,

f is the Friction factor, non-dimensional

The equation, aimed to find linear loss in a pipe, is very important in case of great distances, when the values of Darcy's cannot be disregarded.

In addition, the head losses in valves and fittings are also taken into account in Bernoulli's Theorem. It is expressed with a slight modification of Darcy's equation. The pressure drop across any device is shown as a decrease of the term of velocity head, using a dimensionless coefficient K in the equation.

$$h_S = K\frac{v^2}{2g} \tag{5.6}$$

Where,

K is the resistance coefficient, non-dimensional

Equation 5.6 is valid both for laminar and turbulent flow and any liquid in a pipe. In case of laminar (Re<2000), the friction factor is function of Reynolds number only:

$$f = \frac{64}{Re} \tag{5.7}$$

Whereas in turbulent flow (Re>4000) it also depends on the relative roughness of the pipe (ε/d). To obtain the friction factor, the use of Moody's diagram is of great value (Figure 5.5). The friction factor value is determined by horizontal projection from the intersection of the ε/D curve and the calculated Reynolds number, giving the Darcy friction factor at the left scale of the chart.

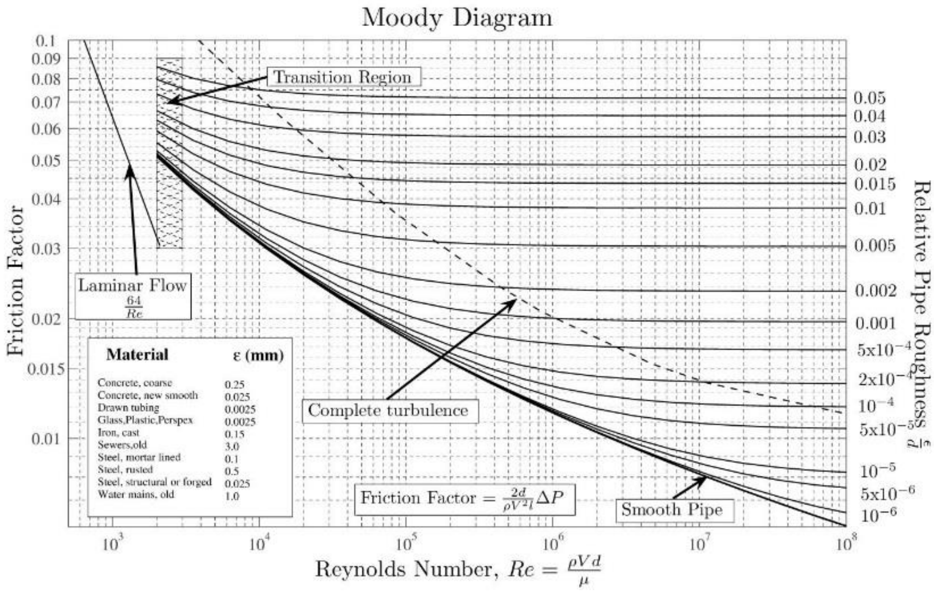


Figure 5.5: Moody's diagram
(Source: http://commons.wikimedia.org/wiki/File:Moody_diagram.jpg)

- Colebrook-White equation

For a more precise result, there is the Colebrook-White equation, which gives the most accurate possible solution by iterating:

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{\varepsilon}{3{,}7d} + \frac{2{,}51}{Re\sqrt{f}}\right] \tag{5.8}$$

Where,

ε is the absolute roughness (mm).

d is the diameter of the pipe (mm).

To find the solution of this iterative equation, a macro in Excel VBA has been implemented. This macro is explained in the appendix.

- Rose equation

The head loss in a filter can be solved with this equation. Yet, many of the parameters refer to the size of particles, being an information that is often difficult to determine.

$$h_S = \frac{1{,}067 C_D}{\varphi g} \, D \, \frac{v_a^2}{\varepsilon^4} \frac{1}{d} \quad (5.9)$$

Where,

φ is the shape factor (m).

C_D is the drag force coefficient, depends on Reynolds number

d is the diameter of sand grains (m)

ε is the porosity

v_a is the approach velocity (m/s)

D is the depth of the filter (m)

Generally, the range of values of the head loss of a cleaned filter are between 0,15 to 0,5 meters. However, it can reach values from 1,8 meters and up to 2,4 meters in case the filter is not clean.

5.5. Pressure Required

To ensure the water flow gets to every plant in the field, it is very important to calculate the losses in the pipes and consequently, find the minimum pressure required to convey all water through the system.

Calculations are based on the furthest dripping point in the irrigation system, which is the one where water crosses the longest distance and accumulates greater losses. Hence, if water supply is guaranteed in that critical point, it will be guaranteed for the rest of them. The process is explained below.

Next step to find the minimum pressure is by doing an energy balance or Bernoulli between the last emitter in the furthest lateral and the tank. However, the mathematical complexity of it cannot be underestimated so the problem has been split in 6 points (5 stretches). The points are numbered in Figure 5.3.

The first stretch between the entrance in the lateral (5) and the last plant in the lateral (6) is the following:

The water flow per lateral is:

$$\frac{74\,\frac{m^3}{day}}{80\;laterals} = 0{,}925\;\frac{m^3}{lateral\_day} = 1{,}07x10^{-5}\;\frac{m^3}{s}$$

Having a total of 25 plants per lateral, each one receives:

$$\frac{0{,}925\;\frac{m^3}{lateral\_day}}{25} = 0{,}037\,\frac{m^3}{day} = 4{,}28x10^{-7}\;\frac{m^3}{s}$$

Therefore, Bernoulli's theorem applied to 5-6 is:

$$\frac{P_5}{\gamma} + \frac{{v_5}^2}{2g} = \frac{{v_6}^2}{2g} + h_L$$

The elevation head is not considered as both points are at the same height. Also, the relative pressure at the exit of the emitter is zero because is out the pipe, so only applies the atmospheric pressure. Taking the lateral diameter of 13,6 mm, the velocities are:

$$v_6 = \frac{Q}{A} = \frac{4{,}28x10^{-7}}{\frac{\pi Ø^2}{4}} = 2{,}95x10^{-3}\;\frac{m}{s}$$

$$v_5 = \frac{Q}{A} = \frac{1{,}07E(-5)}{\frac{\pi Ø^2}{4}} = 7{,}37x10^{-2}\;\frac{m}{s}$$

To calculate the linear loss through the pipe, it is needed the flow. As the lateral flow decreases along the pipe due to diverging flows to plants (Figure 5.6), the remaining flow velocity lowers as well. Therefore Reynolds number, function of the flow velocity, is also affected so the loss in each section varies.

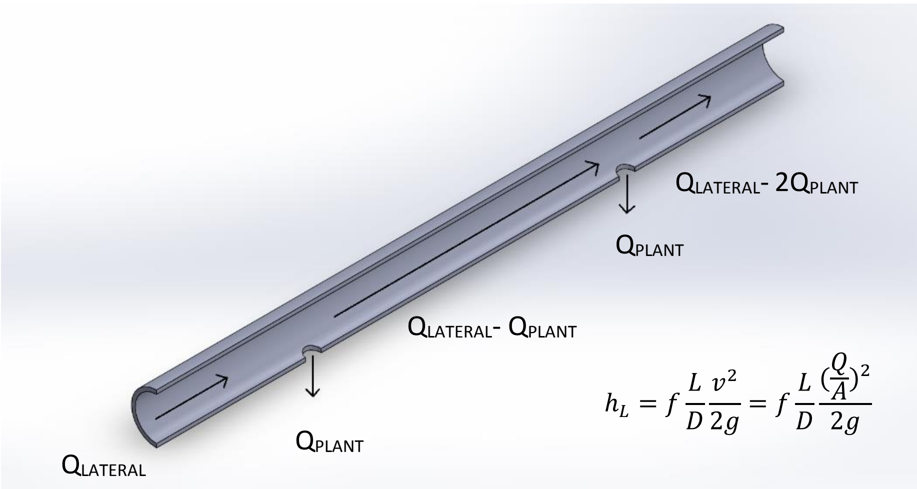


Figure 5.6: Water flow along the secondary pipe

The total amount of loss is the sum of each interval. It is presented in a spreadsheet (Table 5.1) to make the calculation easier:

Table 5.1: Linear Loss for each interval in the lateral pipe

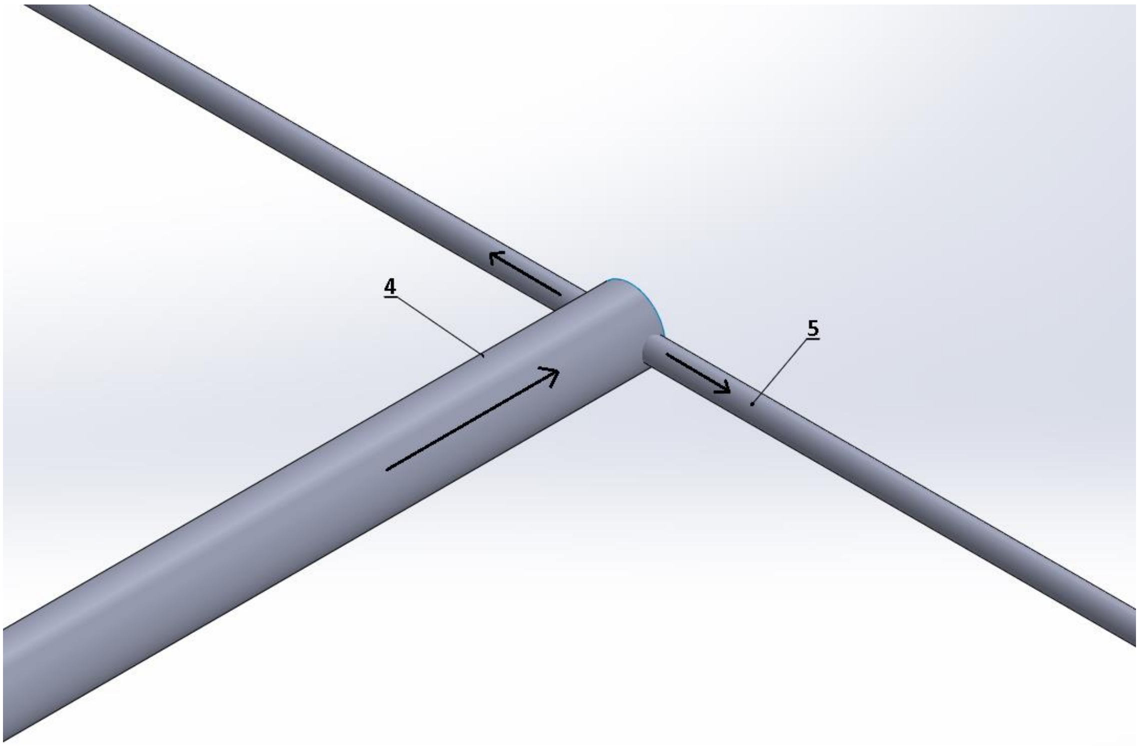
Nº Interval [2m/each]	Q Lateral [m³/s]	V Lateral [m/s]	Reynolds Re	Friction Factor f	Linear Loss H [m]
1	1,07E-05	7,37E-02	1000,3	0,064	0,0026
2	1,03E-05	7,08E-02	960,3	0,067	0,0025
3	9,85E-06	6,78E-02	920,3	0,070	0,0024
4	9,42E-06	6,49E-02	880,3	0,073	0,0023
5	8,99E-06	6,19E-02	840,3	0,076	0,0022
6	8,56E-06	5,90E-02	800,2	0,080	0,0021
7	8,14E-06	5,60E-02	760,2	0,084	0,0020
8	7,71E-06	5,31E-02	720,2	0,089	0,0019
9	7,28E-06	5,01E-02	680,2	0,094	0,0018
10	6,85E-06	4,72E-02	640,2	0,100	0,0017
11	6,42E-06	4,42E-02	600,2	0,107	0,0016
12	6,00E-06	4,13E-02	560,2	0,114	0,0015
13	5,57E-06	3,83E-02	520,2	0,123	0,0014
14	5,14E-06	3,54E-02	480,1	0,133	0,0013
15	4,71E-06	3,24E-02	440,1	0,145	0,0011
16	4,28E-06	2,95E-02	400,1	0,160	0,0010
17	3,85E-06	2,65E-02	360,1	0,178	0,0009
18	3,43E-06	2,36E-02	320,1	0,200	0,0008
19	3,00E-06	2,06E-02	280,1	0,229	0,0007
20	2,57E-06	1,77E-02	240,1	0,267	0,0006
21	2,14E-06	1,47E-02	200,1	0,320	0,0005
22	1,71E-06	1,18E-02	160,0	0,400	0,0004
23	1,28E-06	8,84E-03	120,0	0,533	0,0003
24	8,56E-07	5,90E-03	80,0	0,800	0,0002
25	4,28E-07	2,95E-03	40,0	1,600	0,0001
				TOTAL LOSS	**0,0339**

Due to the Reynolds is under 2000, the flow inside every interval is laminar. Finally, solving Bernoulli's equation:

$$P_5 = 329{,}81\ Pa$$

The second stretch is between the main pipe before diverging to the last lateral (4) and the lateral entry (5), shown below in Figure 5.7

Figure 5.7: From the secondary to the main pipe



The energy balance between these two points is:

$$\frac{P_4}{\gamma} + \frac{{v_4}^2}{2g} = \frac{P_5}{\gamma} + \frac{{v_5}^2}{2g} + h_S$$

With:

$$v_4 = \frac{Q_{MAIN\ PIPE}}{A_{MAIN\ PIPE}} = \frac{2{,}14x10^{-5}}{\frac{\pi \cdot 0{,}04^2}{4}} = 0{,}017\ \frac{m}{s}$$

$$h_S = K\frac{{v_4}^2}{2g} = 2{,}96x10^{-5}\ m$$

Being K = 2 the resistance coefficient that corresponds to the Tee, fitting that diverges the flow. Finally, the obtained pressure is:

$$P_4 = 332{,}67\ Pa$$

The next Bernoulli starts under the tank (3), at the ground level, finishing in last part of the main pipe (4).

$$\frac{P_3}{\gamma} + \frac{{v_3}^2}{2g} = \frac{P_4}{\gamma} + \frac{{v_4}^2}{2g} + h_L + 2h_s$$

In this stretch, the linear losses become more important as the fluid flows through a larger distance. Also, the singular losses in every divergence are taken into account, not having a great impact on the result though.

To obtain the singular loss, it is necessary to calculate the coefficient of resistance, K, of Tees along the pipe. Using the following experimental equations [7]:

$$As \quad \frac{A_{LATERAL}}{A_{MAIN}} = 0{,}11 \leq 0{,}4 \quad then\ K = 0{,}4\left(\frac{Q_{LATERAL}}{Q_{MAIN}}\right)^2 \tag{5.10}$$

Where,

A_i is the area of the pipe *"I"* (m^2).

Q_i is the water flow of the pipe *"I"* (m^3/s)

Therefore, singular loss for one divergence is expressed as:

$$h_{S_i} = 0{,}4\left(\frac{Q_{LATERAL}}{Q_{MAIN_i}}\right)^2 \frac{v_i^2}{2g} = 1{,}48x10^{-6}\ m$$

The total loss in singular divergences is:

$$\sum_{1}^{39} h_{S_i} = 5{,}77x10^{-5}\ m$$

The linear loss through the main pipe varies due to diverging flows. Therefore, calculations are presented by intervals, where every loss differs from the others, and the sum of them gives the result (Table 5.2). In case of turbulent flow, the friction factor has been calculated by using the Colebrook equation.

Table 5.2: Linear Loss Values for every interval in main pipe

Nº interval	Q [m³/day]	Q [m³/s]	V [m/s]	Re	Flow type	Friction factor f	Linear loss H [m]
0	74	8,56E-04	6,82E-01	27208	Turbulent	0,024	0,1071
1	72,15	8,35E-04	6,65E-01	26528	Turbulent	0,024	0,0341
2	70,3	8,14E-04	6,47E-01	25848	Turbulent	0,024	0,0326
3	68,45	7,92E-04	6,30E-01	25168	Turbulent	0,025	0,0311
4	66,6	7,71E-04	6,13E-01	24487	Turbulent	0,025	0,0296
5	64,75	7,49E-04	5,96E-01	23807	Turbulent	0,025	0,0282
6	62,9	7,28E-04	5,79E-01	23127	Turbulent	0,025	0,0268
7	61,05	7,07E-04	5,62E-01	22447	Turbulent	0,025	0,0254
8	59,2	6,85E-04	5,45E-01	21767	Turbulent	0,025	0,0241
9	57,35	6,64E-04	5,28E-01	21086	Turbulent	0,026	0,0228
10	55,5	6,42E-04	5,11E-01	20406	Turbulent	0,026	0,0215
11	53,65	6,21E-04	4,94E-01	19726	Turbulent	0,026	0,0203
12	51,8	6,00E-04	4,77E-01	19046	Turbulent	0,026	0,0191
13	49,95	5,78E-04	4,60E-01	18366	Turbulent	0,027	0,0179
14	48,1	5,57E-04	4,43E-01	17685	Turbulent	0,027	0,0167
15	46,25	5,35E-04	4,26E-01	17005	Turbulent	0,027	0,0156
16	44,4	5,14E-04	4,09E-01	16325	Turbulent	0,027	0,0145
17	42,55	4,92E-04	3,92E-01	15645	Turbulent	0,028	0,0135
18	40,7	4,71E-04	3,75E-01	14965	Turbulent	0,028	0,0125
19	38,85	4,50E-04	3,58E-01	14284	Turbulent	0,028	0,0115
20	37	4,28E-04	3,41E-01	13604	Turbulent	0,029	0,0106
21	35,15	4,07E-04	3,24E-01	12924	Turbulent	0,029	0,0097
22	33,3	3,85E-04	3,07E-01	12244	Turbulent	0,029	0,0088
23	31,45	3,64E-04	2,90E-01	11564	Turbulent	0,030	0,0080
24	29,6	3,43E-04	2,73E-01	10883	Turbulent	0,030	0,0072
25	27,75	3,21E-04	2,56E-01	10203	Turbulent	0,031	0,0064
26	25,9	3,00E-04	2,39E-01	9523	Turbulent	0,031	0,0057
27	24,05	2,78E-04	2,22E-01	8843	Turbulent	0,032	0,0050
28	22,2	2,57E-04	2,04E-01	8162	Turbulent	0,033	0,0043
29	20,35	2,36E-04	1,87E-01	7482	Turbulent	0,033	0,0037
30	18,5	2,14E-04	1,70E-01	6802	Turbulent	0,034	0,0032
31	16,65	1,93E-04	1,53E-01	6122	Turbulent	0,035	0,0026
32	14,8	1,71E-04	1,36E-01	5442	Turbulent	0,037	0,0022
33	12,95	1,50E-04	1,19E-01	4761	Turbulent	0,038	0,0017
34	11,1	1,28E-04	1,02E-01	4081	Turbulent	0,040	0,0013
35	9,25	1,07E-04	8,52E-02	3401	Turbulent	0,042	0,0010
36	7,4	8,56E-05	6,82E-02	2721	Turbulent	0,045	0,0007
37	5,55	6,42E-05	5,11E-02	2041	Laminar	0,031	0,0003
38	3,7	4,28E-05	3,41E-02	1360	Laminar	0,047	0,0002
39	1,85	2,14E-05	1,70E-02	680	Laminar	0,094	0,0001
						TOTAL LOSS	**0,6076**

Finally, solving Bernoulli's equation:

$$P_3 = 6061{,}78\ Pa$$

The next stretch is just above the elbow fitting at 90º (2) to (3). Essentially, the Bernoulli is the same on each side, noting the loss due to the change of direction. The resistance coefficient of the elbow, K, is 1 so the expression is:

$$h_S = K\frac{{v_2}^2}{2g} = 0{,}035\ m$$

$$\frac{P_2}{\gamma} = \frac{P_3}{\gamma} + h_S$$

$$P_2 = 6402{,}60\ Pa$$

Finally, the last stretch goes from the base of the tank (1) till the change of direction of the elbow (2). A representative sample is shown in Figure 5.8.

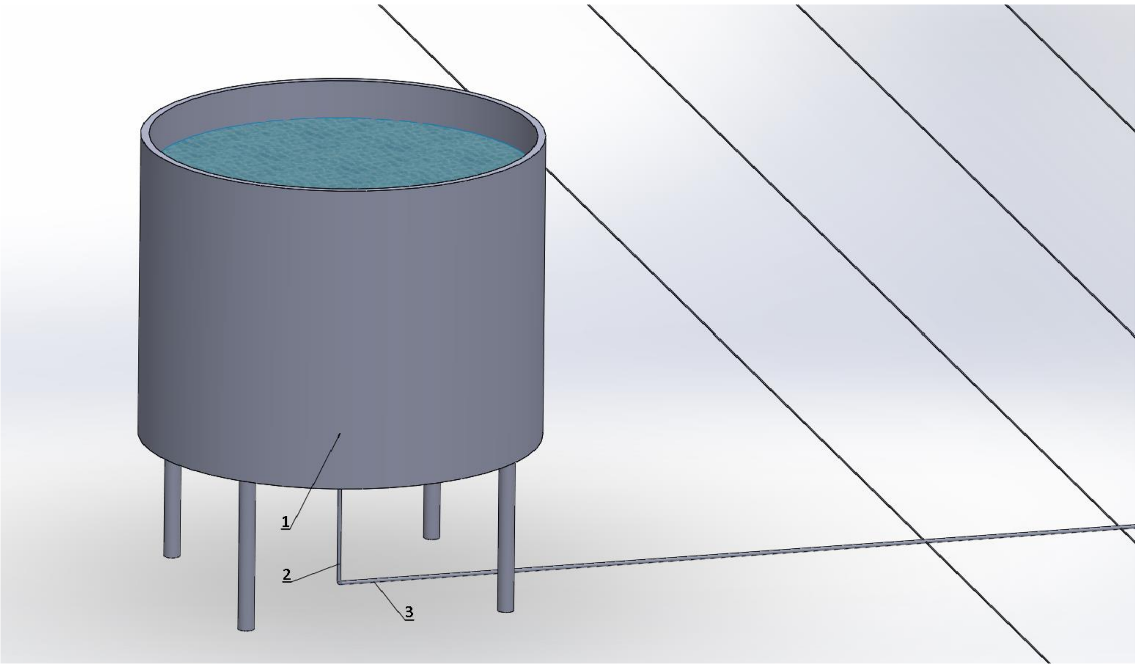


Figure 5.8: Bernoulli - Main pipe and water tank

The energy balance in this case is more complex as the linear loss includes the term distance or height, which is the variable we want to find.

$$Z_1 + \frac{P_1}{\gamma} + \frac{{v_1}^2}{2g} = Z_2 + \frac{P_2}{\gamma} + \frac{{v_2}^2}{2g} + h_L + h_S$$

Where Z_2 is zero because it is at the ground level, v_1 is also zero as the water is static in the tank. P_1 is zero as well, due to the tank is in open air, so it is under atmospheric pressure.

$$Z_1 = \frac{P_2}{\gamma} + \frac{{v_2}^2}{2g} + f\frac{Z_1}{D}\frac{v_m^2}{2g} + h_S$$

The velocity term in the linear loss corresponds to the mean velocity between the two points. It is also used in the friction factor, when the Reynolds number is calculated with this speed. The singular loss corresponds to the filter, which causes an important pressure drop. However, it is not possible to obtain a concrete value of loss as the porosity and size of particles is unknown. Therefore, and taking into account usual values of equation (5.10), an estimated number is given:

$$h_S = 1{,}50\ m$$

Finally, solving the equation, we obtain the minimum height required to irrigate all the field.

$$Z_1 = \frac{\left(\frac{P_2}{\gamma} + \frac{{v_2}^2}{2g} + h_S\right)}{1 - \frac{f}{D}\frac{v_m^2}{2g}} = 2{,}2\ m$$

Chapter 6. Water Pumping and Photovoltaic Systems

In the previous chapter, both the minimum elevation of the tank and its height were calculated. Using these values and RETscreen software, it was possible to dimension both the photovoltaic and the water pumping system.

This chapter deals with both the photovoltaic and water pumping systems, detailing the major characteristics and the proper size for supplying the right amount of water.

6.1. Introduction

Photovoltaic systems are used nowadays for different applications but the most common around the world is the combination of a photovoltaic and a water pumping system. With thousands of systems installed in developed as well as developing countries, this type of system has a lot of small applications such as crop irrigation, supply water for domestic uses and livestock watering.

In water pumping applications, when the photovoltaic system produces more energy than needed during periods of sunshine, it is possible to store this electricity by using batteries. On the other hand, this surplus of electricity can also be used to pump more water and store it in a tank for future use, instead of using batteries that increase the investment and require more maintenance tasks. Moreover, this systems are often placed in locations far from the utility electric grid or where this is non-existent and water resources scarce.

An overview of a photovoltaic water pumping system is shown in Figure 6.1.

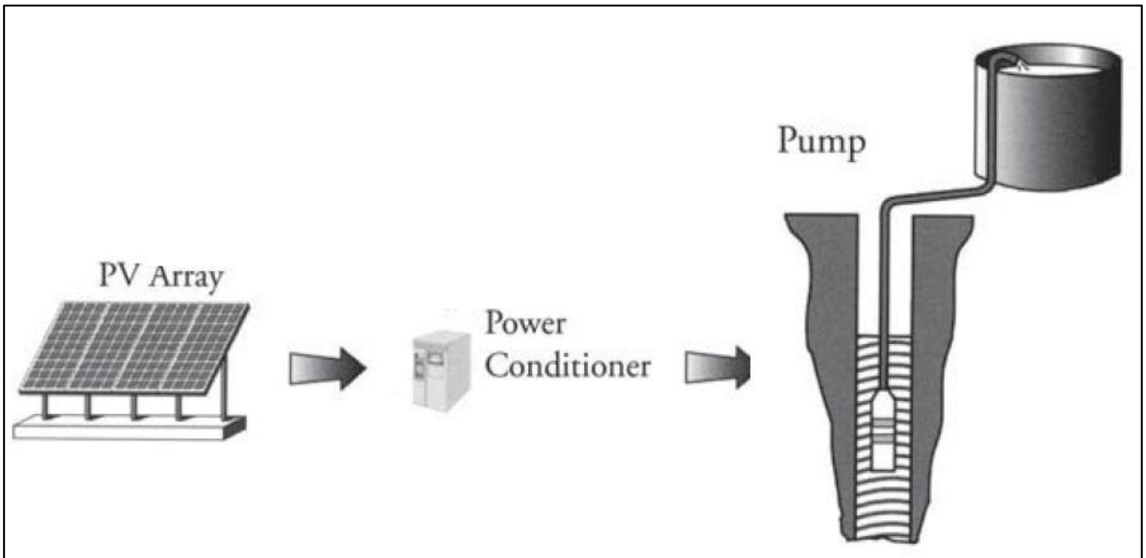


Figure 6.1: General scheme of the whole system
(Source: RETScreen International – Photovoltaic Project Analysis Chapter)

6.2. RETScreen Model

RETscreen is an Excel-based clean energy project analysis software tool that helps decision makers quickly and inexpensively determine the technical and financial viability of potential clean energy projects [19].

The water pumping model used by RETscreen is based on Figure 6.2 and 6.3 and Equation 6.1 used by this software is extracted from the RETscreen manual and explained below.

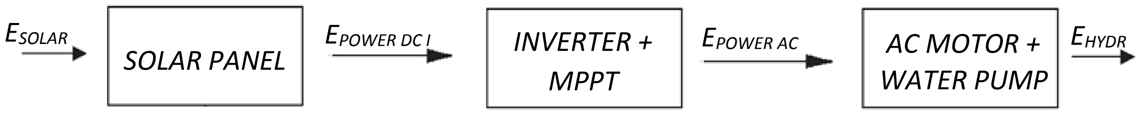


Figure 6.2: AC system - From the solar panel to the water pump

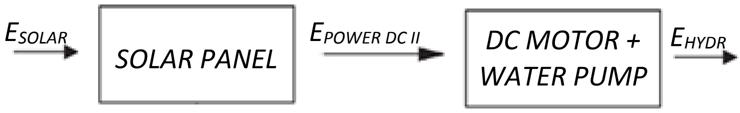


Figure 6.3: DC system - From the solar panel to the water pump

The daily energy demand $E_{HYDRAULIC}$, in Joules, corresponding to lifting water to a height h, in meters, with a daily volume Q, in m^3 per day is:

$$E_{HYDRAULIC} = 86400 * \rho * g * Q * h * (1 + \eta_f) \qquad (6.1)$$

Where,

g represents gravity's acceleration (9,81 m/s^2).

ρ is the density of the water (1000 kg/m^3).

η_f represents the friction losses along the pipe.

In order to convert this hydraulic energy into electrical power, it is necessary to use the efficiency of the pump.

$$E_{POWER\ AC} = \frac{E_{HYDRAULIC}}{\eta_{AC\ PUMP}} \qquad (6.2)$$

$$E_{POWER\ DC\ II} = \frac{E_{HYDRAULIC}}{\eta_{DC\ PUMP}} \qquad (6.3)$$

However, if the pump is AC instead of DC, the equation above has to be modified in order to take into account the inverter's efficiency.

$$E_{POWER\ DC\ I} = \frac{E_{HYDRAULIC}}{\eta_{AC\ PUMP} * \eta_{INVERTER+MPPT}} \qquad (6.4)$$

6.3. Water Pumping Subsystem

6.3.1. Pump

At the present time, there exist several types of pumps depending on the water pumping application. Pumps are divided according to the following parameters:

- Design type: Rotating or positive displacement pumps.
- Location: Surface or submersible.
- Type of motor: AC or DC.

Focusing on the design type, it is known that rotating pumps, such as centrifugal, are more effective for deep wells and larger water flows. On the other hand, positive displacement pumps, such as diaphragm and piston pumps, are usually used for low water volumes and they have a better lift capability. However, they are more sensitive to dust and dirt.

Finally, in order to choose between an AC and a DC system, factors such as price, reliability and available technical support must be taken into account. Moreover, it is also important to know that the connexion between a DC system and a photovoltaic array is easier and more efficient. Although AC systems are cheaper, they also need the use of an inverter connected to the array, which increases the price.

Figure 6.4 shows possible pump options based on the total head (total height the water has to be lifted) in meters and the daily water requirement in cubic meters.

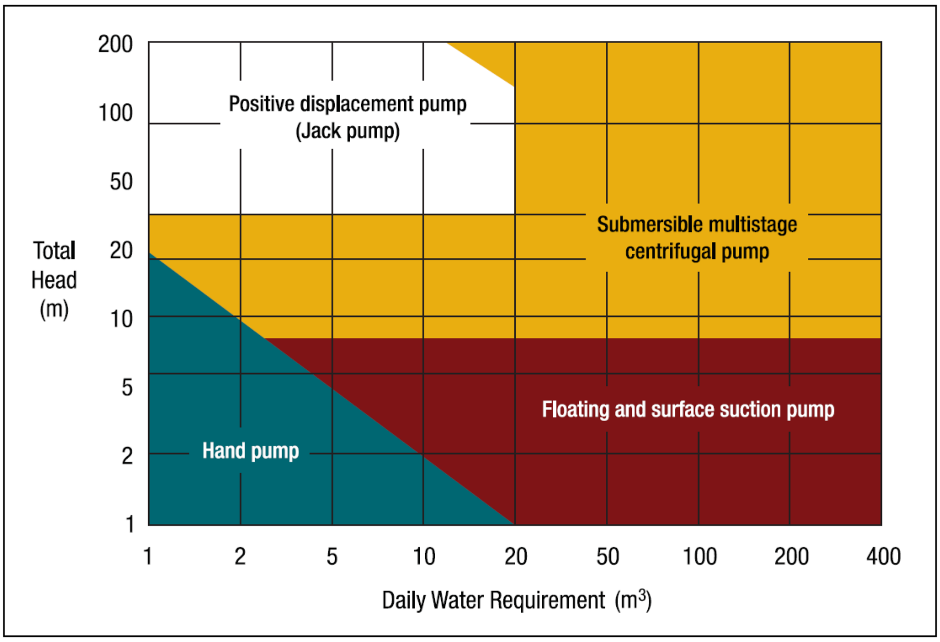


Figure 6.4: Chosen pump - Daily water requirement vs. Total head
(Source: RETScreen International – Photovoltaic Project Analysis Chapter)

Bearing in mind that our water flow demand is 74 cubic meters per day and our maximum height is 7,2 meters, the chosen pump should be a floating and surface suction pump, for instance, centrifugal.

Nowadays, centrifugal pumps are the most common used machines to pump liquids. This type of pumps transport fluids by converting rotational kinetic energy provided by the attached electric motor, into hydrodynamic energy in order to lift an amount of water. In centrifugal pumps, the fluid flows through the pump impeller (Figure 6.5) along the rotating axis, increasing its acceleration. Then, the centrifugal force pushes the fluid to flow radially outward into a diffuser or volute chamber, from where it exits.

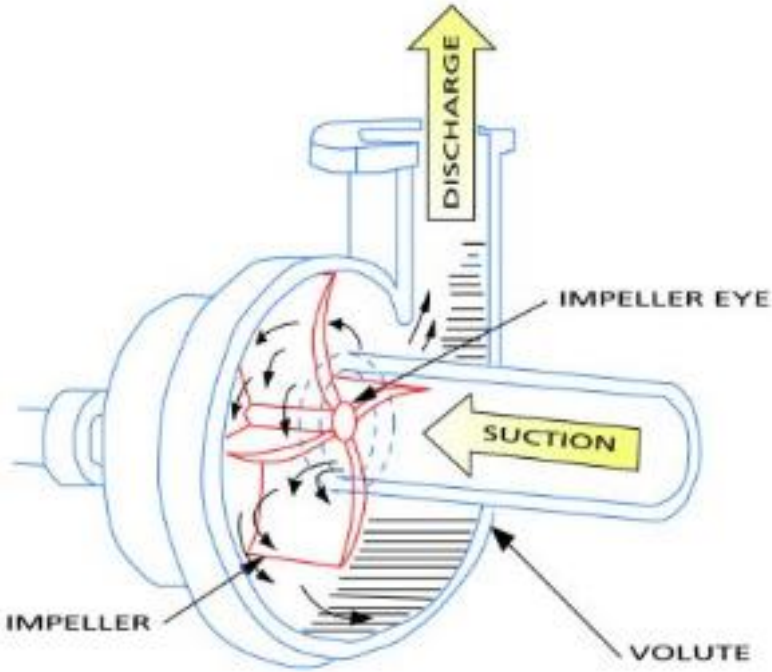


Figure 6.5: Simple centrifugal pump scheme
(Source: http://www.globalspec.com/learnmore/flow_transfer_control/pumps/centrifugal_pumps)

The pump performance is normally described by a set of curves, as can be seen in Figure 6.6. These are fundamental when having to select a pump that matches the requirements for a given application. The data sheet always contains information about the total head (H) that the pump can give to the fluid at different flows (Q), being the most important parameter for a customer when determining the dimensions of the pump.

In addition, the manufacturer generally includes the power consumption (P) of the pump respect the amount of flow. This is very important when the selection of a pump is part of an installation which must supply the pump with energy. Information about the efficiency can also be found in data specifications, which is used to choose the most efficient pump in the specified operating range.

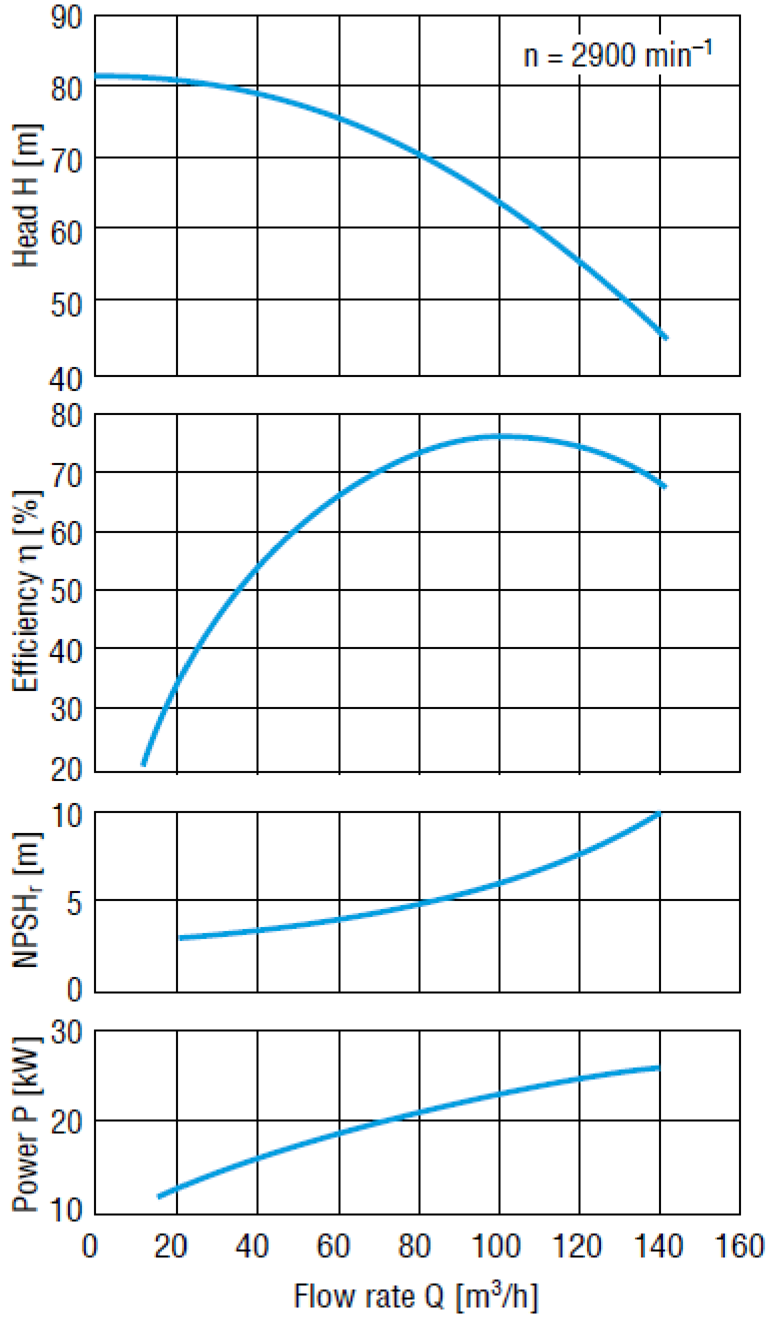


Figure 6.6: An example of the characteristic curves for a centrifugal pump
(Source: Selecting Centrifugal Pumps- http://www.ksb.com)

Moreover, the selection criteria also covers the NPSH or Net Positive Suction Head. That is the difference between the pump's inlet stagnation pressure head and the vapour pressure head. This is an important parameter to take into account to avoid damaging the pump. The low pressure at the suction side of the pump might cause the fluid to start boiling which then would turn into cavitation. NPSH is expressed in meters, usually ranging from 2 to 4, and is function of the flow of fluid.

6.3.2. Motor

In water pumping systems, pumps requires of a device which can produce the rotation needed and, obviously, these devices are usually electrical motors. Moreover, pumps can also be connected to other type of motors such as internal-combustion engines and steam turbines as well as other hydraulic turbines. As stated before and in order to drive photovoltaic water pumping systems, electric motors, either AC-current motors or DC-current motors, are the most appropriate.

One important characteristic of a PV pumping system that must be taken into account in order to choose the type of motor, is that it works at non-constant speed. Therefore, an adjustable-speed device able to control continuously and precisely the rotor's speed with high efficiency is needed.

Focusing on the type of motor, nowadays there are three motor technologies used for photovoltaic water pumping applications:

- Alternating current motors (AC-motors)
- Brushed type permanent magnet (DC-motors)
- Brushless permanent magnet (BDC-motors)

AC-motors such as asynchronous motors, also called cage-rotor induction motors, do not require a large maintenance due to its internal structure and its robust brushless rotor. The fabrication and construction of the rotor is simple and, as a consequence, its cost is lower. Moreover, the main advantage of asynchronous motors in contrast to both DC and BDC motors, is their higher power/weight ratio. That is why this type of motor is the most used in PV pumping systems applications. However, the induction motor has the inconvenience of not being able to change its rotor speed by itself. Its speed is determined by the number of poles of the stator, which determine the number of copper windings, and the frequency. That means that the only way to enlarge the speed range of the asynchronous motor is by using an adjustable-frequency power electronic device or more common known as an inverter. Although the inclusion of this device increases the initial capital cost, this is usually justified by the excellent performance and the lower maintenance costs. Figure 6.7 shows the basic construction of an AC induction motor with the main components.

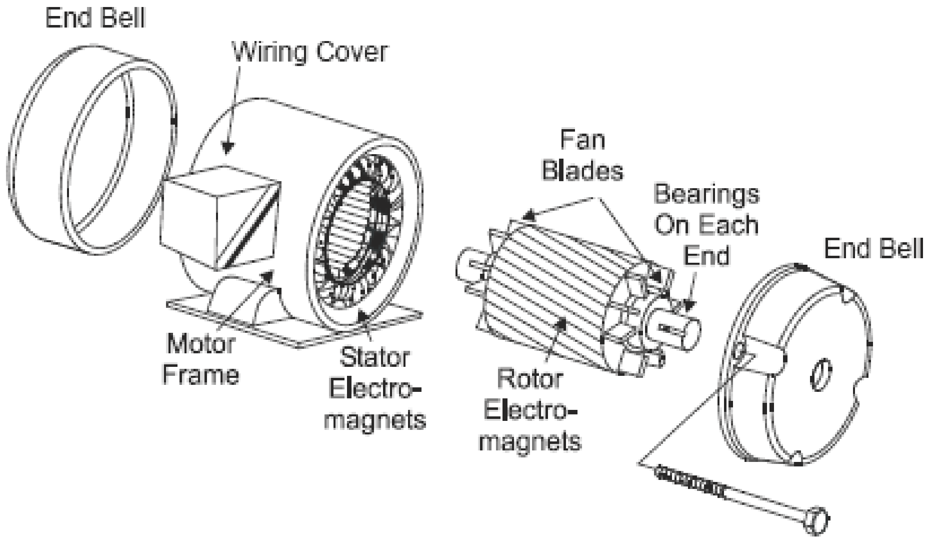


Figure 6.7: Basic components AC-motor
(Source: http://www.globalspec.com/reference/10792/179909/chapter-3-ac-and-dc-motors-ac-motors-magnetic-field-rotor)

In DC-motors, the connection between the photovoltaic array and the motor is easier because the PV-modules produces direct current and, therefore, there is no need for an inverter. Indeed, this type of motor sounds attractive because less specialized equipment is required. However, in small machines, the losses occurring in the copper windings are high and consequently the overall performance is low. Moreover, DC-motors requires of brushes to commutate and connect the rotor with the stator to create the magnetic field. The brushes deteriorate due to friction and abrasion and have to be replaced periodically, thus increasing the maintenance cost.

For that reason, there has been an increase in the use of brushless DC-motors (BDC-motors), also named electronic motors, where the magnetic field is generated by an electronic device instead of using brushes. Obviously, this non-brush system means less maintenance tasks and longer life time of the motor. However, the initial cost of the electronic device is significantly higher than the brushes and if the BDC-motor is used in submersible pump systems, it is also necessary to encapsulate the electronic device in order to protect it from water.

6.3.3. Water Pumping Capacity

RETscreen needs some input parameters in order to calculate the energy required by the water pump and, in this section, all inputs referred to the water pumping system are explained. These parameters can be categorised in two different sections:

Load characteristics

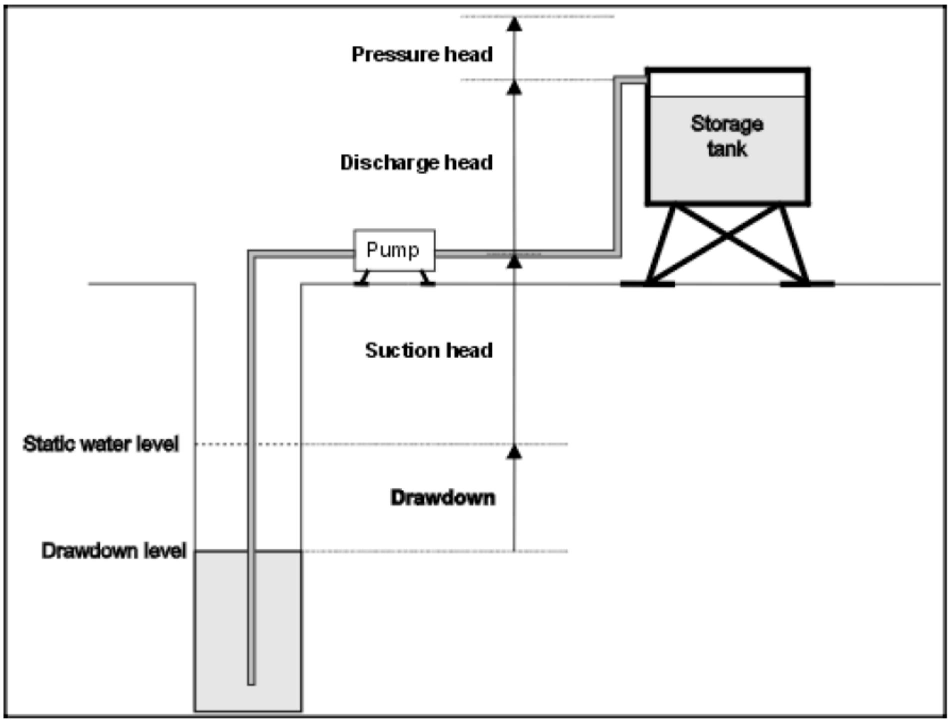


Figure 6.8: Pumping head nomenclature
(Source: RETscreen International – Online User Manual. Photovoltaic Project Model)

Figure 6.8 shows an overview of the input parameters needed to define the load characteristics.

<u>Daily water use</u>

Calculated in chapter 4 with a value of 74 m^3 per day.

<u>Suction head</u>

It is the vertical distance, in meters, from the centre of the pump to the water surface, when the pump is located above water (see Figure 6.8). There is no suction head for floating and submerged pumps and the value can range from zero and should not exceed 8 meters for hydraulic considerations. In our case, its value is 1 meter.

Drawdown

It is the vertical distance, in meters, referred to the water level decrease due to the pumping at wells (see Figure 6.8). For immersed pumps or for river-based pumping systems the value is zero.

Discharge head

It is the vertical distance, in meters, that the water will be lifted from the centre of the pump to the point of free discharge (see Figure 6.8). Its value is 6,2 meters corresponding to the minimum elevation of the tank plus its height.

Pressure head

In fluid mechanics, pressure head is the internal energy of a fluid due to the pressure exerted on its container (see Figure 6.8) [9]. For most systems such as non-pressurized tanks this value will be zero; it will be non-zero for pressurized systems and irrigation sprinklers.

$$Pressure\ Head = \frac{P}{\rho g} \tag{6.5}$$

Friction losses

Friction losses are the pressure losses caused by friction when water moves through the pipes. This value is expressed as a percentage of the total head. As stated in chapter 5, friction losses are function of the pipe's length, pipe's diameter, the material and the water flow.

Pump and motor characteristics

Motor Type

AC or DC depending on the chosen motor. This choice will depend on many factors, including price, reliability and technical support.

In our case, the motor is AC so it is also necessary the implementation of an inverter.

Efficiency

It is referred to the efficiency of the PV powered water pump system. This efficiency should be understood as the ratio between the mechanical power delivered to the water and the electrical power to the motor. Table 6.1 can be used to obtain an average of pump efficiency for different pumps.

Table 6.1: Pump system efficiency
(Source: RETscreen International – Online User Manual. Photovoltaic Project Model)

<table>
<tr><th>Pump type</th><th>Head [m]</th><th>Efficiency [%]</th></tr>
<tr><td>Surface centrifugal</td><td>0-5</td><td>15-25</td></tr>
<tr><td>Surface centrifugal</td><td rowspan="2">5-20</td><td>10-30</td></tr>
<tr><td>Submersible centrifugal multi-stage</td><td>20-30</td></tr>
<tr><td>Submersible centrifugal multi-stage</td><td rowspan="2">20-100</td><td>30-40</td></tr>
<tr><td>Displacement pumps</td><td>30-45</td></tr>
</table>

Figure 6.9 shows the RETscreen display when introducing the water pumping input parameters.

Load characteristics

		Base case	Proposed case
Daily water use	m³/d		
Suction head	m		
Drawdown	m		
Discharge head	m		
Pressure head	m		
Friction losses	%		
Total head	m	0,0	0,0
Mechanical energy - daily	kWh	0,00	0,00
Mechanical energy - annual	kWh	0,0	0,0
Pump & motor			
Description			
Type			
Efficiency	%		

Figure 6.9: RETscreen – Water pumping input parameters

A scheme of the designed water pumping system is shown in Figure 6.10.

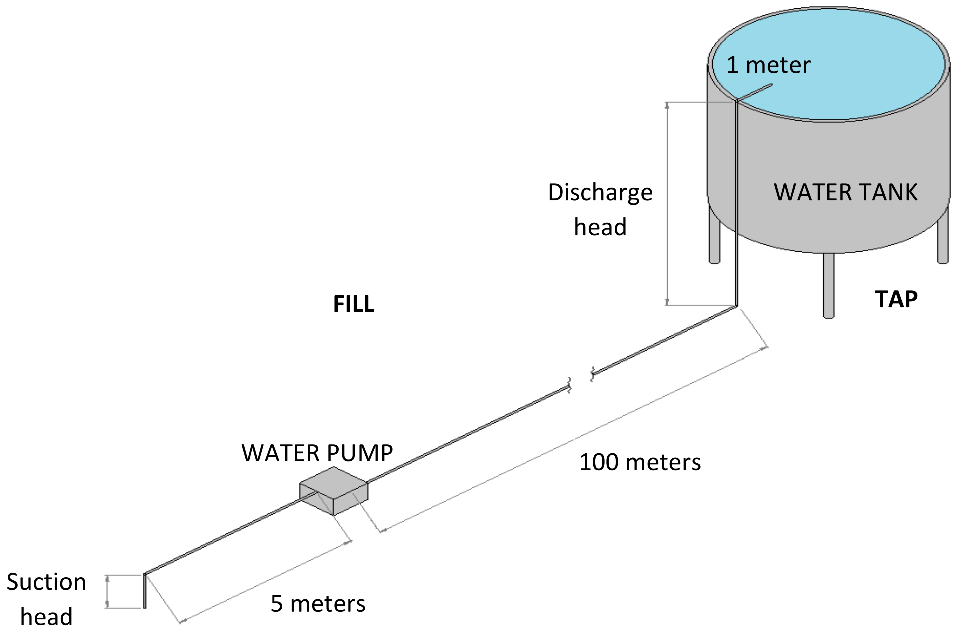


Figure 6.10: Water pumping system

Bearing in mind that the photovoltaic array does not provide energy 24 hours per day, the worst case in terms of water need and sun hours was analysed in order to find the minimum flow rate (Table 6.2).

Table 6.2: Monthly water need and sun hour's ratio

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Sun hour's	5,89	5,81	5,53	4,80	4,48	4,67	5,09	5,25	5,50	5,63	5,27	5,49
Q [m³/day]	12,42	27,17	13,96	7,48	38,34	64,38	70,00	71,22	36,70	16,99	2,15	0,00
Ratio	**2,11**	**4,68**	**2,52**	**1,56**	**8,56**	**13,79**	**13,75**	**13,57**	**6,67**	**3,02**	**0,41**	**0,00**

As it can be observed in the table above, the highest ratio corresponds to June with an approximately value of 14 m^3/sun hour. That means that along this month, both the photovoltaic and the water pumping system must be able to supply enough energy to lift 14 cubic meters of water in one hour.

Focusing on Figure 6.10 and to find the percentage of friction losses, the Darcy's equation was used again to calculate the linear (equation 5.6) as well as the singular losses (equation 5.7). In this water pumping system, the diameter of the pipe is 63 mm, with a water flow of 14 cubic meters per hour and, therefore, a velocity of 1,23 meters per second.

$$h_L = f\frac{L}{D}\frac{v^2}{2g} = 0{,}019 * \frac{113{,}2\,m * \left(1{,}23\,\frac{m}{s}\right)^2}{0{,}063\,m * 2 * 9{,}81\,\frac{m}{s^2}} = 2{,}63\,meters$$

$$h_S = K\frac{v^2}{2g} = 3\,elbows * 1 * \frac{\left(1{,}23\,\frac{m}{s}\right)^2}{2 * 9{,}81\,\frac{m}{s^2}} = 0{,}23\,meters$$

Singular losses are multiplied by three due to there are three elbows with the same features along the pipe. Finally, the percentage of referred to the total head is the following:

$$Friciton\ losses\ [\%] = \frac{h_L + h_S}{Total\ head} * 100 = \frac{2{,}63\,m + 0{,}23\,m}{7{,}2\,m} = 40\%$$

Finally, the input and output values are shown in Figure 6.11.

Load characteristics

		Base case	Proposed case
Daily water use	m³/d	74	74
Suction head	m	1,0	1,0
Drawdown	m	0,0	0,0
Discharge head	m	6,2	6,2
Pressure head	m	0,0	0,0
Friction losses	%	40%	40%
Total head	m	10,1	10,1
Mechanical energy - daily	kWh	2,03	2,03
Mechanical energy - annual	kWh	741,9	741,9
Pump & motor			
Description		Centrifugal	Centrifugal
Type		AC	AC
Efficiency	%	30%	30%
Summary			
Electricity - daily	kWh	6,78	6,78
Electricity - annual	kWh	2.473,04	2.473,04

Figure 6.11: RETscreen - Input and output values

As it can be observed, the daily energy as well as the annual energy required by the water pumping subsystem given by the RETscreen software are 6,78 and 2.473,04 kWh, respectively.

6.4. Photovoltaic Subsystem

The foundations of the PV panels are based on the photovoltaic effect, which produces direct electrical current from the radiant energy of the sun by using semiconductor cells. The vast majority of solar cells are made of Silicon. Although the main differences in semiconductors refer to their performance, the typical power output of a solar cell is 1 Watt. Therefore, to provide larger amounts of power, it is needed to interconnect solar cells both in series and parallel on a module. By doing this, the PV array can generate the current required to meet the power demand of the load.

The operating point of a PV is defined by its I-V characteristics, giving an output power of the current-voltage product at that point. Although every single panel may differ from another, all I-V curves have approximately the same shape (Figure 6.12).

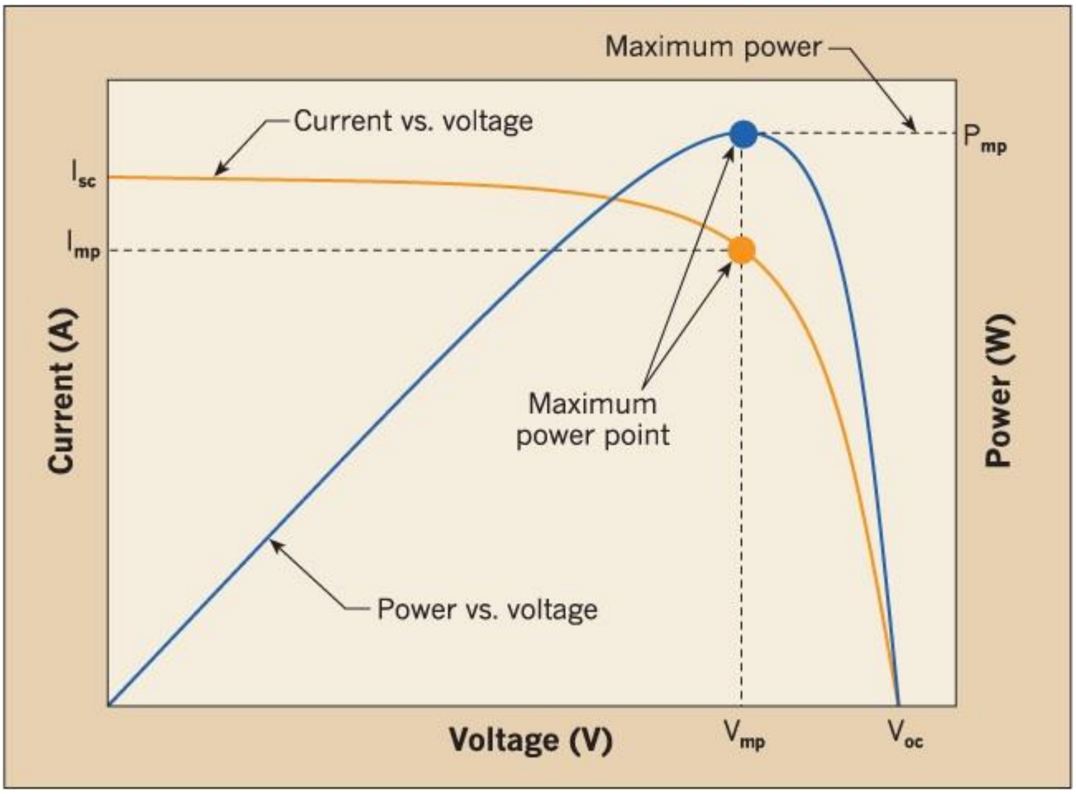


Figure 6.12: Current vs Voltage and Power characteristics of a solar cell
(Source: http://ecmweb.com/green-building/calculating-current-ratings-photovoltaic-modules)

As can be seen in the figure above, there is a single point at which the power is at a maximum. That is the largest rectangle area that can be drawn under the curve, called the maximum power point P_{MPP}, at a certain voltage V_{MPP} and current I_{MPP}. All these parameters are given in the specifications of a solar module by the manufacturer.

Once obtained the energy, there is the need to convert the electrical current of the PV panels from DC to AC in order to supply alternate current to the asynchronous motor. Hence, an inverter is required. The efficiency of the different types of inverters are about 95 %.

Furthermore, to get the most power from the PV array, the use of an inverter equipped with the Maximum Power Point Tracker is of great value. This technique uses a variety of control and logic circuits to constantly adjust the load to work in MPP. Hence, extracting the maximum power available from the cells.

6.4.1. Photovoltaic Capacity

Once the energy required for the water pumping system is found, the minimum amount of electricity the photovoltaic system has to provide it is not difficult to calculate. In section 6.2.4 is stated that the water pumping system needs 6,78 kWh per day to supply the appropriate amount of water. However, due to the system designed integrates an inverter and an MPPT system (Figure 6.5), it is necessary to take into account its efficiency. Bearing in mind that the minimum efficiency of the whole system is 90%, the daily energy supplied by the PV array should be:

$$E_{POWER\ DC\ I} = \frac{E_{POWER\ AC}}{\eta_{INVERTER+MPPT}} = \frac{6{,}78\,\frac{kWh}{day}}{0{,}90} = 7{,}53\ \frac{kWh}{day}$$

Then, the electric power needed is the following:

$$ELECTRIC\ POWER = \frac{ENERGY}{TIME} = 7{,}53\,\frac{kWh}{day} * \frac{1\ day}{4{,}48\ sun\ hour's} = 1{,}73\ kW$$

Note: The value of sun hours applied is the lowest one along the year and corresponds to May (see Table 6.2).

In order to complete the RETscreen analysis, it is also necessary to introduce different inputs. These inputs are referred to the inverter, the resource assessment and the photovoltaic systems.

Inverter

<u>Capacity</u>

One thing that needs to be taken into account is that inverter capacity must be introduced in kW AC. Therefore, its capacity in kW (AC) is the following:

$$ELECTRIC\ POWER = \frac{ENERGY}{TIME} = 6{,}78\,\frac{kWh}{day} * \frac{1\ day}{4{,}48\ sun\ hour's} = 1{,}51\ kW$$

In case there is no AC load, the value of the inverter's capacity must be zero.

Efficiency

The combined efficiency, expressed in percentage, of the electronic devices (MPPT and inverter) used to control the power of the PV array and to convert DC output to AC must be entered into the software. Values between 80 and 95 % are typical and, in our case, 90 % has been taken as the combined efficiency.

Miscellaneous losses

This losses are referred to the power conditioning, for instance, the losses incurred in DC-DC converters or in step-up transformers. However, in most cases this value will be zero.

Inverter		
Capacity	kW	1,5
Efficiency	%	90%
Miscellaneous losses	%	0%

Figure 6.13: RETscreen – Inverter inputs

Resource assessment

Solar tracking mode

There are four different tracking modes available by the software; "fixed", "one-axis", "two-axis" and "azimuth". In our case, the photovoltaic system is mounted on a fix structure due to the low cost compared with the other options.

However, depending whether or not a tracking device is used, the parameters shown in table 6.3 also need to be introduced in the photovoltaic model.

Table 6.3: PV array tracking mode and required parameters
(Source: RETscreen International – Online User Manual. Photovoltaic Project Model)

Tracking Mode	Parameters Required
No tracking	Slope and azimuth of PV array
One-axis tracking	Slope and azimuth of tracking axis
Two-axis tracking	None
Azimuth tracking	Slope of tracking axis

Slope

The angle, in degrees, between the photovoltaic array and the horizontal has to be also introduced. This slope can have different values depending on the type of system:

- For systems working through the year, the slope should be equal to the absolute value of the latitude. This value maximises the annual solar radiation in the plane of the photovoltaic array.

- Equal to the absolute value of the latitude, minus 15°. This slope maximises the solar irradiance in the plane of the photovoltaic array in the summer.

- Equal to the absolute value of the latitude, plus 15°. This slope maximises the solar irradiance in the plane of the photovoltaic array in the winter.
- For fixed arrays, equal to the slope of the land. Although this slope does not represent an optimum in terms of energy production, it can decrease significantly the cost of the installation by avoiding the need for a support structure.

- For fixed arrays, equal to 90°. This slope is recommended if the photovoltaic array is placed on a building façade not to improve its efficiency in terms of energy production but to decrease the installation's cost.

In our case and due to the designed photovoltaic system must be working throughout the whole year, the slope value should be equal to the absolute value of the latitude of the site, which is 2,2°.

Azimuth

The azimuth is referred to the angle between the projection, on a horizontal plane, of the local meridian and the normal to the surface. In addition, it is also necessary to know where the zero degree is placed. In this case, RETscreen places the zero degree due south.

In this cases, the preferred orientation should be with the PV panels facing the equator, in which case the azimuth angle is 180° in the Southern Hemisphere and 0° in the Northern one. Therefore, in our case, the azimuth angle is 180°.

Resource assessment		
Solar tracking mode		Fixed
Slope	°	2,2
Azimuth	°	180,0

Figure 6.14: RETscreen - Resource assessment inputs

Once the parameters above are introduced, RETscreen provides with more information such as the daily solar radiation, both with plane solar panels and tilted ones and the monthly electricity delivered to the load (see Figure 6.15).

Month	**Daily solar radiation - horizontal kWh/m²/d**	**Daily solar radiation - tilted kWh/m²/d**	**Electricity delivered to load MWh**
January	4,93	4,88	0,23
February	5,22	5,19	0,21
March	4,97	4,97	0,23
April	4,83	4,85	0,23
May	4,71	4,76	0,23
June	4,83	4,90	0,23
July	5,14	5,21	0,23
August	5,09	5,13	0,23
September	5,07	5,08	0,23
October	4,68	4,66	0,22
November	4,54	4,50	0,21
December	4,57	4,52	0,22
Annual	**4,88**	**4,88**	**2,70**

Figure 6.15: RETscreen outputs - Solar radiation and delivered electricity

Photovoltaics

Type

At this point, it was necessary to choose between several types of photovoltaic modules. RETscreen provides with seven different options: *mono-Si*, *poly-Si*, *a-Si*, *CdTe*, *CIS*, *spherical-Si* and *others*. The most common PV modules used nowadays are *mono*-Si and *poly*-Si. The highest performance is provided by mono-Si modules (see Table 6.4). However, their costs are relatively high compared with all the others. Poly-Si modules have a similar efficiency in terms of energy and their cost as slightly lower.

Table 6.4: Nominal efficiencies of PV Modules
(Source: RETscreen International – Online User Manual. Photovoltaic Project Model)

Cell type	Default efficiency [%]
mono-Si	13
poly-Si	11
a-Si	5
CdTe	7
CIS	7,5

Moreover, RETscreen recommends the use of these two types of modules as a first selection. The modules chosen for our system are *poly-Si*.

Control method

The control method is referred to the interface between the PV array and the rest of the system. RETscreen offers two possibilities: *Clamped* or *Maximum Power Point Tracker (MPPT)*. As stated in the beginning of this section, MPPT is gathered in the inverter system and *Clamped* is referred to a direct connection between the PV array and batteries. Therefore, MPPT was chosen so the efficiency of the array was optimal.

Miscellaneous losses

This losses are referred to miscellaneous sources that have not been taken into account elsewhere in the software. This include, for instance, losses due to presence of dirt or snow on the modules. This value usually goes from zero to a few percentage and, in some exceptional cases, this value could be as high as 20 %. In our case and bearing in mind the presence of dust in Rwanda, a value of 6 % have been introduced.

Photovoltaic		
Type		poly-Si
Power capacity	kW	
Manufacturer		
Model		
Efficiency	%	
Nominal operating cell temperature	°C	45
Temperature coefficient	% / °C	0,40%
Solar collector area	m²	#¡DIV/0!
Control method		Maximum power point tracker
Miscellaneous losses	%	6,0%

Figure 6.16: RETscreen - Photovoltaic system inputs

Chapter 7. Results

In this chapter, different photovoltaic possibilities are analysed and, by using RETscreen software, a specific pump is chosen. A comparison between the designed system and the grid connection is also presented in order to demonstrate that the first one is more economic. In addition, a sensibility analysis is carried out by modifying key input parameters.

7.1. Photovoltaic Subsystem

7.1.1. Photovoltaic Panel

Once the power capacity was calculated, by using the RETscreen data base we were able to choose among a large list of several photovoltaic systems from companies such as Suntech, BP Solar, Sharp, Shell and Canadian Solar, among others. For our design, Suntech and Sharp companies were chosen and, for each one, the best photovoltaic model in terms of performance was chosen (see Figure 7.1 and 7.2).

Photovoltaic			
Type		poly-Si	
Power capacity	kW	1,92	
Manufacturer		Sharp	
Model		poly-Si - ND-240QCJ	8 unit(s)
Efficiency	%	14,7%	
Nominal operating cell temperature	°C	45	
Temperature coefficient	% / °C	0,40%	
Solar collector area	m²	13,0	
Control method		Maximum power point tracker	
Miscellaneous losses	%	6,0%	
Summary			
Capacity factor	%	18,0%	
Electricity delivered to load	MWh	2,75	111,1%

Figure 7.1: RETscreen - Sharp ND-240QCJ

Photovoltaic			
Type		poly-Si	
Power capacity	kW	1,74	
Manufacturer		Suntech	
Model		poly-Si - STP290 - 24/Vd	6 unit(s)
Efficiency	%	15,0%	
Nominal operating cell temperature	°C	45	
Temperature coefficient	% / °C	0,40%	
Solar collector area	m²	11,6	
Control method		Maximum power point tracker	
Miscellaneous losses	%	6,0%	
Summary			
Capacity factor	%	18,0%	
Electricity delivered to load	MWh	2,70	109,0%

Figure 7.2: RETscreen - Suntech STP290 - 24/Vd

As it can be observed in the figures above, although both photovoltaic systems have similar performances, in order to supply enough amount of energy Sharp panels need two more modules than Suntech panels (8 panels of 240 Watts in front of 6 panels of 290 Watts, respectively). To finally choose between these two models, other parameters such as total price and electricity delivered to load were also analysed (see Table 7.1).

Table 7.1: Comparison between Suntech and Sharp

Company	Model	€/module	Modules	Total price [€]	€/kW	E. delivered [MWh]
SUNTECH	STP290 - 24/Vd	276	6	1.656	0,952	2,70
SHARP	ND - 240QCJ	220	8	1.760	0,916	2,75

In the table above it is shown that the best option in terms of efficiency and total cost is the Suntech photovoltaic system. Moreover, the surplus of energy produced by this type of panel is also lower. Therefore, Suntech photovoltaic system is the one chosen for our system although the differences are not too large.

7.1.2. Solar Inverter and MPPT System

A photovoltaic system needs of a solar inverter in order to convert the provided DC voltage into AC voltage required by the AC pump. Moreover, an MPPT system is also needed to ensure that the PV panels are working in optimal performance. Luckily, nowadays most of solar inverters for off-grid PV systems integrate this MPPT system.

Another aspect to take into account is the efficiency. At present, inverters efficiencies have increased a lot and the typical efficiency figures are well above 90 %. However, the efficiency of the inverter changes depending on the power supplied to the load and usually the manufacturer specifies the efficiency curve of the inverter.

Indeed, there are a lot of different companies and inverter's models that offer a good performance and, for our designed system, an inverter with a rated power similar or equal to the photovoltaics, 1,74 kW, was needed. In our case, the chosen inverter is shown in Table 7.2.

Table 7.2: Solar inverter specifications

Company	Model	Input Power [kW]	Input voltage range [V]	Max. Efficiency [%]	Nominal/Max. Output Power [kW]	Nominal Voltage [V]	Price [€]
Fronius	Galvo 1.5-1	1,2-2,4	120-420	95,8	1,5 kW	230	1.210

7.2. Centrifugal Pump

Following the selection of the PV panel, the pump chosen had to meet numerous requirements. These are the power consumption, the total head that the pump can supply at a given flow of water and the NPSH.

First and above all, section 6.3.4 determined the daily energy needed to pump water. Therefore, the main input to choose a pump from the vast offer in the market is the power required. To find it, we had to divide the required energy by the number of hours the pump would work. Taking into account that the pump works solely when it receives energy from the PV panel, and having it been dimensioned for the worst scenario (May), the number of hours in operation would be 4,48.

$$Minimum\ Pump\ Power = \frac{Daily\ Energy\ Required}{Operating\ hours} = \frac{6{,}78\ \frac{kWh}{day}}{4{,}48\ h} = 1{,}51\ kW$$

The power required of the pump is 1,51 kW. However, whilst introducing the input data in RETcreen we assumed an efficiency of 30 % for a typical pump, as stated in section 6.3.3. This value is very low considering the current market offer. As a result, a pump with less power will work perfectly well under conditions of 30 % and higher efficiencies. Therefore, the theoretical power needed is oversized and allows us to select a pump from a wide range of efficiencies.

In addition to the power of the pump, another factor to consider is the total head that the pump has to supply in order to convey the water to the tank. In section 6.3.3 it was calculated, giving a total head of 10,1 meters.

Last but not least, we had to consider the Net Positive Suction Head as it is crucial in order to ensure the pump works properly. In this case, the suction head is one meter above the water level. Therefore, the pump is required to be able to overcome this height, considering that most centrifugal pumps can operate in NPSH of 2 and even up to 5 meters, depending on the flow.

After establishing the conditions the pump has to fulfil, we researched an appropriate one in the market. We selected a centrifugal pump from BBA Pumps, a company leader in the sector that has multiple offer and assures long-life product.

The chosen model is B50 Electric Drive, with maximum flow of 35 cubic meters per hour and 18 metres as maximum head (Table 7.3). The most important features are presented below, in Figures 7.4, 7.5, 7.6 and 7.7, with data taken from BBA Pumps website.

Table 7.3: Technical Specifications of the Centrifugal Pump

Company	Model	Max. Input Power [kW]	Input Voltage [V]	Max. Flow [m^3/h]	Max. Head [m]
BBA Pumps	B50	2,2	230/400	35	18

Figure 7.3: Total Head at different flows for B50 pump

As can be seen in Figure 7.3, the requirement of total head at the flow of 14 m^3 is reached with this pump, exceeding easily the demand of 10,1 meters.

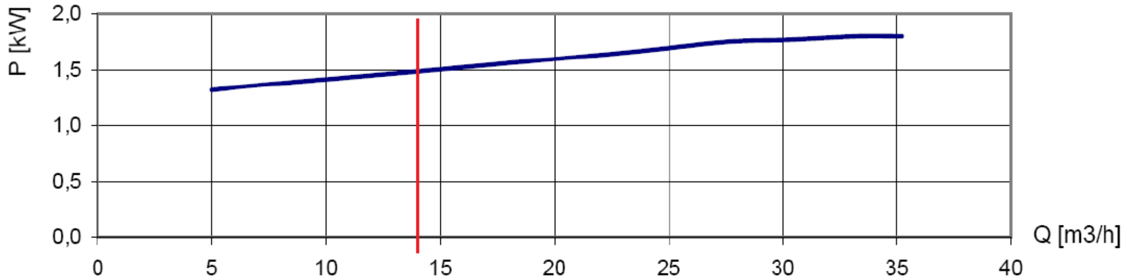


Figure 7.4: Pump Performance

In terms of power, the chosen pump fits perfectly in the application as it consumes 1,5 kW at the maximum flow rate (Figure 7.4).

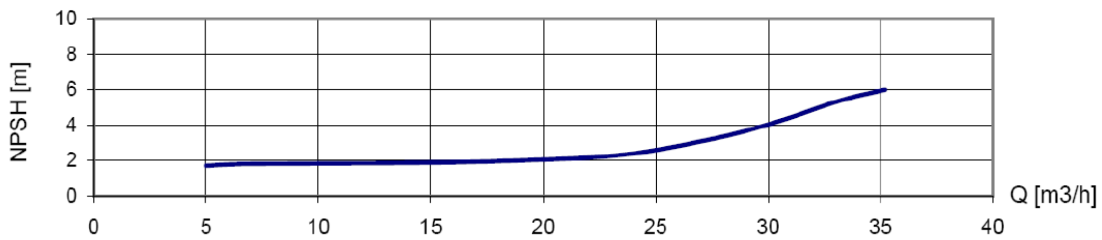


Figure 7.5: NPSH at different Flow Rates

Finally, the Net Positive Suction Head at the target flow is approximately 2 meters, being more than enough to cover the necessity of the system, of only 1 meter (Figure 7.5).

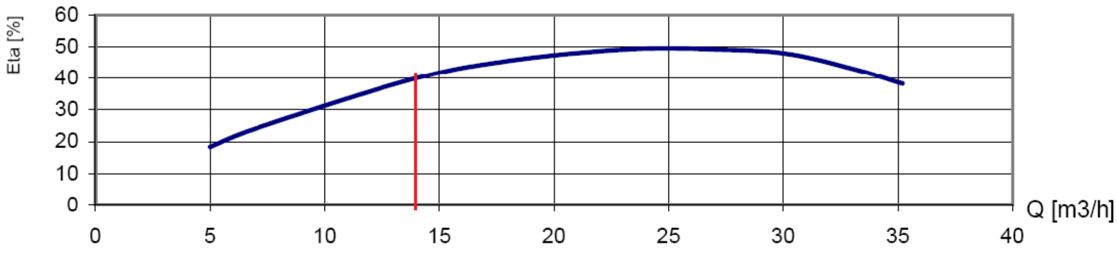


Figure 7.6: Efficiency rate of the pump depending on the Flow

As mentioned before, it is obvious that a pump with the same power but higher efficiency than the required would fit in the application. In this case, the selected pump has an efficiency of roughly 40 % (Figure 7.6), with a power consumption of 1,5 kW. Hence, the total head that the pump can overcome is clearly exceeded, working properly in our system.

7.3. Cost and Investment

In order to evaluate the economic viability of project, the cost analysis must be developed by considering the lifetime of the whole system. As stated in the first chapter as a limitation of the project, the lifetime has been set in 20 years due to the guarantee of the PV panels. Therefore, after the 20 years, is assumed that the photovoltaic system is not worth anymore and it has to be replaced. The following Tables 7.4, 7.5 and 7.6 gives a summary of the costs of the different components of the system divided by PV, pumping and piping systems.

Table 7.4: PV system cost summary

PV System Components	Capital Cost [€]	Installation Cost [€/W]	Total Installation Cost [€]	O&M Cost [€/year]
PV Panels	1.423 [12]	2,28 [14]	3.978	19,89
Solar Inverter	1.210 [13]	-	-	-

The total O&M cost through the lifetime has been calculated as the 10 % of the total installation cost. Then, the annual O&M cost is 19,89 €.

$$O\&M\ annual\ cost = 0{,}1 * \frac{3.978\ €}{20\ years} = 19{,}89\ €/year$$

Due to finding the price of the selected centrifugal pump (BBA Pumps B50) has not been possible, the chosen capital cost corresponds to another pump from a different company with similar characteristics. The company is CNP, the model is MS250/1.5M and the reason why we only select the price is because the pump graphics are not provided by the supplier.

Table 7.5: Pumping system cost summary

Pumping System Component	Capital Cost [€]		
Water Pump	704 [15]		
Pumping System component	**Capital Cost [€/L]**	**Volume [L]**	**Total Capital Cost [€]**
Water Tank	0,18 [14]	78.500	14.130

Table 7.6: Piping system cost summary

Piping System Components	Capital Cost [€/m]	Total length [m]	Capital Cost [€]
Pipe Ø63 PVC	7,25	113,20	820,70
Pipe Ø40 PVC	3,15	107,20	337,68
Pipe Ø13,6 PE	0,69 [16]	4.000	2.760
Piping System Components	**Capital Cost [€/u]**	**Quantity**	**Capital Cost [€]**
Elbow Ø63 PVC	8,64	3	25,92
Elbow Ø40 PVC	4,23	1	4,23
Tee	5,19	1	5,19
Crosses (main - secondary)	16,32	40	652,80

Note: Some of the prices were found in US dollars. To calculate the costs in €, the exchange rate used was extracted from http://www.xe.com/currencyconverter/ and its value was 1$ = 0,914531 € (28/05/2015 at 11:15). The prices of PVC components (pipes, elbows, tees and crosses) are extracted from source [17].

The total investment of the project is showed in the following Table 7.7:

Table 7.7: Total Investment

System	Investment [€]
Photovoltaic	6.611
Water Pumping	14.874
Piping	4.606,52
TOTAL	**26.091,52**

7.4. Comparison with Grid Connection

In general, the implementation of renewable technologies have a higher capital cost although the cost of photovoltaic solar panels has been reduced drastically in the past years. However, the related operation and maintenance (O&M) costs are significantly small throughout the lifetime of the system. For that reason, is necessary to analyse the viability of the system and the evolution of the cost during the whole lifetime. Depending on this, the photovoltaic system can become more expensive than extending the main electric grid.

The first alternative is to implement the designed system. Then, the cost of the photovoltaic system, the inverter and the MPPT system as well as the cost of installation and maintenance have to be taken into account. Piping and water pumping costs have not been considered due to they appear in both alternatives. The second alternative is to extend the lines of the general grid. In this case, both the cost of extending the grid and the cost of the annual energy have been considered (Table 7.8).

Table 7.8: Grid connection cost summary

ALTERNATIVE	Installation Cost [€/km]	Energy Cost [€/kWh]	Energy needed [kWh/year]	Total energy cost [€/year]
Grid Connection	20.120 [18]	0,20	2.475	520

According to Mr. Habyarimana, F., Renewable Energy PhD student at University of Agder, the cost of the energy supplied by the electric grid in Rwanda is around 0,20 €/kWh.

The following Figure 7.7 shows the evolution of the costs of the two presented alternatives. In this case, and to demonstrate that the photovoltaic system is more viable and economical than the other alternative, the figure shows that even if there was no need of grid extension, the PV alternative is better in terms of cost.

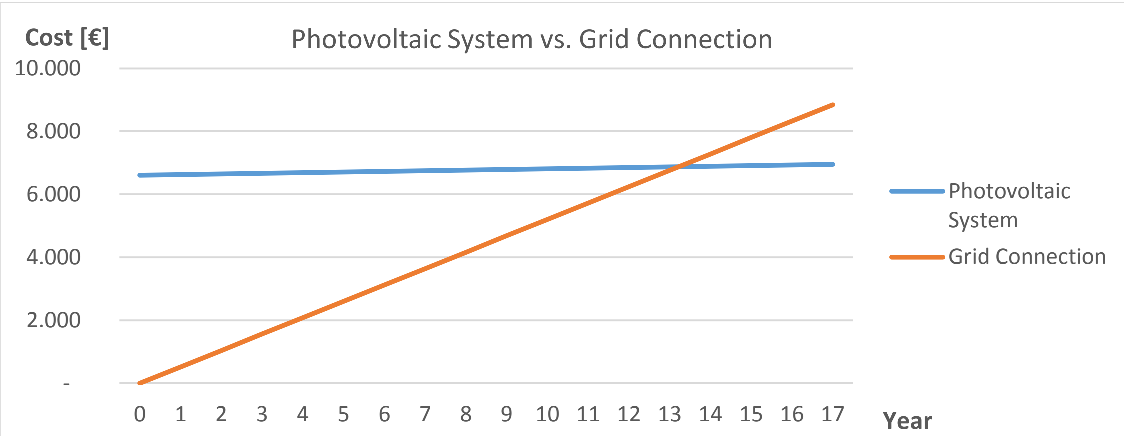


Figure 7.7: Cost Evolution – PV system vs. Grid Connection

$$6.611€ + 19{,}89\frac{€}{year} * t = 520\frac{€}{year} * t \;\rightarrow t = \frac{6.611€}{520\frac{€}{year} - 19{,}89\frac{€}{year}} \rightarrow t = 13{,}21\ years$$

Indeed, the investment and the cost of the first thirteen years of the PV system are significantly higher than the grid connection but, afterwards, the cost of the second alternative is above.

7.4.1. Levelized Cost of Energy (LCOE)

LCOE is the cost per kWh of electrical energy consumed throughout the lifetime of the system. Indeed, LCOE is a measure of a power source which attempts to compare different methods of electricity generation on an equal and comparable basis. The LCOE of the electricity generated by a photovoltaic system and the grid connection can be calculated from the following equation.

$$LCOE = \frac{Total\ Annualized\ Cost\ \left(\frac{€}{year}\right)}{Total\ Energy\ Consumed\ \left(\frac{kWh}{year}\right)} \tag{7.1}$$

The LCOE analysis has been performed considering a lifetime of 20 years. All relevant costs including the initial capital investment and operating and maintenance cost have been taken into account in this analysis.

LCOE Photovoltaic System

$$LCOE_{PV\ SYSTEM} = \frac{6.611\ € + 19{,}89 \frac{€}{year} * 20\ years}{2.475\ \frac{kWh}{year} * 20\ years} = 0{,}14 \frac{€}{kWh}$$

LCOE Grid Connection

$$LCOE_{GRID\ CONNECTION} = \frac{20.120\ \frac{€}{km} * X\ km + 520 \frac{€}{year} * 20\ years}{2.475\ \frac{kWh}{year} * 20\ years}$$

$$LCOE_{GRID\ CONNECTION} = 0{,}21\ \frac{€}{kWh} + 0{,}41 \frac{€}{kWh\_km} * X\ km$$

It has been found that the LCOE obtained for the case of photovoltaic system is 0,14 €/kWh during the whole lifetime of 20 years. This cost is significantly lower compared to the LCOE of the grid alternative. Actually, even if there is no need of grid extension, the LCOE of the non-renewable alternative is still higher, 0,21 €/kWh.

Hence, it can be concluded that the PV system is more economical to implement than the conventional grid alternative.

Chapter 8. Discussion

The objective of the thesis has been to show that using a PV system to convert solar energy into electric power to pump water for irrigation is a more cost effective solution than providing the same amount of energy from the electric grid. The system was designed for a rural region in central Africa, more specifically, in Bugesera, one of the seven districts of the eastern province of Rwanda. The maximum demand of water to irrigate a hectare of banana is 74 m^3/day, thus the system has been sized according to that peak of load.

The Bugesera region receives an large amount of sunlight with an annual average solar radiation of 5,28 kWh/m2_day. Furthermore, Bugesera is one of the driest areas within the eastern province of Rwanda, where the precipitation is the lowest in the country, with values below 900 millimetres per year, and its average temperature is high, with values above 21°C. Thus, these factors have led to select Bugesera as an interesting candidate to perform our study, using solar technology as a resource for electricity.

The overall system consists of PV panels with a rated power of 1,74 kW, an inverter with MPPT and a centrifugal pump, which consumes 1,5 kW. The purpose is to pump water from a lake to a tank, where via gravitation, water is conveyed to the crop through a piping system. Further analysis has been done to identify whether the system proposed is more cost efficient than using the conventional grid, taking into account the investment and future costs of the alternatives within the project lifespan, 20 years.

Moreover, the obtained solution can be placed in different locations. Actually, if the environment's conditions such as solar radiation, sun hours and water requirement are similar, the efficiency and performance of the system should be similar as well. In case some factors change, the designed system could also be adapted by increasing the power of the photovoltaics, pump or by designing a larger water tank.

In addition, a levelized cost of energy (LCOE) analysis has been developed. The LCOE of the photovoltaic system obtained throughout the lifetime of the project, including O & M, is 0,14 €/kWh meanwhile the LCOE of the non-renewable alternative is 0,21 €/kWh plus 0,41 € per kWh and km. This significant difference is due to two main reasons. The cost of extending the grid to rural areas is extremely high, around 20.000 € per km of the line and the cost of the energy is also significantly higher than the photovoltaic alternative. Hence, it can be concluded that the PV system is more economical to implement than the conventional grid alternative.

Chapter 9. Conclusion

The objective of the thesis has aimed at finding an alternative to grid water pumping by using a photovoltaic system. It is a fact that this technology already exists and has been used for that purpose. That being said, our solution is to implement a whole photovoltaic and water pumping system that can truthfully contribute to the development of a region in Rwanda. In particular, our solution scope is beyond a pure PVP solution. Indeed, it extends to the analysis of the most suitable area and crop to make a difference in the inhabitants.

Gathering climate data and water resources has been key to understand where this system can most likely be useful. The research showed a country with large solar radiation and low rain-fed, especially in the Eastern Province. Thus, the suitability of using renewable energies to produce electricity to pump water proved to be feasible. A further analysis was conducted to determine the monthly water need for a group of crops. The thesis has also taken into account the irrigation system by providing a simple but effective layout. Hence, the minimum pressure required in the system to distribute water has been calculated as well.

Solar energy power systems cannot provide a continuous supply of electricity without an intermedium storage, being a serious inconvenient in case of necessity of water in a cloud cover day. Hence, a water tank has also been added to the system instead of a costly battery. In order to ensure the supply, the energy needed to convey water from the source to the tank has been calculated. After introducing this input in RETscreen, it has been possible to dimension both the photovoltaic and pumping system. First, choosing an AC pump for simplicity and long-life. As a consequence, an inverter has been selected to convert the DC current of the PV panels to AC, to power the pump. Finally, considering the large offer of PV panels in the market, we chose a Poly-Si type due to its high performance-cost ratio. Indeed, the performance is about 15 %, which is quite high regarding photovoltaic panels.

The obtained solution can be exported to other environments and locations only if the yearly solar irradiance and the sun hours are similar. Moreover, the water resource should also be close to the field irrigated. Besides, the solution can be scaled to supply water to a larger field, by increasing the power of the photovoltaics and the pump. Thus, the targeted amount of water to irrigate more than one hectare could have provided.

The results of the renewable system have shown that, although the initial capital investment is higher, it is much more economical throughout the lifetime than the grid connection. Thus, the levelized cost of energy of the photovoltaic system is 0,14 €/kWh in front of 0,21 €/kWh plus 0,41 € per kWh and km.

Finally, having proposed a PVP system that irrigates a hectare of field in Rwanda, further steps might be done so as to complement this solution:

- An exhaustive study of the irrigation layout, including all the fittings and valves needed for proper work.

- Analyse how to manage irrigation throughout the day and evaluate the use of an automatic system.

- Propose a suitable O & M scheme for both the PVP and the irrigation system to guarantee the supply and a long-life performance.

- Develop an entire financial and business model, taking into account all the elements that configure the system and analysing the economic situation in Rwanda as well.

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BUGESERA									
Month	**Min T [ºC]**	**Max T [ºC]**	**Humidity [%]**	**Wind [km/day]**	**Sun [hours]**	**Precipitation [mm/month]**	**Irradiance [kWh/m2_day]**	**Effective Precipitation [mm/month]**	**ETo [mm/day]**
Jan	14,70	28,60	75,00	193,54	5,89	118,73	5,89	71,00	4,01
Feb	15,30	30,80	70,90	199,58	5,81	96,88	5,81	53,50	4,50
Mar	16,10	28,90	78,40	189,22	5,53	142,29	5,53	89,80	3,99
Apr	15,80	27,70	77,70	204,77	4,80	150,90	4,80	96,70	3,61
May	16,10	31,60	59,40	260,06	4,48	87,11	4,48	45,70	4,87
June	16,20	34,40	47,90	298,08	4,67	29,10	4,67	7,50	6,08
July	16,00	36,00	44,30	285,12	5,09	24,18	5,09	4,50	6,50
Aug	17,30	38,10	43,70	273,89	5,25	41,23	5,25	14,70	6,92
Sept	17,60	37,60	48,00	232,42	5,50	60,60	5,50	26,40	6,50
Oct	16,50	31,10	68,50	197,86	5,63	97,65	5,63	54,10	4,67
Nov	15,50	27,00	81,00	183,17	5,27	129,60	5,27	79,70	3,59
Dec	15,10	27,00	80,00	167,62	5,49	131,75	5,49	81,40	3,53
MEAN	**16,02**	**31,57**	**64,57**	**223,78**	**5,28**	**92,50**	**5,28**	**52,08**	**4,90**

NYAGATARE									
Month	**Min T [ºC]**	**Max T [ºC]**	**Humidity [%]**	**Wind [km/day]**	**Sun [hours]**	**Precipitation [mm/month]**	**Irradiance [kWh/m2_day]**	**Effective Precipitation [mm/month]**	**ETo [mm/day]**
Jan	14,50	29,00	72,40	196,13	5,83	106,95	5,83	61,60	4,11
Feb	15,20	31,20	68,30	203,04	5,78	89,04	5,78	47,20	4,66
Mar	16,00	29,30	77,30	187,49	5,49	143,22	5,49	90,60	4,06
Apr	15,90	27,50	79,30	189,22	4,80	168,30	4,80	110,60	3,54
May	15,60	30,10	64,60	225,50	4,49	110,05	4,49	64,00	4,24
June	15,80	33,00	51,30	265,25	4,72	41,40	4,72	14,80	5,44
July	16,10	35,00	46,50	245,38	5,05	35,34	5,05	11,20	5,82
Aug	17,10	36,40	48,30	235,01	5,03	58,90	5,03	25,30	6,05
Sept	16,90	34,70	57,30	203,90	5,33	81,00	5,33	40,80	5,45
Oct	16,20	29,00	75,80	180,58	5,40	118,42	5,40	70,70	4,05
Nov	15,50	26,60	82,20	171,07	5,30	136,50	5,30	85,20	3,46
Dec	14,90	27,00	79,20	161,57	5,48	123,07	5,48	74,40	3,51
MEAN	**15,81**	**30,73**	**66,88**	**205,34**	**5,23**	**101,02**	**5,23**	**58,03**	**4,53**

NGOMA									
Month	**Min T [ºC]**	**Max T [ºC]**	**Humidity [%]**	**Wind [km/day]**	**Sun [hours]**	**Precipitation [mm/month]**	**Irradiance [kWh/m2_day]**	**Effective Precipitation [mm/month]**	**ETo [mm/day]**
Jan	14,80	27,70	75,00	171,07	5,83	128,96	5,83	79,20	3,82
Feb	15,60	29,80	71,40	180,58	5,73	105,28	5,73	60,20	4,29
Mar	16,20	28,40	77,90	164,16	5,56	150,97	5,56	96,70	3,89
Apr	15,80	27,20	77,60	176,26	4,62	154,80	4,62	99,80	3,45
May	15,80	31,00	58,50	223,78	4,19	94,55	4,19	51,70	4,50
June	15,90	33,50	46,50	259,20	4,59	35,10	4,59	11,10	5,62
July	15,90	35,00	42,70	243,65	5,05	30,38	5,05	8,20	5,96
Aug	17,10	36,80	43,00	229,82	5,20	52,70	5,20	21,60	6,26
Sept	17,20	36,20	49,30	196,13	5,51	79,20	5,51	39,40	5,88
Oct	16,30	29,90	70,70	166,75	5,72	117,18	5,72	69,80	4,34
Nov	15,60	26,40	81,10	151,20	5,29	147,30	5,29	93,80	3,47
Dec	15,20	26,40	79,70	141,70	5,47	140,74	5,47	88,60	3,42
MEAN	**15,95**	**30,69**	**64,45**	**192,02**	**5,23**	**103,10**	**5,23**	**60,01**	**4,58**

KIREHE									
Month	**Min T [ºC]**	**Max T [ºC]**	**Humidity [%]**	**Wind [km/day]**	**Sun [hours]**	**Precipitation [mm/month]**	**Irradiance [kWh/m2_day]**	**Effective Precipitation [mm/month]**	**ETo [mm/day]**
Jan	14,80	27,70	75,00	171,07	5,38	128,96	5,38	79,20	3,76
Feb	15,60	29,80	71,40	180,58	5,44	105,28	5,44	60,20	4,23
Mar	16,20	28,40	77,90	164,16	5,30	150,97	5,30	96,70	3,83
Apr	15,80	27,20	77,60	176,26	4,62	154,80	4,62	99,80	3,45
May	15,80	31,00	58,50	223,78	4,47	94,55	4,47	51,70	4,54
June	15,90	33,50	46,50	259,20	4,65	35,10	4,65	11,10	5,62
July	15,90	35,00	42,70	243,65	5,02	30,38	5,02	8,20	5,93
Aug	17,10	36,80	43,00	229,82	5,11	52,70	5,11	21,60	6,23
Sept	17,20	36,20	49,30	196,13	5,25	79,20	5,25	39,40	5,84
Oct	16,30	29,90	70,70	166,75	5,30	117,18	5,30	69,80	4,26
Nov	15,60	26,40	81,10	151,20	4,84	147,30	4,84	93,80	3,38
Dec	15,20	26,40	79,70	141,70	4,88	140,74	4,88	88,60	3,32
MEAN	**15,95**	**30,69**	**64,45**	**192,02**	**5,02**	**103,10**	**5,02**	**60,01**	**4,53**

KAYONZA									
Month	**Min T [ºC]**	**Max T [ºC]**	**Humidity [%]**	**Wind [km/day]**	**Sun [hours]**	**Precipitation [mm/month]**	**Irradiance [kWh/m2_day]**	**Effective Precipitation [mm/month]**	**ETo [mm/day]**
Jan	14,50	29,00	72,40	196,13	5,55	106,95	5,55	61,60	4,08
Feb	15,20	31,20	68,30	203,04	5,50	89,04	5,50	47,20	4,60
Mar	16,00	29,30	77,30	187,49	5,30	143,22	5,30	90,60	4,02
Apr	15,90	27,50	79,30	189,22	4,59	168,30	4,59	110,60	3,50
May	15,60	30,10	64,60	225,50	4,27	110,05	4,27	64,00	4,20
June	15,80	33,00	51,30	265,25	4,52	41,40	4,52	14,80	5,41
July	16,10	35,00	46,50	245,38	4,92	35,34	4,92	11,20	5,78
Aug	17,10	36,40	48,30	235,01	4,91	58,90	4,91	25,30	6,02
Sept	16,90	34,70	57,30	203,90	5,05	81,00	5,05	40,80	5,41
Oct	16,20	29,00	75,80	180,58	5,27	118,42	5,27	70,70	4,03
Nov	15,50	26,60	82,20	171,07	4,90	136,50	4,90	85,20	3,39
Dec	14,90	27,00	79,20	161,57	4,97	123,07	4,97	74,40	3,42
MEAN	**15,81**	**30,73**	**66,88**	**205,34**	**4,98**	**101,02**	**4,98**	**58,03**	**4,49**

GATSIBO									
Month	**Min T [ºC]**	**Max T [ºC]**	**Humidity [%]**	**Wind [km/day]**	**Sun [hours]**	**Precipitation [mm/month]**	**Irradiance [kWh/m2_day]**	**Effective Precipitation [mm/month]**	**ETo [mm/day]**
Jan	14,50	29,00	72,40	196,13	5,61	106,95	5,61	61,60	4,09
Feb	15,20	31,20	68,30	203,04	5,65	89,04	5,65	47,20	4,64
Mar	16,00	29,30	77,30	187,49	5,36	143,22	5,36	90,60	4,04
Apr	15,90	27,50	79,30	189,22	4,71	168,30	4,71	110,60	3,52
May	15,60	30,10	64,60	225,50	4,40	110,05	4,40	64,00	4,21
June	15,80	33,00	51,30	265,25	4,66	41,40	4,66	14,80	5,43
July	16,10	35,00	46,50	245,38	4,97	35,34	4,97	11,20	5,79
Aug	17,10	36,40	48,30	235,01	5,02	58,90	5,02	25,30	6,04
Sept	16,90	34,70	57,30	203,90	5,16	81,00	5,16	40,80	5,43
Oct	16,20	29,00	75,80	180,58	5,33	118,42	5,33	70,70	4,03
Nov	15,50	26,60	82,20	171,07	5,05	136,50	5,05	85,20	3,43
Dec	14,90	27,00	79,20	161,57	5,25	123,07	5,25	74,40	3,48
MEAN	**15,81**	**30,73**	**66,88**	**205,34**	**5,10**	**101,02**	**5,10**	**58,03**	**4,51**

RWAMAGANA									
Month	**Min T [ºC]**	**Max T [ºC]**	**Humidity [%]**	**Wind [km/day]**	**Sun [hours]**	**Precipitation [mm/month]**	**Irradiance [kWh/m2_day]**	**Effective Precipitation [mm/month]**	**ETo [mm/day]**
Jan	14,50	29,00	72,40	196,13	5,64	106,95	5,64	61,60	4,10
Feb	15,20	31,20	68,30	203,04	5,61	89,04	5,61	47,20	4,63
Mar	16,00	29,30	77,30	187,49	5,39	143,22	5,39	90,60	4,04
Apr	15,90	27,50	79,30	189,22	4,67	168,30	4,67	110,60	3,51
May	15,60	30,10	64,60	225,50	4,38	110,05	4,38	64,00	4,20
June	15,80	33,00	51,30	265,25	4,68	41,40	4,68	14,80	5,42
July	16,10	35,00	46,50	245,38	5,05	35,34	5,05	11,20	5,79
Aug	17,10	36,40	48,30	235,01	5,03	58,90	5,03	25,30	6,03
Sept	16,90	34,70	57,30	203,90	5,15	81,00	5,15	40,80	5,42
Oct	16,20	29,00	75,80	180,58	5,30	118,42	5,30	70,70	4,04
Nov	15,50	26,60	82,20	171,07	4,97	136,50	4,97	85,20	3,42
Dec	14,90	27,00	79,20	161,57	5,10	123,07	5,10	74,40	3,46
MEAN	**15,81**	**30,73**	**66,88**	**205,34**	**5,08**	**101,02**	**5,08**	**58,03**	**4,51**

Appendix B

To solve the Colebrook equation in Excel/VBA we used the VBA code derived from Clamond's MATLAB implementation.

http://thatcadguy.blogspot.no/2010/02/how-to-solve-colebrook-equation-in.html

The algorithm was extracted from the web-site above and it is the following:

"Function Colebrook (R As Double, K As Double) As Double

Dim X1 As Double, X2 As Double, F As Double, E As Double

*X1 = K * R * 0.123968186335418*

X2 = Log(R) - 0.779397488455682

F = X2 - 0.2

E = (Log(X1 + F) + F - X2) / (1 + X1 + F)

*F = F - (1 + X1 + F + 0.5 * E) * E * (X1 + F) / (1 + X1 + F + E * (1 + E / 3))*

E = (Log(X1 + F) + F - X2) / (1 + X1 + F)

*F = F - (1 + X1 + F + 0.5 * E) * E * (X1 + F) / (1 + X1 + F + E * (1 + E / 3))*

F = 1.15129254649702 / F

*Colebrook = F * F*

End Function"