UPPSALA UNIVERSITET

SLU

UPTEC W 19043
Examensarbete 30 hp
Augusti 2019

Water management for agriculture under a changing climate: case study of Nyagatare watershed in Rwanda

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Abstract

Water management for agriculture under a changing climate: case study of Nyagatare watershed in Rwanda

Madeleine Green

Sub-Saharan Africa is today facing a big challenge regarding food deficiency and water scarcity due to climate change. One of these countries is Rwanda, a small landlocked country in the middle of Africa. Rwanda strongly depend on agriculture, both in the aspect of reducing poverty and hunger but also because their economy security depend on it. Because of increasingly fluctuating rainfalls their agriculture becomes more dependent on irrigation and the availability to water resources.

To investigate how the climate change will affect the amount of water resources in the coming decades, this study is focusing on the watershed and marshland of Muvumba P8 in Nyagatare, Rwanda. A hydrological model was created, in a software called Soil and Water Assessment Tool (SWAT), with soil, land use and slope maps for the watershed. Calibrating the model was done with help of Climate Forecast System Reanalysis (CFSR) data and run for nine different climate model datasets. An uncertainty had to be taken into account regarding both the measured local data and the downloaded data. To be able to compare the amount of water resources and the irrigation requirements for the rice crop the farmers were growing on the marshland, the crop water requirements for rice was estimated with FAO's program called CROPWAT. The irrigation system on the marshland allows a double cropping of rice every year and consist of a system depending on elevation differences to create natural fall. There was three reservoirs along the marshland but to limit the project, only the first reservoir was taken into account. This was complemented with existing data and field survey.

Six out of nine climate models showed a decrease in median discharge over the coming 30 years compared to the CFSR historical median discharge. This means that less water in general will reach the outlet of the watershed in the years to come. At the same time all climate models indicate an increase in irrigation requirements for the rice crops. The seasons are probably going to change, a longer and drier season between June and August and a rainier season between September and November are projected.

Keywords: climate change, hydrological model, SWAT, CROPWAT, Nyagatare, Rwanda, marshland, watershed, climate model, irrigation, rice crop

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ISSN: 1401-5765, UPTEC W 19043

REFERAT

Hantering av vatten för jordbruk under ett förändrat klimat: en fallstudie på Nyagatares avrinningsområde i Rwanda

Madeleine Green

Subsahariska Afrika möter idag en stor utmaning när det gäller både mat- och vattenbrist på grund av klimatförändringar. Ett av dessa länder är Rwanda som är ett litet land i mitten av Afrika. Rwanda är beroende av sitt jordbruk, både i aspekten att minska fattigdom och svält, men också för att deras ekonomi huvudsakligen är beroende av jordbruk. På grund av ökande variationer i nederbörd blir jordbruket mer beroende av bevattning och tillgången av vattenresurser.

För att undersöka hur klimatförändringarna kommer påverka vattenresurserna de kommande åren, fokuserar den här studien på våtmarken Muvumba P8 i Nyagatare, Rwanda, med tillhörande avrinningsområde. En hydrologisk modell skapades, i en mjukvara kallad Soil and Water Assessment Tool (SWAT), med jord-, landanvändning- och sluttningskartor över avrinningsområdet. Till hjälp togs Climate Forecast System Reanalysis (CFSR) data för att kalibrera modellen och modellen kördes sedan för nio olika klimatmodellers dataset. En osäkerhet gällande både lokal uppmätt data och nerladdade data behövdes tas i beaktning. För att kunna jämföra vattentillgången med det bevattningsbehov som finns för de risgrödor som bönderna odlade på fälten så beräknades risgrödornas vattenbehov med hjälp av FAO's program kallad CROPWAT. Bevattningssystemet på våtmarken tillät skörd två gånger om året och bestod av ett system som skapade ett naturligt fall genom höjdskillnad. Det fanns tre reservoarer längs våtmarken, men för att avgränsa projektet så undersöktes bara den första reservoaren. Detta kompletterades med existerande data och fältundersökning.

Sex utav nio modeller visade en minskning i medianflöde för de kommande 30 åren jämfört med CFSR historiska medianflöde. Detta innebär att under de kommande åren kommer generellt sett mindre vatten nå utloppet av avrinningsområdet. Samtidigt indikerar alla klimatmodeller på ett ökat behov av bevattning. Säsongerna kommer också att ändras med en längre och torrare torrperiod mellan juni och augusti och en regnigare period mellan september och november.

Nyckelord: klimatförändring, hydrologisk modell, SWAT, CROPWAT, Nyagatare, Rwanda, våtmark, avrinningsområde, klimatmodell, bevattning, ris

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PREFACE

This master thesis covers 30 credits and is the final work for the Master's Programme in Environmental and Water Engineering at Uppsala University (UU) and Swedish University of Agricultural Sciences (SLU). The study has been conducted at the Department of Earth Sciences, SLU, and has included a Minor Field Study (MFS), supported by the Swedish International Development Cooperation Agency (SIDA). Supervisor has been Youen Grusson and academic supervisor Abraham Joel, both at the Department of Earth Sciences, SLU. Examiner has been Gabriele Messori at the Department of Earth Sciences, UU.

I would like to give a big thank you to Youen for all the support, help, tolerance and guidance during this project and to Abraham for all the help and patience, and for making this project possible. Further thanks to the staff and students at the University of Rwanda (UR), and especially to Prof. Sankaranarauanan for his hospitality and providing me with all the support I needed. A thanks to Mrs. Niyonkuru Rose for being my supervisor on site in Rwanda and a thanks to SIDA for financially supporting this project and being part of making this project possible.

Finally, I would like to thank my mum who has always been my biggest support. I would also like to thank my friends and family in Uppsala for helping me create such a wonderful study time. An extra thanks to my dear friend Ivana for always being there and listening to my ups and downs and to my travel buddy Emma, who has been just a phone call away whenever I needed it during this project.

Uppsala, June 2019

Madeleine Green

UPTEC W 19043, ISSN 1401-5765
Published digitally at the Department of Earth Sciences, Uppsala University, Uppsala, 2019

POPULÄRVETENSKAPLIG SAMMANFATTNING

Världen över har börjat påverkas av den klimatförändring som sker på jordklotet i form av extremväder, så som översvämningar, torka eller orkaner. Klimatförändringarna kan också påverka lokalt, genom att säsongerna förändras, så som kortare vintrar, blötare somrar eller längre och torrare torrperioder. Detta är något som påverkar kontinenten Afrika. I södra delen om öknen Sahara, finns idag ett stort problem gällande mat- och vattenbrist till en växande befolkning, vilket också kommer att påverkas av ett förändrat klimat. Därför är det viktigt att det finns ett hållbart jordbruk som kan förse befolkningen med mat. För att på ett hållbart sätt kunna förbereda sig på hur ett förändrat klimat kan påverka jordbruket är det lämpligt att göra studier om hur framtida klimat kan tänkas påverka vattentillgången. Detta görs genom hydrologiska modeller, vilket är modeller som beskriver vattentillstånd och flöden. Med hjälp av uppmätt historisk väderdata kan modellen kalibreras, det vill säga ställa in modellen så att resultatet från modellen matchar dagens klimat. För att sedan förutspå ett framtida klimat används så kallade klimatmodeller i den hydrologiska modellen. Det finns en mängd olika klimatmodeller som alla baseras på olika antaganden så som utsläpp, sociala och ekonomiska aspekter samt olika ekvationer, vilket gör att alla klimatmodeller ger olika resultat. Dessa klimatmodeller används sedan i den hydrologiska modellen för att ta reda på hur ett framtida klimat möjligen skulle kunna se ut baserat på dagens förhållanden. Eftersom det inte finns något rätt eller fel svar i hur klimatet kommer se ut i framtiden är det också svårt att säga vilka av modellerna som ger korrekt resultat.

Just detta, att beräkna vattentillgången i framtiden, gjordes på en våtmark i närheten av en by som heter Nyagatare i nordöstra Rwanda. På fältet odlar de lokala bönderna ris som de kan skörda två gånger per år. Detta kan de göra med hjälp av ett bevattningssystem som hämtar vattnet från en flod som rinner förbi våtmarken. Rwanda är ett kulligt och, relativt, till andra Afrikanska länder, litet land där klimatet är väldigt lokalt. Generellt över hela landet är dock att de har två regnsäsonger och två torrsäsonger. Denna studie tittar på hur vattentillgången i den flod som rinner förbi våtmarken kommer att se ut över de kommande 30 åren. För att ta reda på detta så skapas en hydrologisk modell över det avrinningsområde som mynnar ut vid en bevattningsdam i anslutning till våtmarken. Ett avrinningsområde är det landområde, inklusive sjöar och vattendrag, där allt vatten som finns eller kommer till avrinningsområdet, bland annat nederbörd, rinner ut till samma vattendrag. Avrinningsområdet avgränsas av topografin, så som berg och dalar. Nio olika klimatmodeller används och resultatet visar en generell minskning av vattentillgång i floden jämfört med historiska data som användes för att beräkna dagens vattentillgång. Resultatet visade också att säsongerna kommer ändras i avrinningsområdet, bland annat kommer torrsäsongen mellan juni och augusti bli längre och torrare medan regnsäsongen mellan september och november få mer nederbörd.

För att kunna avgöra om denna förändring i vattentillgången kommer påverka risodlingen som bönderna gör ute på våtmarken, så beräknas också behovet av vatten som ris kräver för att kunna växa ordentligt. Riset på våtmarken kräver relativt mycket vatten jämfört med andra växter då bönderna odlar så kallade paddyris, där riset står i vatten under största delen av odlingsperioden. Det visade sig att alla nio klimatmodeller gav ett ökat behov av bevattning ute på risfälten. Så tillsammans med en minskad vattentillgång och ett ökat bevattningsbehov är det viktigt att ta till vara på resurserna under rätt förhållanden.

I bevattningssystemet finns tre reservoarer, det vill säga som tre stora dammar, som är till för att samla in vatten för att sedan kunna användas när det finns brist på vatten i floden. Projektet begränsades till att bara se till den första dammen.

ACRONYMES

CFSR: Climate Forecast System Reanalysis

CWR: Crop water requirements

DBS: Distribution-based scaling

DEM: Digital elevation model

ECDF: Empirical cumulative distribution function

ET: Evapotranspiration

ET_c: Crop evapotranspiration under standard conditions

ET_o: Potential evapotranspiration from a reference crop

FAO: Food and Agriculture Organization of the United Nations

GCM: General Circulation Model/Global Climate Model

GIS: Geographic Information System

HRU: Hydrologic response units

HWSD: Harmonized World Soil Database

IPCC: Intergovernmental Panel on Climate Change

K-S test: Kolmogorov-Smirnov test

MP8RGCO: Muvumba P8 Rice Grow Cooperative

RAB: Rwanda Agriculture Board

RCP: Representative concentration pathways

RCM: Regional Climate Model

RCMRD: Regional Centre for Mapping of Resources for Development

RSSP: Rural Sector Support Project

SCS: Soil Conservation Service

SPAW: Soil-Plant-Air-Water

SWAT: Soil and Water Assessment Tool

TAW: Total available water

UR: University of Rwanda

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1. INTRODUCTION

Today's sub-Saharan Africa (countries below the Saharan desert) is facing a big challenge regarding large food deficiency and water scarcity due to a number of factors such as increased water withdrawals and change in climate (Rockström, et al., 2003). The population in the sub-Saharan region is estimated to double by year 2050 which will need an increase of food production. Over 60 % of the sub-Saharan population depends on rain-based rural economies, which also stands for 30-40 % of the countries' gross domestic product (GDP) (Rockström & Falkenmark, 2015) (Rockström, et al., 2003).

One of the countries in the sub-Saharan region is Rwanda, which is a landlocked country placed in the middle of the African continent, just below the equator and has a tropical climate (Ministry of Natural Resources, 2011) (REMA, 2011). Compared to other African countries has Rwanda a relatively small land area (26 338 km^2). Despite the small surface has the country a large variety in topography (Ministry of Natural Resources, 2011). Even though Rwanda is a country endowed with abundant surface water resources such as lakes, marshlands and rivers (REMA, 2011), is it a water stressed country due to its high population. Rwanda is facing problems with increasing water demands and at the same time struggling with declining water quality and quantity. In the agriculture sector the struggle is mainly due to the lack of efficiency in water use. Climate change increase uncertainty through a potential increase of extreme events, like prolonged drought and shorter but more intense rain periods. Because of the increasingly fluctuating rainfalls the agriculture becomes more dependent on irrigation and the availability to water resources (Ministry of Natural Resources, 2011).

Vision 2020 is a document developed by the Office of the President of the Republic of Rwanda between the years 1998 and 1999 and describes the future of Rwanda's development and which goals the country wants to achieve by 2020. This document works as a framework for how the country should develop and expresses a vision of becoming a middle-income country in an equitable way. To be able to make the necessary long term transformations in Rwanda, six priority pillars are identified, where the fifth pillar is *Productive High Value and Market Oriented Agriculture*. The most critical issue for agriculture is not the land size but the inefficiency on the productivity and traditional farming which has to improve (Ministry of finance and economic planning, 2000) (Republic of Rwanda, 2012). Different documents were conducted to extend the country's development where for instance significant investments are planned to increase irrigated areas. Even though Rwanda is developing its economy, the main backbone for their sustained economic growth is the agriculture which provides high quality livelihoods and living standards for the population (Ministry of Agriculture and Animal resources, 2018).

Rice is one of the most important crop in the world. Around half of the world's population eat rice and is the most common food source for poor people in the world (Maclean, et al., 2002). The crop production of rice has been encouraged by the Rwandese government and that is why the farmers grow rice on the Muvumba wetlands in the Nyagatare region (north-East of the country), where an irrigation scheme has been developed to allow double cropping of rice every year. Until now this scheme has brought good result allowing a regional development by an increase of the life quality and incomes of the farmers (The World Bank, 2016). The wetlands are not used to their fullest potential and the question have been raised to expand the farmlands. However this region face a shortage of precipitation during some parts of the year, which has to be compensated by irrigating, at the driest periods, both day and night (RAB, 2016). A sustainable expansion of the farmland would then imply a more intensive use of water resources.

The focus of this study is to investigate the future evolution of water resources and water demands for the marshland in a context of changing climate. It is important to secure the access to water to get a high yield from the rice production since rice is a water demanding crop.

1.1. THE PROJECT OBJECTIVES AND RESEARCH QUESTIONS

Since Rwanda strongly depends on agriculture, for both aspect of reducing poverty and hunger, but also for the economic development of the country, is it very important that the agricultural production is sustainable. To improve the productivity on Muvumba marshland, irrigation systems have been installed to be able produce rice twice a year. However, rice require a lot of water which will become an issue if the water resources would decrease in the future. It is therefore important to know if the regional agricultural system is sustainable. This project will assess the future water availability, such as surface runoff, expected water flow and rain deficit, in the Nyagatare region and evaluate if the water resources will be sufficient to support the current agricultural practices.

This will be done by modelling the landscape and climate with the hydrological model SWAT and assess the irrigation requirements with a computer program called CROPWAT. The study will be complemented with collection of existing data and field survey.

To be able to achieve the objectives in this project, these research questions have been set:

- How will the water resources availability change in the future?
- Will the need for water change in the future due to changing irrigation requirements?
- Is the design of the irrigation scheme suitable for the area and is it working as intended?

2. SCIENTIFIC BACKGROUND

2.1. CLIMATE IN RWANDA

Climate change is suspected to affect Rwanda thus projections show increased temperatures, more intense rainfalls and prolonged dry seasons. It is believed that the eastern and south western parts of Rwanda will suffer from droughts and desertification (Netherlands Ministry of Foreign Affairs (MFA), 2015). Analysing precipitation trends has shown an increasing occurring of extremes over time where the rainy seasons have become shorter but more intense, mostly in the northern and western provinces. In the eastern region climate changes have been shown through tendency of decrease in rainfall over some years whereas some years suffers from an excess of precipitation (REMA, 2009). During the last decades Rwanda has already been confronted with either prolonged dry seasons or serious flooding and tendency of desertification, which all are suspected to be associated with climate change (Ministry of Lands, Environment, Forestry, Water and Mines, 2006). Depending on which climate model that is considered, the projection indicates either a drier or wetter future for Rwanda. In Tenge et al. (2013) four different downscaled global climate models were used with the SRA1B scenario. The A1B scenario assumes a fast economic growth, a population that peaks mid-century and a development of new technology. The models that are used are CNRM-CM3, ECHAM 5, MIROC 3.2 and CSIRO Mark 3. An average in annual precipitation models predict a change between -100 to +400 mm between the years 2000-2050. The report does not tell if the data from climate model have been bias corrected or not (Tenge, et al., 2013). Muhire et al (2016) are trying to quantify the projected change in mean precipitation and rainy days between 2015 and 2050 with scenario SRB1 assuming that Rwanda is a country characterized by high population growth, rapid changes in economic structures and improved environmental concern. The precipitation data were projected with four GCMs named BCM2.0, CSIRO-MK3.0, MPI-M-EH5 (or RCHAM 5-OM) and CNRM-CM3. No information regarding corrected data was given. The result shows a decline in mean precipitation on average but some parts of the country are going to get an increase whereas others are going to get a decline. The rainy seasons are also going to change, dependently on where you look in the country some places are going to increase number of days with rain whereas other places are going to have a decrease, see figure 1 (Muhire, et al., 2016). Both Tenge et al. (2013) and Muhire et al. (2016) have used the special report on emissions scenarios (SRES) from the Intergovernmental Panel on Climate Change (IPCC) that was published in 2000. Today, IPCC has replaced SRES with representative concentration pathways (RCP) models which has other scenarios.

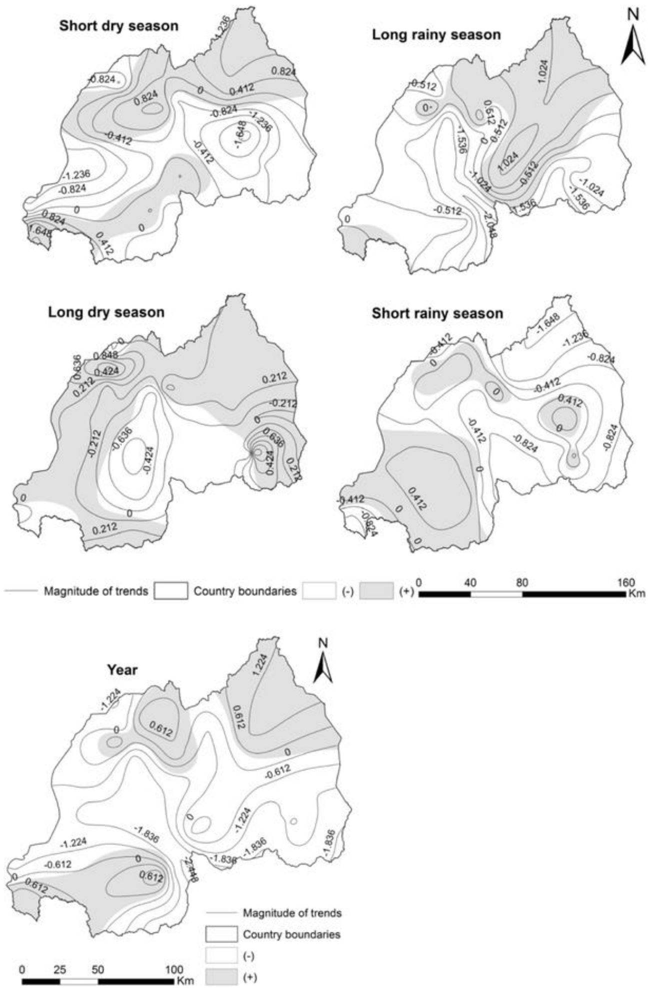

Figure 1. *The result from Muhire et al. (2016) shows the projected magnitude in mm and the changing trends of mean precipitation, increase (+) or decrease (-), between 2015 and 2050. Permission to use picture from Muhire.*

More recent studies made in Africa with RCP scenarios has been made by Tariku, T.B. & Gan, T.Y. (2018) in their report Regional climate change impact on extreme precipitation and temperature of the Nile river basin. They project future precipitation and temperature for the Nile river basin with the regional climate model called Weather research and forecasting (WRF). Four GCMs (CanESM2, ACCESS1-3, GFDL-ESM2M and MPI-ESM-LR) are used for two climate scenarios: RCP4.5 and RCP8.5 for 2050 and 2080. Quantile-based and linear scaling are used as bias-correction methods for the regional climate model simulation (Tariku & Gan, 2018).

Rwanda is very dependent on agriculture since around 31 % of the GDP in 2018 depends on the agriculture (Mundi, 2018). This makes Rwanda highly vulnerable to climate change. Statistics from 2004 places Rwanda as number one in terms of *natural resources dependency* among all African countries (Vincent, 2004). Natural resources dependency is one of the indicators for social vulnerability to climate change (Nabalamba, et al., 2011).

Weather data scarcity in Africa, and also Rwanda, is a general problem which creates a limitation when choosing a study area (Faniriantsoa, et al., 2018). The chosen marshland for the conducted study was selected due to previous studies made on the field by the University of Rwanda (UR), which also has a campus close by. However this created a problem with the belonging catchment that suffers from limited data, especially regarding past climate data which makes it difficult to create a hydrological model. However, SWAT has a global weather database, using data from the Climate Forecast System Reanalysis (CFSR), which can be used in the hydrological model. The CFSR data are spatially interpolated based on real measurements. In the study of Dile & Srinivasan (2014) the assessment of the applicability with CFSR climate data, by modelling the hydrology of the Upper Blue Nile basin, is done. They compare with a simulation from conventional station and the results showed that the conventional weather station performed satisfactory for three gauging stations whereas the CFSR performed satisfactory for two. The conclusion was that in data-scarce regions the CFSR weather could be useful when doing a hydrological prediction where conventional gauges are not available. Worqlul et al. (2017) evaluates the CFSRs advantages and limitations in hydrological models in comparison to sparsely network of rain gauges, also in the Upper Blue Nile basin. CFSR slightly over predicted the rainfall pattern but were able to reproduce the streamflow well (Worqlul, et al., 2017). To project future water assessment, SWAT (for description see 3.4.1.) has been used in multiple studies regarding catchments in Africa. For instance Näschen et al. (2018) made a study about the impact of the developments on catchment-wetland water resources using SWAT. The studied area is characterized by data scarcity. The result shows that the wetland is dependent on the enclosed catchment, especially during dry season and sustainable management should therefore be taken into account. Ndomba et al. (2010) test the SWAT models applicability for a catchment of a natural wetland in Rwanda. According to the results, SWAT is potentially useful when studying the hydrology of natural wetland catchments where data is limited.

2.2. ASSES THE FUTURE NEED OF WATER

The need of irrigation can be computed via a modelling tool. CROPWAT model from the Food and Organization of the United Nations (FAO) (for description see 3.5.1.) is a common tool used in this purpose and several studies have already used it. In the research of Bouraima et al. (2015) they look at the need for irrigation for *Oryza sativa L.* (rice) in Benin’s sub-basin of Niger River in West Africa by using the FAO’s CROPWAT model. By using climatic data, crop and soil data for the area and the crop coefficient value the evapotranspiration from reference crop (ET_o), crop evapotranspiration (ET_c) and crop irrigation requirements were estimated. (Hossain, et al., 2017) uses CROPWAT as well to create an irrigation scheduling for rice in Bangladesh. Al-Najar (2011) discussed in his paper the need for irrigation were he, through CROPWAT, computed how much was needed and compared it with how much the farmers irrigate through their own experience. It turned out that the farmers used 30 % more water than needed. However this stud was not only conducted on rice but also for different types of crops in the Gaza Strip.

Studies have also been conducted with CROPWAT and climatic data to assess the future need of water. For example the study from Doria et al. (2006) tries to determine the impacts of potential climate change on daily and total crop water requirements using climate scenarios from Statistical Downscaling Model (SDSM) in CROPWAT. The result was showing an increase of crop water requirement for all scenarios even when the irrigation requirements decreased. In the study from Smith (2000), CROPWAT and climatic data are used to develop a practical criteria in planning and management of irrigated and rainfed production.

2.3. PRINCIPLES OF HYDROLOGY FOR AGRICULTURE

Evapotranspiration

Evapotranspiration is the total amount of water evaporating from the ground, surface water and from plants (through transpiration). The potential evapotranspiration from a reference crop (ET_o) is the evapotranspiration rate from a referent crop which is shortgrass. The crop evapotranspiration under standard conditions (ET_c) is the evapotranspiration for a specific crop under excellent agronomic and soil water conditions (Allen, et al., 1998).

Effective rainfall

The effective rainfall (P_{eff}) is the amount of water that effectively can be used by the crops. Some of the rain is lost through runoff and deep percolation. To know how much water that infiltrates the soil depends on the soil type, slope, crop canopy, storm intensity and initial soils water content. High effect of rainfall is when there are little or no runoff whereas a small amount of rainfall is less effective because most of it is lost due to evaporation (FAO, u.d.).

Crop coefficient

To determine the water requirement for a crop, the most easily way is to use the crop coefficient K_c-values. When determine the crop water requirement it is done by calculating the reference evapotranspiration loss from the cropped field because the water requirement is supposed to compensate for the water loss. The equation (see equation 1) for crop evapotranspiration under standard conditions is

$$ET_c = K_c \times ET_0 \qquad [1]$$

where ET_c is the crop evapotranspiration, K_c is the crop coefficient and ET_0 is the reference crop evapotranspiration. There are three different K_c-values for the different stages (figure 2) where you have $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ (Allen, et al., 1998).

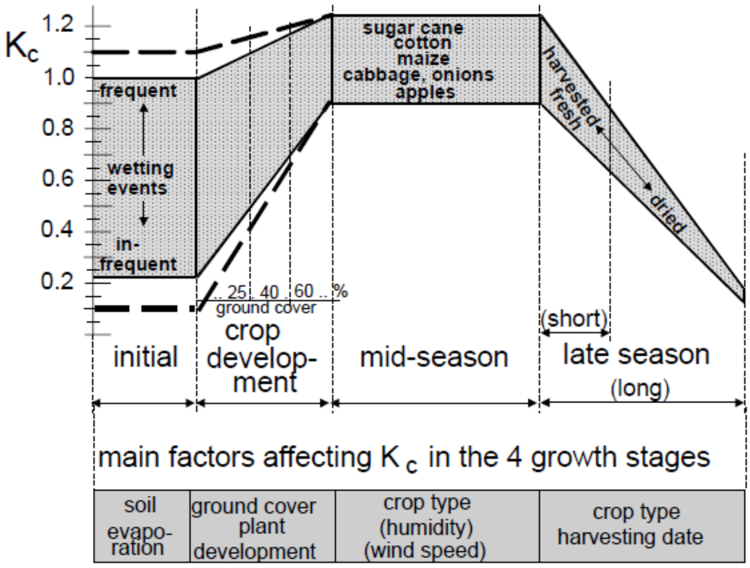

Figure 2. *The variation in K_c values for different crops. They are influenced by weather factors and crop development. Source: FAO Crop Evapotranspiration.*

The K_c-values for rice in the different stages is seen in table 1 based on values from FAO.

Table 1. The K_c-values for the different stages for rice from two different FAO-sources (CROPWAT and FAO paper no. 56). Values from FAO irrigation paper no. 56 is for non stressed, well-managed crops in sub-humid climates where the RH_{min} approximately is 45 % and wind speed around 2 m/s. For CROPWAT the values are found in the database (FAO, u.d.) (Allen, et al., 1998)

Source	**Initial**	**Mid-season**	**Late-season**
CROPWAT	1.10	1.20	1.05
No. 56	1.05	1.20	0.90-0.60

Stages of development

There are usually four growing stages for a crop which are related to the K_c-value. These are the initial stage, development stage, mid-season stage and late season stage. The initial stage is from the planting or transplanting stage to an approximately 10 % ground cover. How long the stage is depends on the type of rice, planting date and climate. In the development stage is the amount of days dependent on how long time it takes for the crop to go from 10 % covering of the ground to full cover. The mid-season stage is from full cover to start of maturity and the late-season stage is from maturity to harvest (FAO, u.d.).

Table 2. The amount of days in each stage according to FAO (Allen, et al., 1998)

	Initial	**Development**	**Mid-season**	**Late-season**	**Total**
Days	30	30	60	30	150

Yield response factor

The yield response factor (K_y) determines how well the response of yield to water supply is. It gives a relation between decrease in yield and relative evapotranspiration deficit. The deficit is expressed as a ratio between crop evapotranspiration under non-standard conditions ($ET_{c\ adj}$) and ET_c (FAO, u.d.). A K_y-value above 1 means that the crop response is very sensitive to water deficit whereas a value below 1 means that the crop has a higher tolerance to water deficit. Is the K_y-value equal to 1 is the yield reduction directly proportional to reduced water use (Steduto, et al., 2012). FAO's K_y values for rice at the different stages are seen in table 3. This are also the values that are used in the CROPWAT database.

Table 3. The yield response factor (K_y) for the different stages for rice (FAO, u.d.)

	Initial	**Development**	**Mid-season**	**Late season**	**Total**
K_y	1.00	1.09	1.32	0.50	1.10

Critical depletion fraction

The critical depletion fraction (p) represents at which critical soil moisture level the first drought stress occurs and which affects the crop evapotranspiration and production. It is expressed as a fraction of Total Available Water (TAW). TAW is the total amount of water available to the crop. Values for p are usually between 0.4 and 0.6, were the lower value are for sensitive crops and the higher for less sensitive crops. However lower values can be applied for more sensitive crops with limited rooting systems under conditions with high evaporation. Higher values can be applied for crops with deeper rooting systems and lower evaporation rates. The value of p varies depending on the crop and a numerical approximation to adjust the value of p depending on the crop evapotranspiration (ET_c) can be done according to equation 2.

$$p = p_{table\ 22} + 0.04(5 - ET_c) \qquad [2]$$

The value of $p_{table\ 22}$ is found in table 22 in FAO's Irrigation and drainage paper 56 (Allen, et al., 1998) and the function of value p in relation to evapotranspiration can be seen in figure 3 (FAO, u.d.).

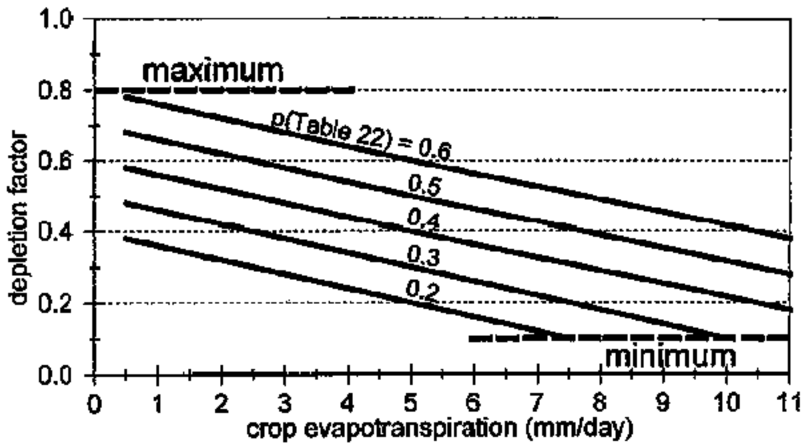

Figure 3. *The relation between p and ET_c where ET_c affects the value of fraction p. Source: CROPWAT/FAO.*

Gross and net irrigation

Gross irrigation is the amount of water that is applied on the field. However the water that does not reach the crop root zone are counted as water loss through seepage, leakage or evaporation. Thus the gross irrigation takes into account the amount of water needed to meet the water requirement for the crops and for the amount of water loss (FAO, u.d.) (FAO 1, 1997).

Net irrigation is the amount of water that beneficially is used by the crop, which means the necessary amount of water needed for the crop to grow (FAO, u.d.) (FAO 1, 1997).

Crop water requirement

To compensate for the loss due to evapotranspiration the crop water requirement (CWR) is defined. Under standard conditions the CWR and the ET_c are identical but the CWR refers to the amount of water that needs to be supplied whereas ET_c refers to the amount of water lost through evapotranspiration. To calculate the crop water requirements the crop coefficient is used (FAO, u.d.).

Definition for crop water requirements according to (FAO, 1992) is

> *the depth of water needed to meet the water loss through evapotranspiration (ET_c) of a disease-free crop, growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment.*

2.4. RICE CROP

The rice plant is highly adaptable to its environment and because of selections done by humans the rice plant can grow in many different places. The dominant rice species is

Oryza sativa which origin from Asia but can today be found in Asia, Africa, Europe, America and Oceania. *Indica rice* are mostly grown in tropical regions whereas *Japonica rice* are adapted to cooler areas. However all rice types can be grown in subtropical regions. Between 1 to 6 ton/ha is the average yield for rice production (Rockström, et al., 2003).

The temperature is important for the rice crop and therefore are extreme temperatures are destructive for the growth of the plant. The temperature should normally be between 20 ºC and 30 ºC, but this varies depending on which growth stage the rice crop is in. With irrigation the growth and yield is mostly determined by temperature and solar radiation whereas for rainfed rice culture the most critical limitation is rainfall, if the temperature is within the critical low and high ranges. It is hard to do a general water requirement of rice due to variety in topography, soil characteristics and growing period in different areas (Yoshida, 1981) (Rockström, et al., 2003).

Rice is a salt-sensitive crop compared to for example maize and wheat. It is not sensitive in all growing stages but the tolerance is not the same for the different stages which is what makes it sensitive. It is most sensitive during seeding and reproduction, but relatively tolerant during the other stages. The salt stress affects the crop through osmotic stress, salt toxicity and nutrient imbalances. For inland areas the source of the salinity can be salt deposits inherently present in the soil or bedrock. It can also be due to use of saline irrigation water (Bouman, et al., 2007).

3. MATERIALS AND METHOD

The methods in this report were based on secondary data, i.e. not collected from the author of this report, but collected for example from qualitative and quantitative data of government institutions, the UR and the FAO. It was based on observing the scenery and talking to local people too. The methodology to determine the future water assessment was to use a geographic information system (GIS) to prepare the digital elevation model file (DEM-file), land use map and soil map. The gross irrigation requirements were calculated to determine the amount of water needed on the rice fields.

3.1. SITE DESCRIPTION

Since Muvumba P8 covered a large area, approximately 1 750 ha, limitations were made by only looking at the first reservoir and the diversion dam. It was however difficult to collect data regarding the diversion dam, the reservoir or get information about the rice crops growing on the field.

3.1.1. Nyagatare district and Muvumba river catchment

The district of Nyagatare is located in the north-eastern corner of Rwanda. There are lack of water resources in the district due to the limitation of rivers and lakes. On the east side of the district flows the Akagera river at the border to Tanzania, the Kagitumba river flows in the north at the border to Uganda and the Muvumba river flows across the district. Those are the only perennial rivers in Nyagatare district which makes the river network a serious handicap for both people and animals. There are a lot of livestock in the area which alongside the crop production compete about the water (Ministère de Lagriculture et des Ressources Animales, 2008).

The catchment of Muvumba River belongs to the Nile basin and is trans-boundary between Rwanda and Uganda. The part of the catchment located in Rwanda is found in the north-eastern part of the country. The part of Muvumba river starting in Rwanda is located at an altitude of 2 030 m in the mountainous region in the central northern part of Rwanda whereas Muvumba river joins the Akagera river in the north-eastern corner of Rwanda at an altitude of 1 280 m (Water for Growth Rwanda, 2017).

The areas downstream Muvumba river have already been suffering from long periods of droughts and these water shortages can potentially get worse in the future. Increasing water demand due to population growth, climate change and macro-economic development. During 2016 an inspection was carried out to investigate the most important water users in the catchment, which were coffee washing stations, hydropower plants, water treatment plants, mineral extraction sites, dams, irrigation schemes, fishing farms and industries. Many water users were having their water source in the Muvumba river (Water for Growth Rwanda, 2017).

According to Rural Sector Support Project (RSSP), the Muvumbra river always provides the needed water for irrigation regardless season and if there is water deficiency it is due to losses of water through inadequate water distribution by farmers (Ramazani Bizimana (RSSP), personal communication, April 4, 2019).

3.1.2. The Muvumba perimeter 8 (P8)

According to an inventory in 2016 the Nyagatare district contains ten marshlands where four of them are used for agricultural production, whereas six are not developed. The developed marshland closest to Nyagatare, see figure 4, is called Muvumba P8 which stands for Muvumba perimeter 8 (RAB, 2016). Before they developed the marshland in Nyagatare, the area was covered with forest (Agronomist at MP8RGCO, personal communication, March 13, 2019). Muvumba P8 is limited by environmental aspects, soil and topography and the main area is about 1 660 ha and is restricted to be between the mountains in Piemonte and a forested area. The marshland stretches about 25 km along Muvumba river and has a width between 200 and 800 m. The forested area at one side of the marshland was excluded from the area that were going to be developed. Also slopes bigger than 0.3 % on the hillside have been classified as unappropriated for rice cropping and do not include in the development (Ministère de Lagriculture et des Ressources Animales, 2008).

Figure 4. *The location of Muvumba P8 in Nyagatare district. Source: Google maps 2019.*

The reason for the development of Muvumba River and marshlands is to increase the agricultural production due to the governments fight against poverty (CIMA+ International, 2012). On Muvumba P8 the farmers are growing rice, Japonica (*Oryza sativa japonica*) and Indica (*Oryza sativa*), with a double cropping every year. Both types are so called Paddy Rice (Edouard Cyubahiro (RAB), personal communication, March 13, 2019) which gives a yield approximately around 6 t/ha pro season which gives a total yield of 12 t/ha/year (S. K. Pande (UR), personal communication, March 13, 2019). The double cropping is split in two seasons where the first (season A) usually starts on 15th of July and ends around 15th of December and the second (season B) starts the 15th of January and ends around 15th of June. This means that the fields have a rest for one month between the seasons.

The marshlands are managed by the government who created a cooperative which controls the marshlands. Each plot on the farmland is leased by the farmers who pay a small amount to the cooperative for using the plot (T. Rutayisire (UR), personal communication, March 13, 2019).

Salinity is a known problem in the marshland, which has had the consequence that big areas of the marshland has to be abandoned for growing. About 2 ha each year is estimated to be lost due to salinity. That the area contained salt in the soil was known before the exploitation of the marshland (Agronomist at MP8RGCO, personal communication, March 13, 2019)(RAB, 2016).

3.1.3. Rainfall, climate and soil

Due to the variety in the topography both the climate and the rainfall varies in the country. The average rainfall in the country is 1 400 mm but the distribution is from about 2 000-1 500 mm in the mountains in north-west to around 700 mm in the south-eastern plains (REMA, 2011)(Ministry of Natural Resources, 2011). The district of Nyagatare has a relatively low precipitation rate compared to the rest of the country with an annual rainfall around 827 mm (RAB, 2016). Most of the precipitations occur during the two rainy seasons, a longer one between March and May and a shorter one between September and November. Between these rainy periods comes dry periods where the shorter is between December and February and a longer between June and August (REMA, 2009). The temperature varies from 15°C-30°C depending on the location, with the lower temperature in the west and the higher temperature in the east. In the volcano region the temperature can drop as low as 0°C in some areas (REMA, 2011).

Climate data for Muvumba P8 in Nyagatare

The climate data was collected from a weather station located in Nyagatare between 1954 and 2017. Due irregular measurements over the years the temperature, evaporation, humidity and rainfall were only used for 2010-2015. To see the distribution for the whole measured period, see appendix 8.2.2.

Maximum and minimum temperature

Figure 5 shows the variation of maximum and minimum temperature and the average daily temperature between 2010 and 2015. All the values in the plot were average values for every month each year based on daily values for every month. The boxplot shows the diversity of the temperatures for these six years whereas the line in the middle of the box shows the median value. The average temperature line was the average temperature of both maximum and minimum temperature.

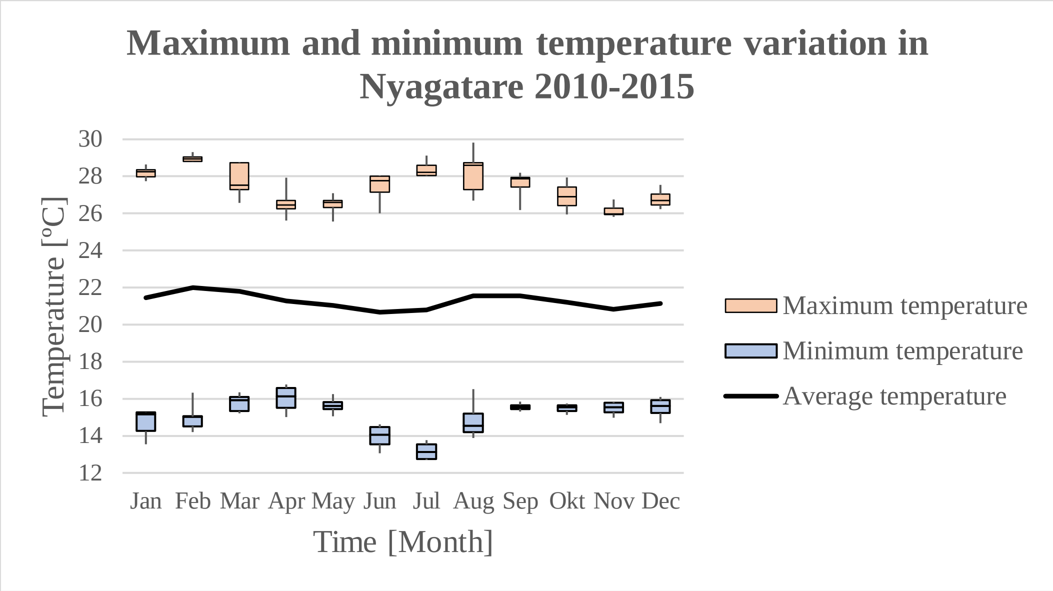

Figure 5. *The maximum and minimum temperature variation and an average daily temperature over the marshland in Nyagatare.*

Rainfall, evaporation and humidity

In figure 6 the rainfall, evaporation and humidity shows an average daily amount of water between the years 2010 and 2015 in Nyagatare. The rainfall was presented as boxplots showing the distribution of the daily rainfall every month over the chosen six years and a median value represented by the line in the box. Humidity and evaporation were presented as daily average values every month over the six years.

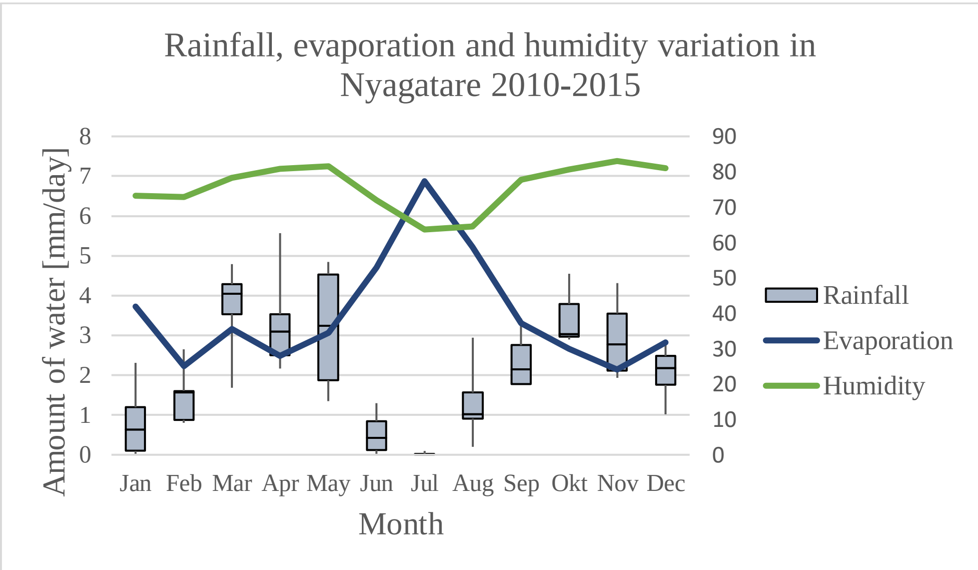

Figure 6. *Average daily rainfall, evaporation and humidity over the marshland in Nyagatare between 2010 and 2015.*

An average of the total amount of rainfall and evaporation for every month between 2010 and 2015 were made and compared in figure 7.

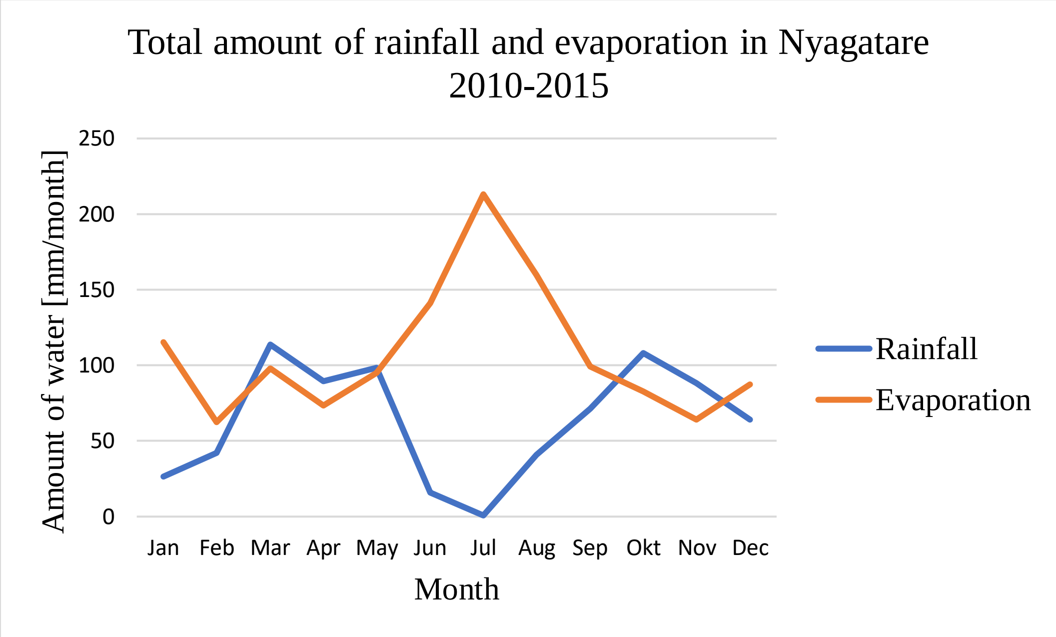

Figure 7. *Average total amount of rainfall and evaporation per month in Nyagatare between 2010 and 2015.*

Wind speed and sun hours

The average wind speed and sunshine hours (the duration of daylight without clouds) was measured at the climate station in Nyagatare, around 2-2.5 meter above ground on an altitude of 1 377 m between the years 2010 and 2017. They were presented in figure 8.

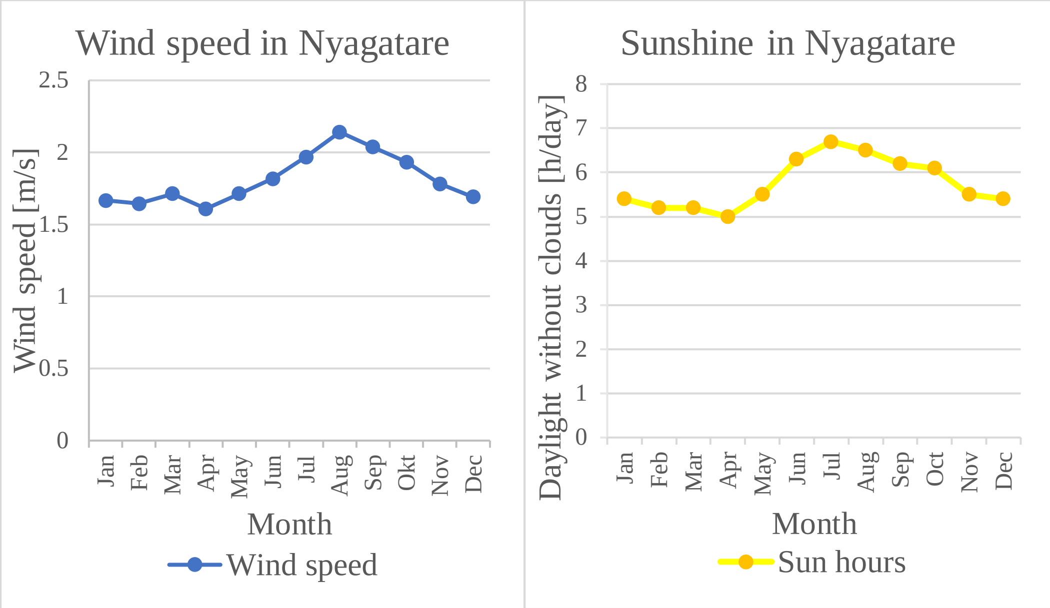

Figure 8. *Graphs over the average wind speed and sunshine hours in Nyagatare between the years 2010 and 2015.*

3.2. IRRIGATION SCHEME

The irrigation system of Muvumba P8 was developed by RSSP as one of the projects to develop sustainable wetlands in rural areas and was built in 2011 (CIMA+ International, 2012). To get a natural fall through the irrigation system the river was elevated by building a diversion dam that allowed water to both enter the distribution channel and continue flowing in Muvumba river (S. K. Pande (UR), personal communication, March 13, 2019). Regarding the diversion dam, and despite an intensive investigation with the local authorities, no historical data regarding the discharge could be found. However according to RSSP the discharge in March 2019 was around 16.6 m^3/s (Alfred Gasigwa (RSSP), personal communication, March 31, 2019). The distribution channel, or main channel, distributed the water from the river to the reservoirs and out on the marshland and was approximately 27 km long. The first 262 m of the diversion dam was covered in a stone masonry whilst the rest of the channel was an earthen channel. The channel had a trapezoidal cross section and the slopes were streamlined, which in this case meant they had a slope of 1:1. Except for the part that was covered in stone masonry which had the shape of a rectangular (CIMA+ International, 2012). The main channel was dimensioned for a discharge of 2.80 m^3/s (Ministère de Lagriculture et des Ressources Animales, 2008). There were three reservoirs along the marshland were each had an inlet and an outlet. The main channel continued around each reservoir so the water height in the channel was not dependent on the water level in the reservoirs (CIMA+ International, 2012). Before the channel reached the first reservoir, water could be extracted through a secondary channel and transport water through natural fall out onto the fields. To the secondary channel were tertiary channels connected which distributed the water on the fields, see figure 9. Farmers on the other side of the channel, i.e. not the side of the marshland, were using water from the channel through pumping up water and distributing it on their fields (field observation, March 13, 2019). The Muvumba P8 irrigation scheme covered 1 750 ha of marshland along the Muvumba River (Water for Growth Rwanda, 2017).

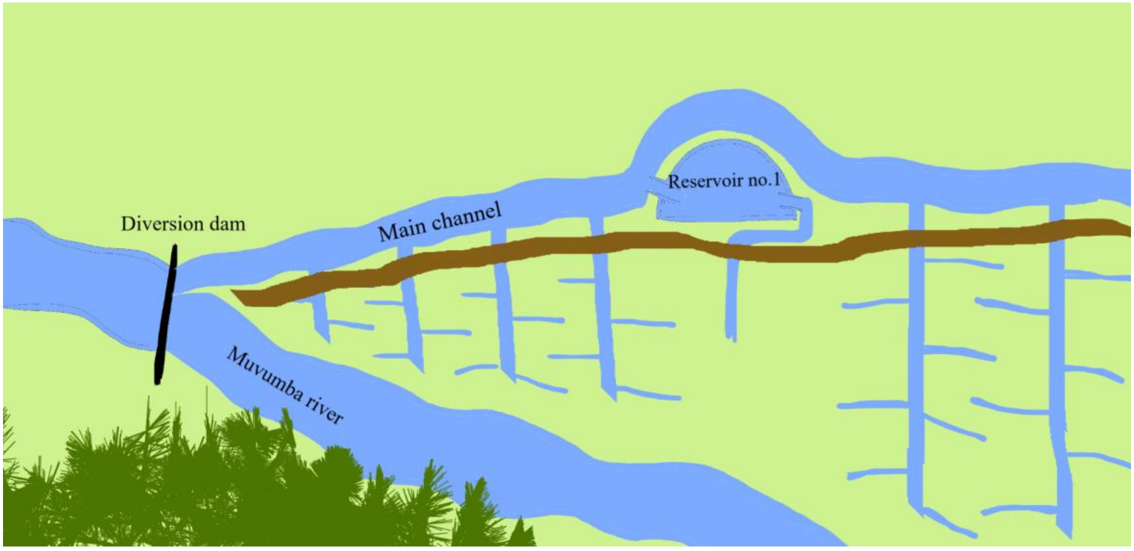

Figure 9. *A simplified layout of the irrigation system with the diversion dam, the main channel, the reservoir and the Muvumba river. The secondary and tertiary channels that leads the water out on the fields are presented in the figure. The brown line was the road going parallel with the main channel and the dark green area indicated the forest between Nyagatare and the marshland.*

Even though the construction was relatively new, built in 2011, and was designed for a lifespan of 50 years with a minimal maintenance (CIMA+ International, 2012). There was a real problem with sedimentation in the reservoirs and the channels (RAB, 2016). Reservoir two was not fit for using anymore since the outlet was built with a higher elevation than the dam and water could therefore not exit the reservoir (T. Rutayisire (UR), personal communication, March 13, 2019).

The first reservoir (reservoir no. 1) was located about 5 km from the diversion dam, see figure 10. According to the official report the reservoir had a capacity of 101 750 m^3 and a purpose to supply an irrigated area of 5 ha with water, which also the manager for the water users association said (Ministère de Lagriculture et des Ressources Animales, 2008) (Water users association manager, personal communication, March 20, 2019).. However according to RSSP the first reservoir was supposed to cover an area of 300 ha, the so called Tabagwe zone, and the reservoir had a capacity of around 40 000 m^3 of water (Alfred Gasigwa (RSSP), personal communication, March 31, 2019).

Figure 10. *Location of reservoir no. 1 in comparison of the diversion dam. Source: Google Maps 2019.*

3.2.1. Irrigation

Basin irrigation was used on Muvumba P8 which was a suitable method for paddy rice, which was grown on the fields. To obtain an even water level in the basins the slope should be relatively flat. Basins could also be built in a steeper slope but are then usually built as terraces, which looks like staircases. Paddy rice are best grown on clayey soils which allows a low loss of water through percolation. It can also be grown on sandy soils but then the percolation loss increases and requires more water to maintain a high water table. Depending on the wetting pattern and the management of the basins the crop growth can be affected. The right quantity of water must be supplied to the root zone and wetted uniformly. With too little water the crop can suffer from drought stress and with too much water losses can occur through deep percolation (Brouwer, et al., u.d.).

3.2.2. Yearly discharge at the outlet point

To get the discharge at the diversion dam in Muvumba river the median discharge value [m^3/s] collected from every model, were multiplied with 31 536 000 ($= 60 \times 60 \times 24 \times 365$) to get the discharge in [m^3/y]. This gave an approximately value on how much water were passing through at the outlet of the watershed in total every year.

3.3. PROJECTED CLIMATE DATA

To determine how the temperature of the earth were changing due to increased radiation, general circulation models, commonly known as global climate models (GCM), were used. The model describes physical processes happening on earth through mathematical models, such as the circulation of the atmosphere or ocean. The model simulated the earth climate dependent on the chosen representative concentration pathways (RCP) scenario. RCP are scenarios of how the greenhouse effect will intensify in the future. There are four RCPs which are labelled after the possible range of radiative forcing values in the year

2100 and they are called RCP2.6, RCP4.5, RCP6 and RCP8.5. In the GCM the resolution made it hard to study the climate on a regional scale and therefore were the result connected to a regional climate model (RCM) which had a higher resolution. The regional climate scenario was a combination of RCP, GCM and RCM. In this study the RCP8.5 was used and the RCM RCA4 had been used to scale down the GCM, the models can be seen in table 4 (Sjökvist, et al., 2015).

Table 4. The nine climate models used in this study (Sjökvist, et al., 2015)

Model	Institute	GCM	RCM
1	CCCma, Canada	CanESM2	SMHI RCA4
2	CSIRO-QCCCE, Australia	CSIRO-Mk3-6-0	SMHI RCA4
3	ICHEC, European consortium	EC-EARTH	SMHI RCA4
4	IPSL, France	IPSL-CM5A-MR	SMHI RCA4
5	MIROC, Japan	MIROC5	SMHI RCA4
6	MOHC, Great Britain	HadGEM2-ES	SMHI RCA4
7	MPI, German	MPI-EMS-LR	SMHI RCA4
8	NCC, Norway	NorESM1-M	SMHI RCA4
9	GFDL, United states	GDFL-ESM2M	SMHI RCA4

To make a suitable hydrological climate change impact assessment the distribution-based scaling (DBS) was a tool that was used for bias correction of climate model results. The RCM data had to be post-processed because it contained systematically errors, so called bias. Such errors could be seen as overestimated temperatures during winter or to long dry season etc. In DBS, a specific variable (for example precipitation) were fitting the observed and simulated values to a suitable theoretical frequency distribution (for example it could be the Gaussian distribution). The simulated distribution could be mapped to the observed distribution and, by assuming it was valid also in the future, the correction of simulated future climate projections could be made. Changes made to both mean values and variability estimated by the climate model would be preserved in the bias-corrected data (SMHI, 2017). The climate dataset used in this study came from the Swedish meteorological and hydrological institute (SMHI) and is the first ever regionalized bias corrected dataset for Africa.

3.4. ASSESSMENT OF SURFACE RUNOFF

3.4.1. Soil and Water Assessment Tool (SWAT)

The Soil and Water Assessment Tool (SWAT) is a river basin, or watershed, scale model developed to predict how different environmental changes impact hydrology over time. The model is a continuous time model which means that it is a long-term simulation model and not designed for single-events. SWAT model is physically based and requires specific information about weather, soil properties, topography, vegetation and land use within the simulated watershed.

The simulated watershed in SWAT is divided into subbasins based on topography. Within each subbasin the defined HRU (hydrological response unit) is based on topographic (slope), soil and land use properties.

Simulation of the hydrology in SWAT is divided in two parts. First part is land based and simulate the amount of water, sediment, nutrient and pesticides that reaches the main channel in each subbasin. In the second part, those same components are routed through the watersheds channel network from subbasin to subbasin until the outlet of the watershed (Neitsch, et al., 2011).

In the land phase of the hydrological cycle the model simulate it based on the water balance equation where the output is the result of the amount of water entering and exiting the system (equation 3).

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \qquad [3]$$

SW_t is the final soil water content [mm H_2O], SW_0 is the initial soil water content on day i [mm H_2O], t is the time [days], R_{day} is the amount of precipitation on day i [mm H_2O], Q_{surf} is the amount of surface runoff on day i [mm H_2O], E_a is the amount of evapotranspiration on day i [mm H_2O], w_{seep} is the amount of water entering the vadose zone from the soil profile on day i [mm H_2O] and Q_{qw} is the amount of return flow on day i [mm H_2O] (Neitsch, et al., 2011).

Evapotranspiration: Hargreaves Method

To estimate the potential evapotranspiration, SWAT had three options: Hargreaves, Priestley-Taylor and Penman-Monteith. For this report the Hargreaves equation would be used (equation 4) because of the simple input parameter, which were air temperature, due to limited data from the area. The equation used in SWAT is the one published in 1985.

$$\lambda E_o = 0.0023 \times H_0 \times (T_{mx} - T_{mn})^{0.5} \times (\bar{T}_{av} + 17.8) \qquad [4]$$

λ is the latent heat of vaporization [MJ/kg], E_o is the potential evapotranspiration [mm/d], H_0 is the extraterrestrial radiation [MJ/m^{2}d], T_{mx} is the maximum air temperature for a given day [ºC], T_{mn} is the minimum air temperature for a given day [ºC] and $\bar{T}_{av}$ is the mean temperature for a given day [ºC] (Neitsch, et al., 2011).

Run off: SCS curve number procedure

To calculate the runoff in SWAT, the model used two different types of models, the Soil Conservation Service (SCS) curve number procedure or Green & Ampt infiltration method. In this report the SCS curve number procedure will be used. It is an empirical model which is based on a rainfall-runoff relationship. The equation is based on a SCS curve number which is a function of the soil's permeability, land use and former soil water conditions. In SWAT the curve number default setting is appropriate for a 5 % slope (Neitsch, et al., 2011).

3.4.2. SWAT input data

DEM-file

A digital elevation model (DEM) is a representation of the surface, for example the earth, and are created from the terrain's elevation data. To create the DEM-file the data was downloaded from SRTM Data (http://srtm.csi.cgiar.org/download) with a *Tile Size* of 5x5 degree and in *Geo TIFF* format (georeferenced images in 16 bit TIF format). Because the area for the watershed was between two raster-files, two files had to be downloaded. The two files were merged by using *Mosaic to new raster* in the ArcToolbox (figure 11).

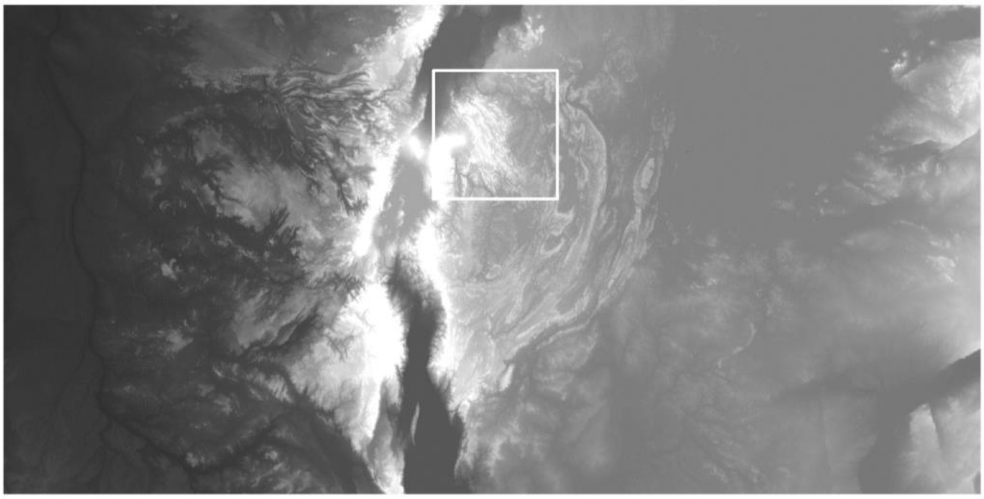

Figure 11. *Two raster files merged to create one DEM-file. The square area showing the extracted area that would be used in the model. Source: SRTM Data.*

Polygon-files for the country borders was downloaded, the TM_WORLD_BORDERS-0.3.zip file was chosen (http://thematicmapping.org/downloads/world_borders.php).

Soil data for SWAT

The FAO/UNESCO Soil Map of the World at a 1:5 000 000 scale for Africa (FAO & UNESCO, u.d.) was used for the soil data. Since the FAO/UNESCO Soil Map of the World was published between 1974 and 1978 the assumption was made that the FAO74 classification system was used for the soil profile information. A limited area of the whole map (see figure 12) was used where only data for the relevant soil was produced (table 5). The dominant soil was used to determine which data to use for each soil type.

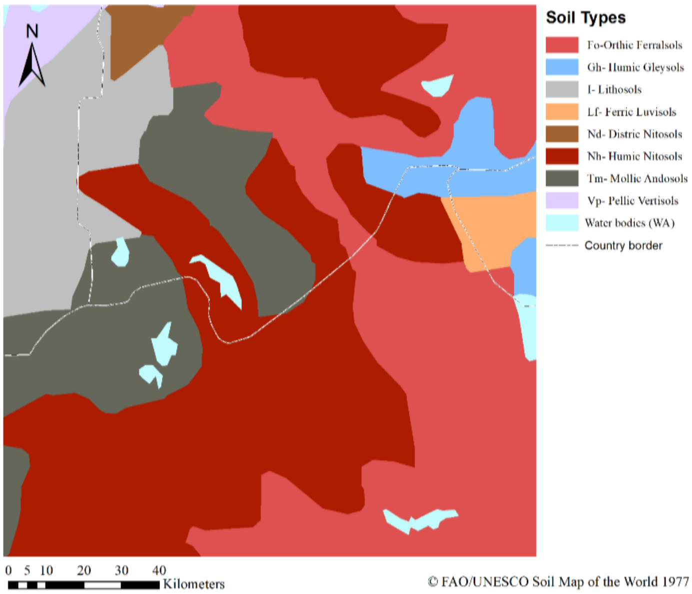

Figure 12. *The soil map used to limit the soil types. Source: FAO/UNESCO Soil Map of the World 1977.*

Table 5. Description of the soil for the chosen area. Italic marked soil were the soils not used by SWAT due to the watersheds boundaries

FAOSOIL	DOMSOIL (dominant soil)	Soil Units in the Legend (FAO74)
Fo97-3b	Fo	Orthic Ferralsols
Gh7-2a	*Gh*	*Humic Gleysols*
I-c	*I*	*Lithosols*
Lf80-2bc	*Lf*	*Ferric Luvisols*
Nd13-3bc	*Nd*	*Dystric Nitosols*
Nh7-2/3c, Nh5-2/3c, Nh2-2c	Nh	Humic Nitosols
Tm9-2c, Tm10-2bc	Tm	Mollic Andosols
Vp46-3a	*Vp*	*Pellic Vertisols*

To manually insert data for different soil types in SWAT-database there were some parameters that were mandatory, whereas some were not. The mandatory parameters were described in table 6.

Table 6. Variables that were required for SWAT were # is the number of layer (SWAT, 2012)

Variable name	Definition	Unit
SOL_ZMX	Maximum rooting depth of soil profile	mm
SOL_Z(layer #)	Depth from soil surface to bottom of layer	mm
SOL_BD(layer #)	Moist bulk density	Mg/m^3 or g/cm^3
SOL_AWC(layer #)	Available water capacity of the soil layer	mm H_2O/mm soil
SOL_K(layer #)	Saturated hydraulic conductivity	mm/hr
SOL_CBN(layer #)	Organic carbon content	% soil weight
CLAY(layer #)	Clay content	% soil weight
SILT(layer #)	Silt content	% soil weight
SAND(layer #)	Sand content	% soil weight
ROCK(layer #)	Rock fragment content	% total weight
SOL_ALB(layer #)	Moist soil albedo	-
USLE_K(layer #)	USLE equation soil erodibility (K) factor	0.013×(ton m^2 hr)/(m^3 ton cm)

Most of the values for the variables was either collected from data files that came along with the FAO/UNESCO Soil Map of the World or from the Harmonized World Soil Database (HWSD), which combines existing regional and national updated soil map information over the world with the information in the FAO/UNESCO Soil Map of the World. The data taken from HWSD was collected for FAO74 because it would match the chosen maps legend. Values for SOL_Z, SOL_BD, SOL_CBN, CLAY, SILT and SAND was collected from enclosed data to the FAO/UNESCO Soil Map of the World. USLE_K and SOL_K was calculated, SOL_ZMX and SOL_ALB had different sources and SOL_AWC and ROCK was collected from the HWSD.

The saturated hydraulic conductivity (SOL_K) was calculated by a hydrological model called SPAW (Soil-Plant-Air-Water). It contained a program called *Soil Water Characteristics* and was used to simulate soil water tension, conductivity and water holding capacity. It was valid for all textures except for soils with a clay content exceeding 60 % and organic matter higher than 8 % (Saxton & Rawls, u.d.). Saxton et al. 2006 was used to calculate the saturated hydraulic conductivity. A parameter that needed to be calculated in order to use SPAW was organic matter, for equations see appendix 8.1.

The organic matter content was calculated and the results could be seen in table 7. Only the relevant soil types were described in table 7, based on table 5.

Table 7. The organic matter content calculated from the organic carbon content for both layers

Soil	Organic Carbon Content Topsoil [%]	Organic Matter Content Topsoil [%]	Organic Carbon Content Subsoil [%]	Organic Matter Content Subsoil [%]
Fo	1.92	3.3	0.67	1.15
Nh	4.04	6.95	1.47	2.53
Tm	3.95	6.79	1.93	3.32

When values for sand, clay, organic matter and gravel was inserted, the SPAW model produced an estimated value for saturated hydraulic conductivity. Salinity and compaction was unknown for all soil types and was therefore set to 0 dS/m respectively 1 (normal) as default values. Figure 13 shows the layout of the model.

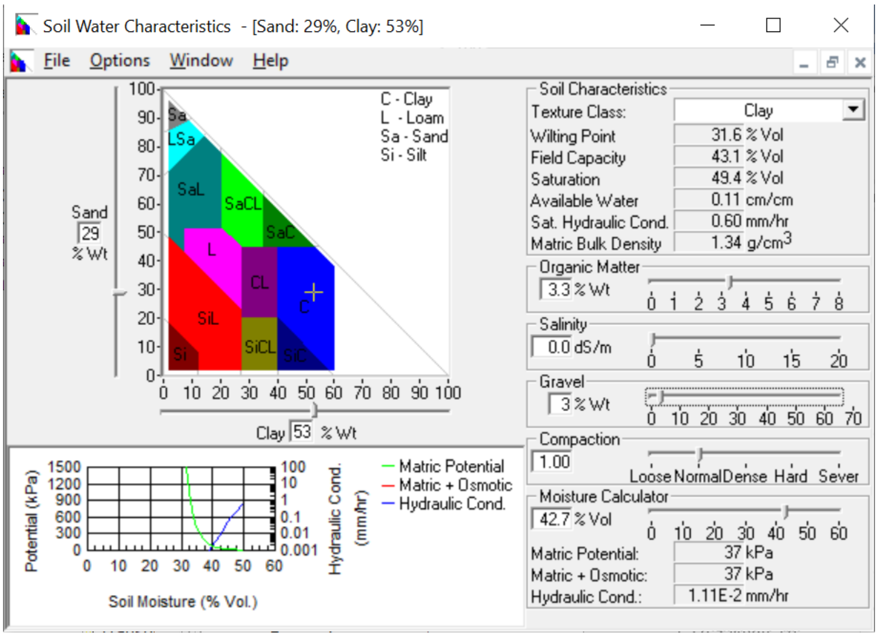

Figure 13. The Soil Water Characteristic program in SPAW (input values for Fo topsoil).

Because of the upper limits of clay, where it could not exceed 60 %, the saturated hydraulic conductivity for Nh could be misleading.

Land cover or land use

When talking about the use of the land, there is a distinction between land use and land cover. Land cover is the observed physical cover which is seen from the ground. This is for example vegetation (natural or planted), human construction (building, roads, etc.) or natural surfaces such as water, ice, bare rock or sand. Land use is for what purpose the land is being used. It can be defined as a series of activities to produce one or more services. One land use can take place on one or more pieces of land, one piece of land could also have several land uses occurring at the same time (FAO 2, 1997).

The data regarding the land use over the area was collected from Regional Centre for Mapping of Resources for Development (RCMRD) (http://geoportal.rcmrd.org/) where both maps for Rwanda and Uganda could be found. The map for Rwanda was from 2015 whereas the map for Uganda was from 2014. Regarding the land types the two maps differed from each other. For example had Rwanda fourteen different types whereas Uganda had seventeen, see figure 14. This became a problem when trying to merge the two maps and therefore had the maps to be reclassified.

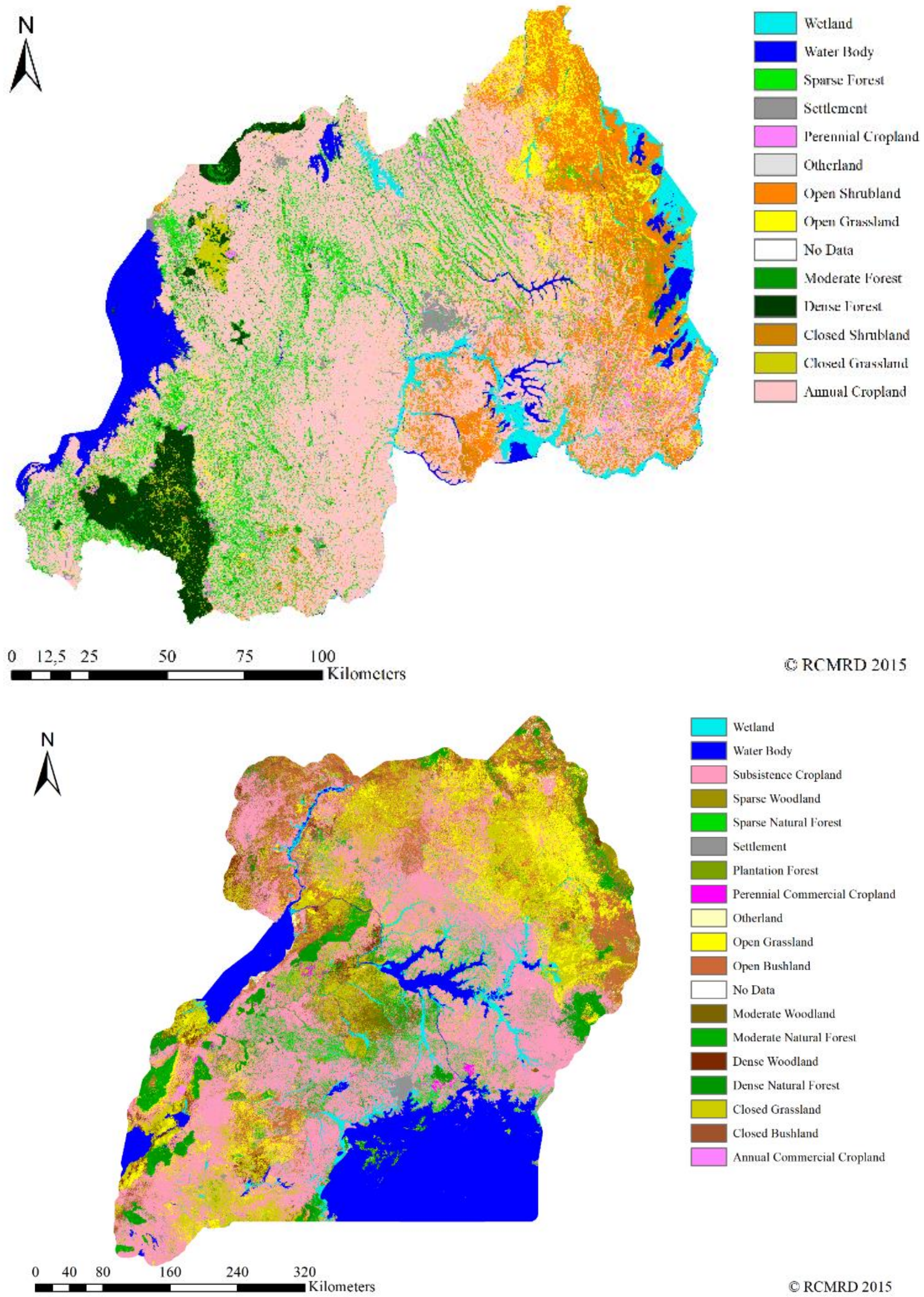

Figure 14. *Rwanda (top) and Uganda (bottom) land use map and their different land types. Source: RCMRD 2015.*

Because RCMRD did not specify the types of crop that was grown in the different types of croplands the classification for croplands would be based on FAO's report Land use map of Rwanda (FAO, 2010). For perennial crops (crops lasting years) belonged banana, coffee and tea plantation whereas for seasonal crops was herbaceous crops the main type. However there could be numerous crops fitting as an herbaceous crop such as maize, sorghum and soybeans. Annual cropland (one-year crops) was included in the seasonal cropland because the seasonal cropland had two cropping's each year which made the land used almost all year round.

Since there were no specifications for which type of land use there was in the maps for Rwanda and Uganda, the *Generic Land Cover* in SWAT database was used to reclassify the different land uses. FAOSTAT 2017 for Rwanda and Uganda showed that maize was the annual crop that matched the biggest harvested area in both countries (for data, see appendix 8.3**.**). Maize was therefore chosen as the general crop for the annual cropland and sweet corn was chosen as the maize type. Because there were fewer SWAT classes that matched the RCMRD classes, the amount of land use classes would be reduced. The new defined classes were: Wetlands-Non-Forested, Water, Agricultural Land-Generic, Bananas, Residential-Medium Density, Range-Grasses, Range-Brush, Forest-Evergreen and Not Classified (see table 8). Because cropland covered most of the area, it was the most important land use to determine in the reclassification. The reason that *Otherland* was reclassified as *No Data* was because it was not known what it stood for.

Table 8. The SWAT classes that were used and which RCMRD classes that were covered in the new system

SWAT class name	**Corresponding crop value in SWAT**	**RCMRD classes**
Wetlands-Non-Forested (WETN)	Alamo Switchgrass	Wetland
Water (WATR)	-	Water Body
Sweet corn (SCRN)	Sweet corn	Subsistence Cropland, Annual Cropland, Annual Commercial Cropland
Bananas (BANA)	Bananas	Perennial Cropland
Residential – Medium Density (URMD)	-	Settlement
Range – Grasses (RNGE)	Little Bluestem (LAI_{max} =2.5)	Open Grassland, Closed Grassland
Range – Brush (RNGB)	Little Bluestem (LAI_{max}=2.0)	Open Shrubland, Closed Shrubland
Forest – Evergreen (FRSE)	Pine tree	Sparse Forest, Moderate Forest, Dense Forest, Plantation Forest, Sparse Woodland, Moderate Woodland, Dense Woodland
Not Classified (NOCL)	-	No Data, Otherland

3.4.3. Data used in SWAT

Climate data for Muvumba P8 catchment

The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) is a worldwide observed weather reanalysis, available over a period of 36 years between 1979 and 2014. From the Global Weather Data for SWAT (https://globalweather.tamu.edu/) the daily CFSR data (precipitation, wind, relative humidity and solar) were available to download in SWAT file format (Texas A&M University, 2019).

Four weather stations could be found in the area of the watershed with one placed inside the watershed (see figure 15).

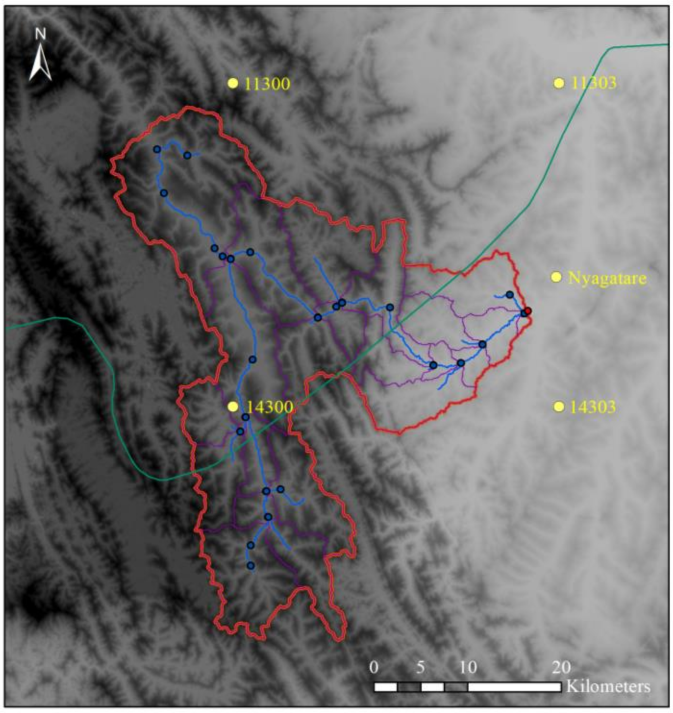

Figure 15. *The four weather stations downloaded from SWAT and a local weather station in Nyagatare were marked on the map. The red line marked the edge of the watershed and the green line was the country boundary between Rwanda and Uganda.*

By comparing the precipitation and temperature for the stations around and in the watershed and also by comparing with precipitation and temperature maps over the area, only station 11303 and 14303 were chosen to be used (see appendix 8.2. for tables). This due to the fact that the other two station had precipitation very much out of range to what the average annual precipitation were in the area, see table 9.

Table 9. The table shows the average annual precipitation for the four chosen stations downloaded from SWAT and also for Nyagatare. They were based on precipitation maps over Rwanda and Uganda. The average values for the given data were based on precipitation between 2011 and 2013 because it was the only data in common with the Nyagatare station (see table 19 in appendix 8.2.1.)

	Nyagatare	11300	11303	14300	14303
Annual average precipitation (from map)	900	900-1100	700-900	1200	900
Average for data from station	764.3	4494.6	1091.9	4871.6	896.2

The temperature from the two selected stations had been compared to the Nyagatare station and had been found to be 10 % lower than the field measurement. Since Nyagatare was placed between the two chosen stations assumptions were made that the temperature should be similar. Decision had been made to increase CFSR temperature data by 10 %, see table 10.

Table 10. Comparing the selected stations with the temperature in Nyagatare and with how much the temperature from the SWAT data differed from the data collected in Nyagatare. This was based on the data in tables 26-28 which can be seen in appendix 8.2.1.

	Nyagatare	11303	14303
Average maximum temperature [ºC]	27.4	25.3	24.8
Average minimum temperature [ºC]	15.0	13.9	13.3
Average temperature [ºC]	21.4	19.6	19.0
Difference maximum temperature [%]		-7.8	-9.5
Difference minimum temperature [%]		-7.6	-11.9
Difference temperature [%]		-8.3	-10.9

ArcGIS

ArcGIS were used to prepare the land use and soil maps that were used in ArcSWAT. Since the catchment area was both in Rwanda and Uganda and a land use map covering both countries couldn't be found, two land use maps had to be merged into one, as described in section 3.4.2. The resulting map can be seen in figure 16 (where the area was limited by the area of the watershed, see figure 31 in appendix 0.).

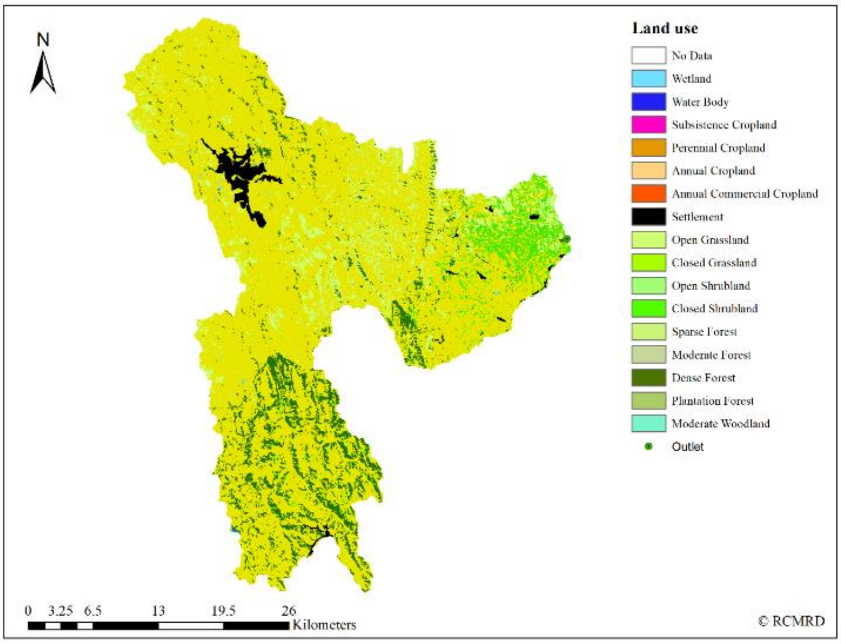

Figure 16. *The map for Uganda and Rwanda merged and reclassified.*

When limiting the soil map to the watershed for the marshland only three different soil types were used in ArcSWAT, which can be seen in figure 17, compared to figure 12 in section 3.4.2.

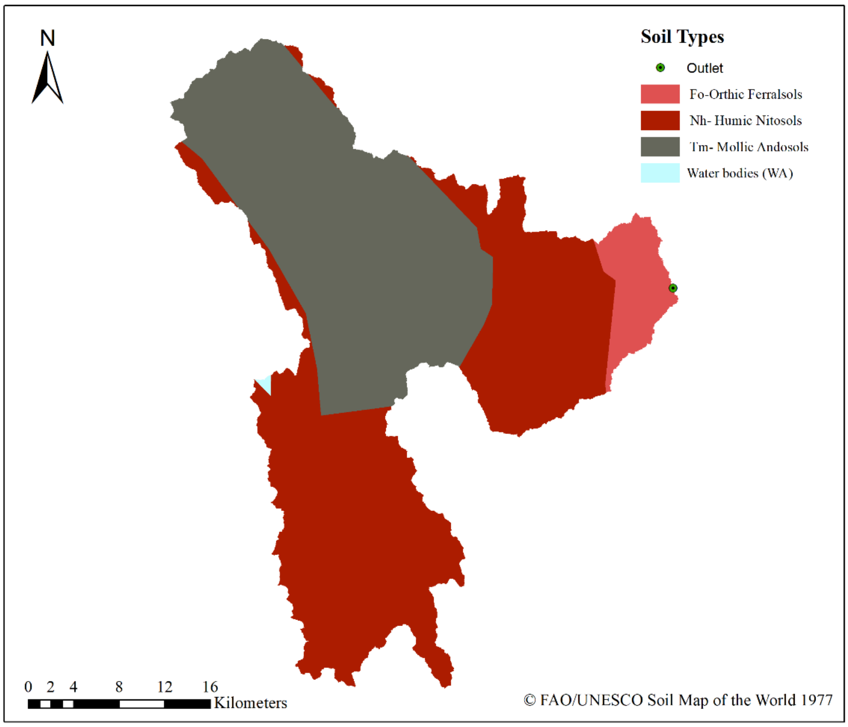

Figure 17. *Soil map showing which of the soil types were used in ArcSWAT.*

ArcSWAT

As a result in ArcSWAT a hydrological model was created. It was used to project the future water amount at the watersheds outlet which was placed at the diversion dam. The watersheds border can be seen in appendix 0.

In ArcSWAT the land use and soil map was reclassified with help of the SWAT database (see figure 18 and 19). However, the reclassification of the slope map was done by investigating different intervals that suited the area best (see appendix 0.) and one map was chosen (see figure 20).

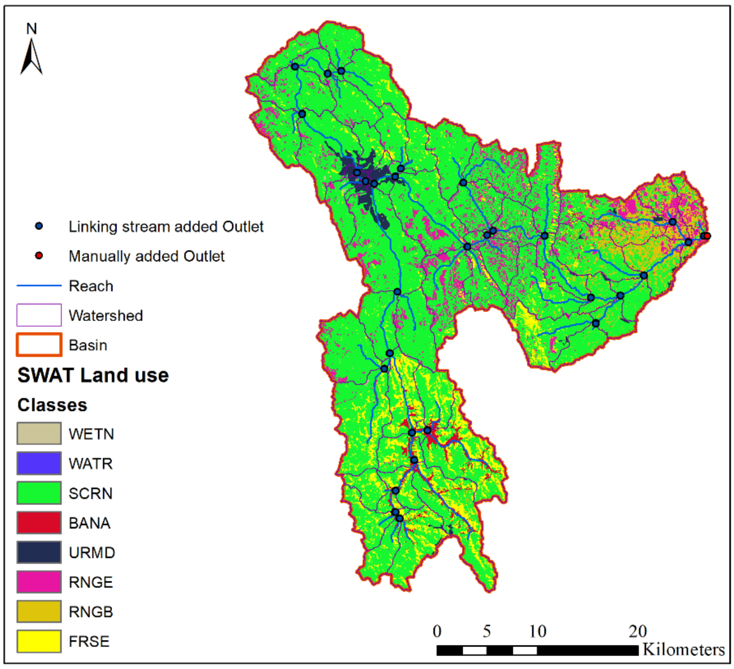

Figure 18. *Land use map reclassified in ArcSWAT with SWAT classes. The definitions of the different land use classes can be seen in table 8 in section 3.4.2.*

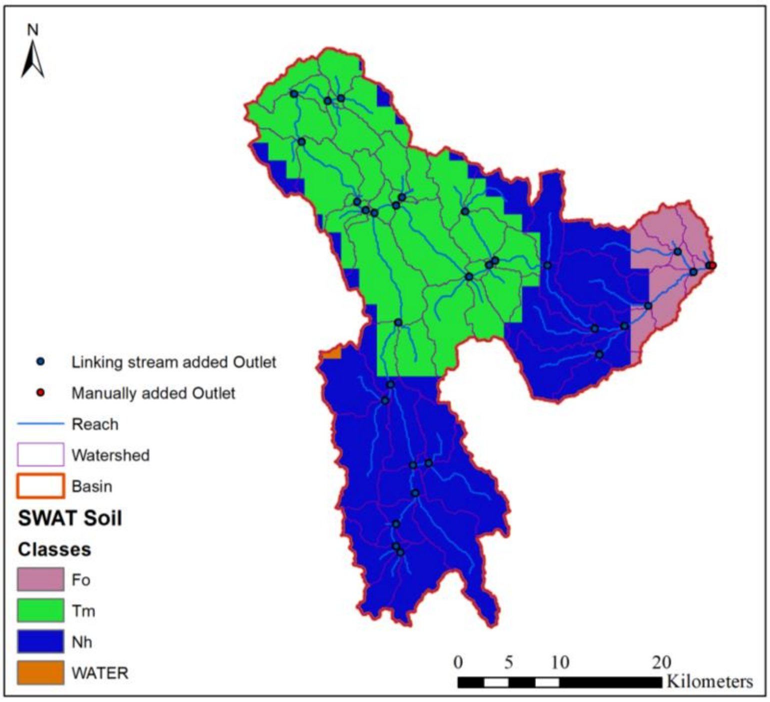

Figure 19. *The soil map reclassified in SWAT. The definitions of the soil classes can be seen in table 5 in section 3.4.2.*

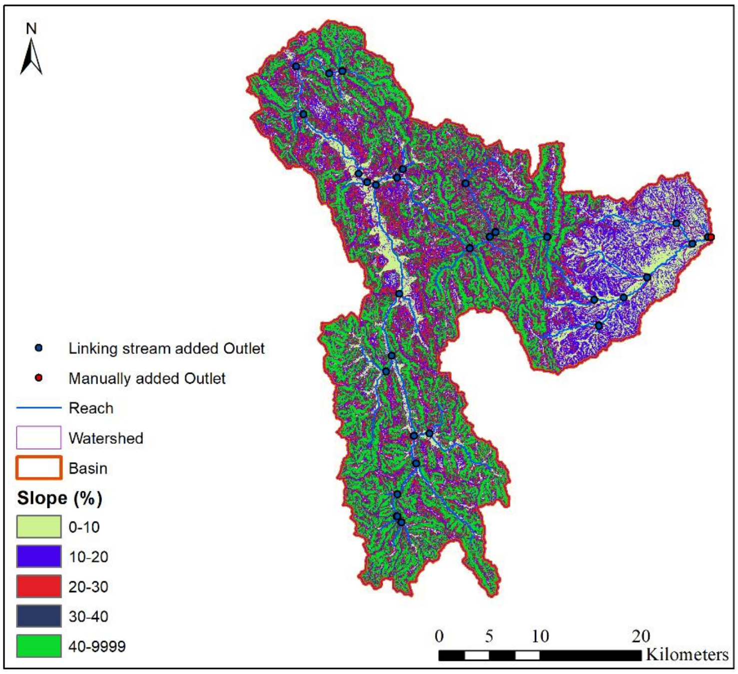

Figure 20. *The intervals chosen for the slope map used in SWAT. To compare with other slopes, see appendix 0.*

Climate models

The SWAT model was run for the SWAT data and the data of the nine models between the years 1984-2013 with a four years warm up period (total of 34 years). Warm up period is the amount of time the simulation will run before it starts to collect results since the simulation will start empty. It was also run for the nine models for the years 2021-2050 with six years warm up period (total of 36 years). All of the models where run both monthly and yearly.

3.4.4. Model calibration and validation

Due to lack of discharge data the model had to be calibrated with help of changing different parameters in SWAT. Since there was lack of information regarding discharge data, evapotranspiration, surface runoff etc. over the catchment, or Rwanda in general, the calibration was aiming towards general values that could be found over Africa instead. Since the model started with giving a high percolation, low surface runoff and low evapotranspiration the parameters controlling this had to be modified. This was done mostly by modifying percolation, surface runoff and soil evaporation. As mentioned in section 3.4.3. the temperature for the CFSR data was modified.

To modify the *percolation* the REVAPMN and GW_REVAP parameters were changed. The REVAPMN commands the threshold depth of water in shallow aquifer for loss (revap) to occur and GW_REVAP was the coefficient for groundwater revap. This meant that REVAPMN controlled the threshold of water level in the shallow aquifer to revap or to percolate to the deep aquifer. If GW_REVAP approached the value 0, the water reaching the root zone from the shallow aquifer was restricted whereas if it approached the value 1, the rate of water transferring to the root zone from the shallow aquifer approached the rate of potential evapotranspiration (SWAT 1, u.d.). For the *surface runoff* volume, the SWAT model was using the SCS curve number procedure which were adapted for a slope of 5 %. Therefore the *adjust curve number for slope* had to be chosen so the model chose an appropriate curve number for slopes above or below 5 %. The SCS curve number was used to predict runoff and infiltration, a higher number gave increased surface runoff potential compared to a lower (Neitsch, et al., 2011). The ESCO-parameter, which was the *soil evaporation* compensation factor, was lowered to 0.7 to allow more ET. ESCO determined at which level the model could extract more of the evaporative demand (Neitsch, et al., 2011). With a lower number the model was able to extract more of the evaporative demand from a lower level (SWAT 2, u.d.). The transportation of water in SWAT can be seen in figure 21.

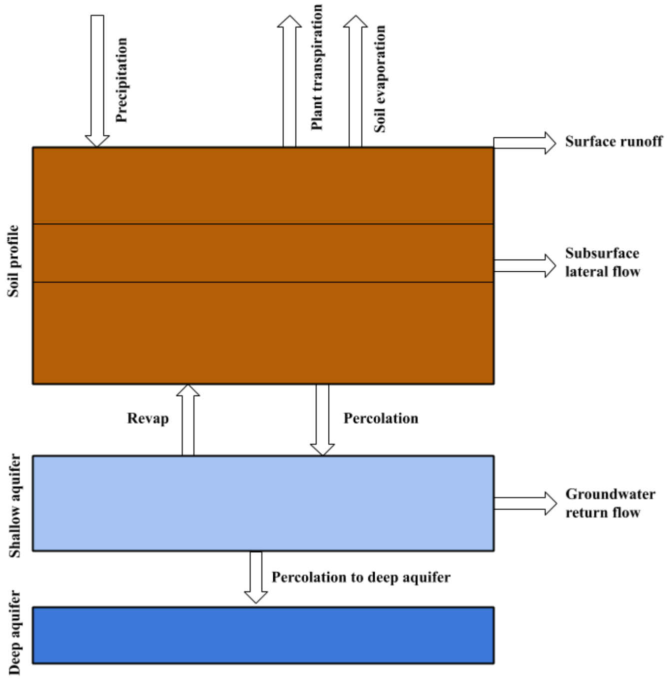

Figure 21. *The flow of water in SWAT.*

3.4.5. Statistical tests

Kolmogorov-Smirnov test

The Kolmogorov-Smirnov test (K-S test) is a non-parametric test, which works for either a discrete or continuous distribution, that either compare a sample with a reference distribution or compare two samples with each other, i.e. one sample K-S test or two-sample K-S test. For the two-sample K-S test it compares the difference between location and the shape of the empirical cumulative distribution functions (ECDF) between the two samples. The null hypothesis for two-sample K-S test are saying that the two samples are coming from a common distribution. An alternative hypothesis are saying that the two samples are not coming from a common distribution. A significance level of 5 % are chosen, i.e. the chosen p-value (Upton & Cook, 2014).

Wilcoxon signed rank test

The Wilcoxon signed rank test or Wilcoxon t-test is a non-parametric test comparing the average of two dependent samples. It does not require a special distribution for the dependant samples. In short, the test are comparing the average between the two samples and therefore are the null hypothesis that the two samples have statistically the same mean value. An alternative hypothesis are therefore that they don't have the same mean value. If having the same mean value is it indicating that the two samples would have a similar distribution. A significance level for Wilcoxon t-test are also chosen to 5 % (Clapham & Nicholson, 2014).

3.5. IRRIGATION REQUIREMENTS

3.5.1. CROPWAT

CROPWAT was developed by FAO and is used to calculate the CWR and irrigation schedules. This is based on data that the user provides. In CROPWAT there were five different “input sections” that contain different input parameters. Those input sections were Climate/ET_o, Rain, Crop, Soil and Crop pattern. To calculate CWR, the Climate/ET_o, Rain and Crop input was needed. Only temperature was a compulsory parameter in the Climate/ET_o input, however it was more suitable if also humidity, sunshine hours and wind speed were known. If only the temperature was available the model would estimate the other mentioned climatic data with help of temperature and altitude data. The module calculated both the radiation and the ET_o. Data was also needed for rainfall input, which was used in CROPWAT to calculate the effective rainfall. In Crop input, CROPWAT was designed to calculate the CWR for two different types of crop, either for dry crop or for rice. For rice the user could decide if it was highland or lowland rice that was calculated (FAO, u.d.).

By choosing the values for median, 25% quartile (dry year) and 75% quartile (wet year) from the projected discharge values, a prediction of irrigation requirements were made in CROPWAT. The upper percentile represents a wet year, i.e. there is more discharge at the outlet due to more precipitation in the watershed, and the lower percentile represents a dry year. A dry year means that there is a lower discharge at the outlet due to less precipitation in the watershed. For the median value the discharge is between the wet and dry season. The data for temperature and precipitation was chosen for the last subbasin, i.e. the subbasin connected to the outlet point, to match the weather in Nyagatare and Muvumba P8.

Climate/ET_o input

To calculate the monthly ET_o for today’s irrigation requirements the input parameters were minimum temperature, maximum temperature, humidity, wind and sunshine hours. For all five parameters, the average temperature for every month between the years 2010 and 2015 were used. Not all years had every month, so the average value was based on irregular number of months. When calculating the future need for irrigation the settings were changed so only temperature was required as input for Climate/ET_o. In CROPWAT the monthly ET_o was calculated with the FAO Penman-Monteith approach (equation 5). The required inputs were information on the meteorological station (country, name, altitude, latitude and longitude) and climatic data. Compared to the Hargreaves method, that was chosen for SWAT, the climatic data used in CROPWAT was the measured data from Nyagatare which had data over humidity, sunshine hours and wind speed. For the future scenarios, CROPWAT estimates the ET_o based on temperature and altitude/latitude data (FAO, u.d.).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad [5]$$

Where ET_o is the reference evapotranspiration [mm day^{-1}], R_n the net radiation at the crop surface [MJ m^{2}day^{-1}], G the soil heat flux density [MJ m^2 day^{-1}], T the mean daily air temperature at 2 m height [ºC], u_2 is the wind speed at 2 m height [m s^{-1}], e_s the saturation vapour pressure [kPa], e_a the actual vapour pressure [kPa], e_s-e_a the saturation vapour pressure deficit [kPa], Δ the slope vapour pressure curve [kPa ºC^{-1}] and γ the psychrometric constant [kPa ºC^{-1}].

Rainfall input

The rain module of CROPWAT required monthly, decade or daily basis precipitation values. The effective rainfall was calculated through the model with the measured rainfall as an input (FAO, u.d.). CROPWAT had four different methods to account for losses due to runoff or percolation. Those were fixed percentage, dependable rainfall, empirical formula or USDA Soil Conservation Method (USDA S.C. Method) developed by Unified Soil Classification System (USCS). The last method was chosen for this study to calculate P_{eff}, as seen in equation 6 and 7, for monthly rainfall steps (P_{month}). Depending on the amount of precipitation every month either equation 6 or 7 were used by CROPWAT.

$$P_{eff} = \frac{P_{month} \times (125 - 0.2 \times P_{month})}{125} \qquad \text{for } P_{month} \leq 250 \text{ mm} \qquad [6]$$

$$P_{eff} = 125 + 0.1 \times P_{month} \qquad \text{for } P_{month} > 250 \text{ mm} \qquad [7]$$

((FAO), u.d.).

Calculation of the effective rain was done with monthly rainfall as input parameter. The rainfall was the average sum of every month between 2010 and 2015 for the data of Nyagatare. Not all years had values for every month, so the average values were based on irregular number of months.

Crop input

The input for the crop module required data for planting date, crop coefficient, stages, rooting depth, critical depletion fraction and yield response factor. Crop height was optional but could be provided (FAO, u.d.). According to FAO was the maximum height for rice 1.00 m (FAO, u.d.) (Allen, et al., 1998). Every season was approximately 150 days long and assumptions were therefore made that the amount of days for each stage for rice was according to table 2. According to FAO the depletion fraction, for an ET-value of approximately 5 mm/day, was 0.2 of saturation for rice (Allen, et al., 1998). K_c-values were chosen to follow FAO no. 56 (table 1) due to the more adjusted climate factor than the values from CROPWAT database. The rooting depth was chosen to 0.6 m because the median was 0.4 m according to the Muvumba P8 Rice Grow Cooperative (MP8RGCO) agronomist and CROPWAT database had a default value of 0.6 m as rooting depth. The crop height was put to 1.00 m as it was the maximum height for rice crops.

4. RESULTS

4.1. CALIBRATION OF THE HYDROLOGICAL MODEL

In figure 22 the result from the calibrated hydrological model are shown. The average SCS curve number was increased to 84.27 which resulted in an increased surface runoff and a decrease in percolation. The evapotranspiration was 63 % and the surface runoff was 18.7 % compared to the precipitation.

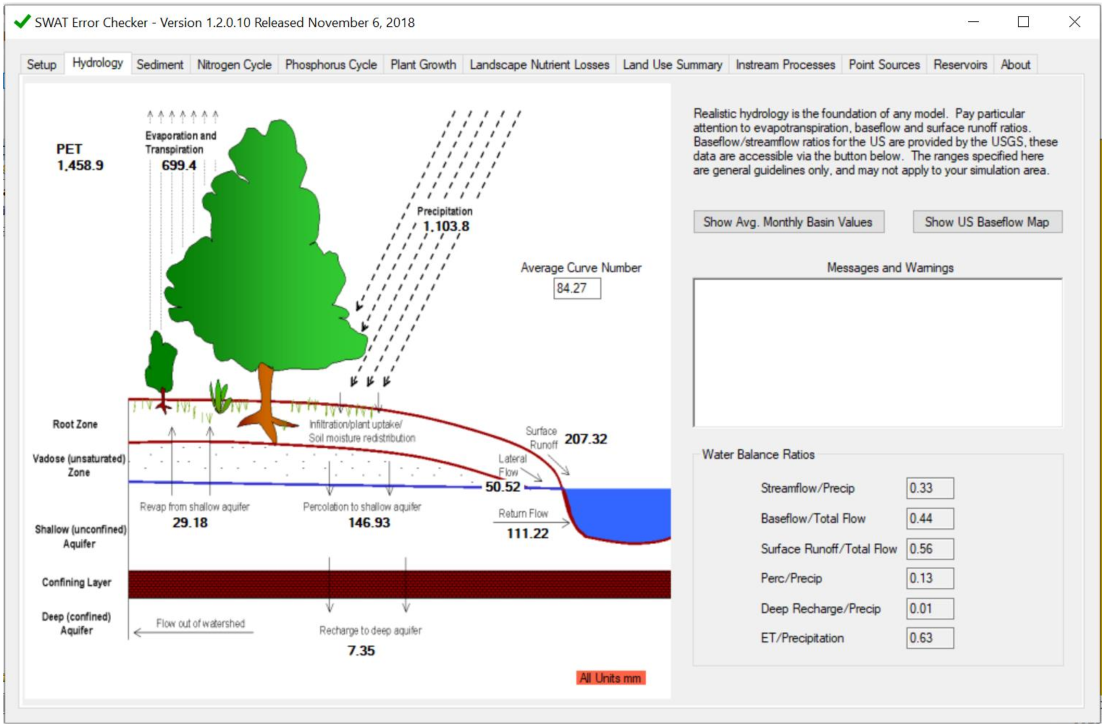

Figure 22. *The result of the hydrological model visualised in the error checker of SWAT.*

4.2. ASSESSMENT OF THE CLIMATE MODELS

To determine how well the climate models fit for the historical years, they are along with CFSR data run for data over the past, from 1984 to 2013. They are presented in figure 23 as boxplots where the distribution of the discharges can be seen. The black line in the middle of the box represents the median discharge value.

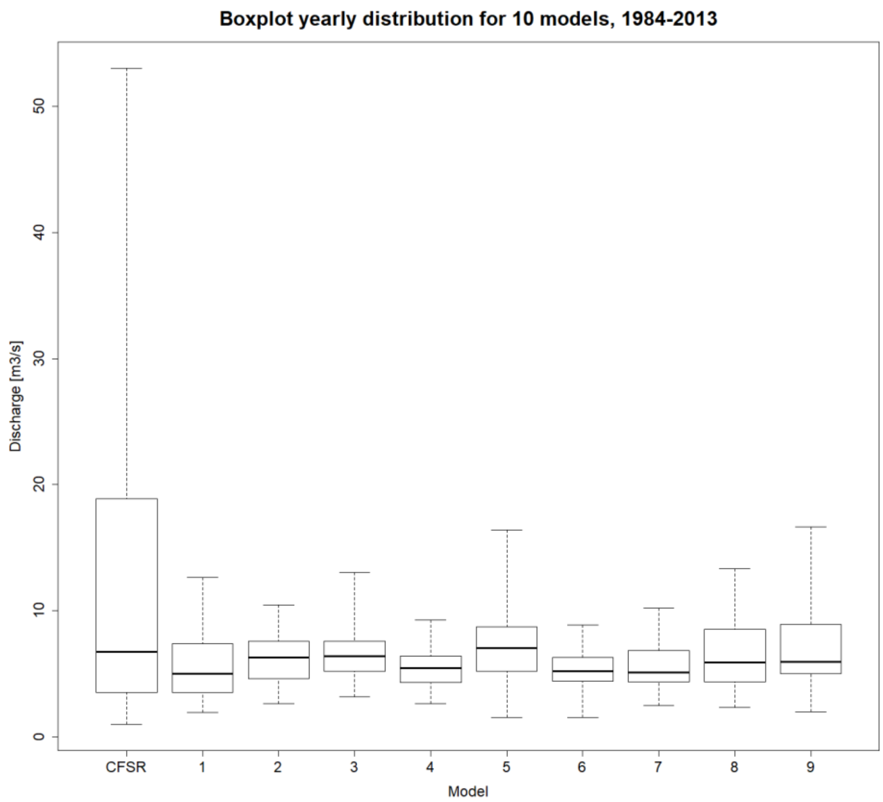

Figure 23. *Comparing the CFSR data with the data from the nine models over the period 1984-2013.*

4.3. EVOLUTION OF THE DISCHARGE OVER THE NEXT 30 YEARS

The nine climate models are run for the years 2021-2050 and are compared to the CFSR data between 1984 and 2013. They are presented in figure 24 as boxplots. The medians are compared to the median of CFSR.

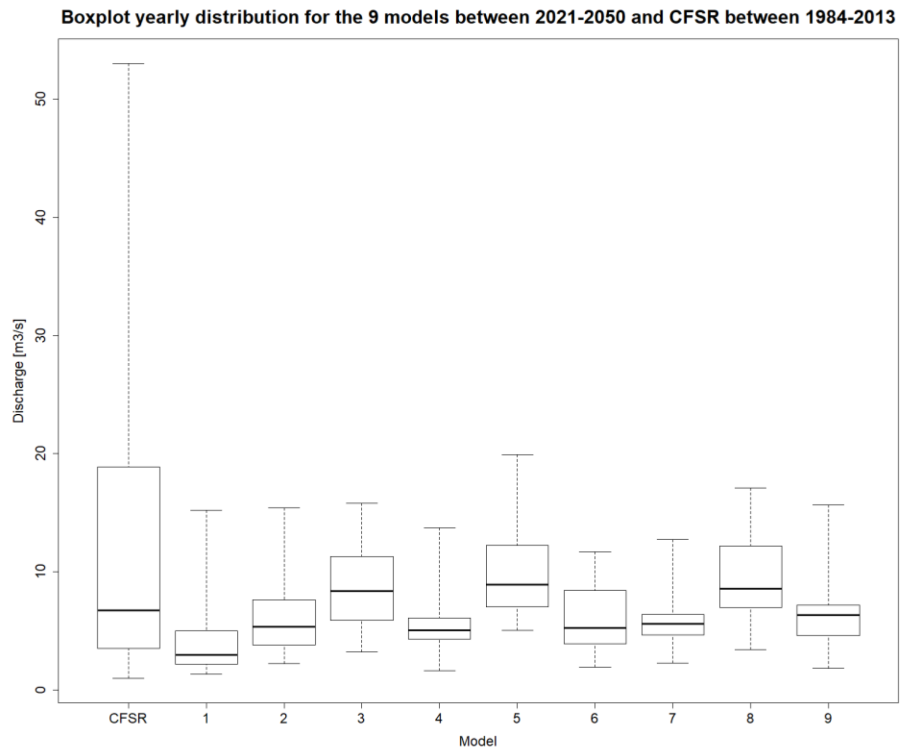

Figure 24. The yearly distribution for all nine datasets for year 2021-2050 compared to CFSR data from 1984-2013.

Comparing the change in discharge for each climate model by placing the climate models historical (1984-2013) and projected (2021-2050) discharge boxplots next to each other, as seen in figure 25.

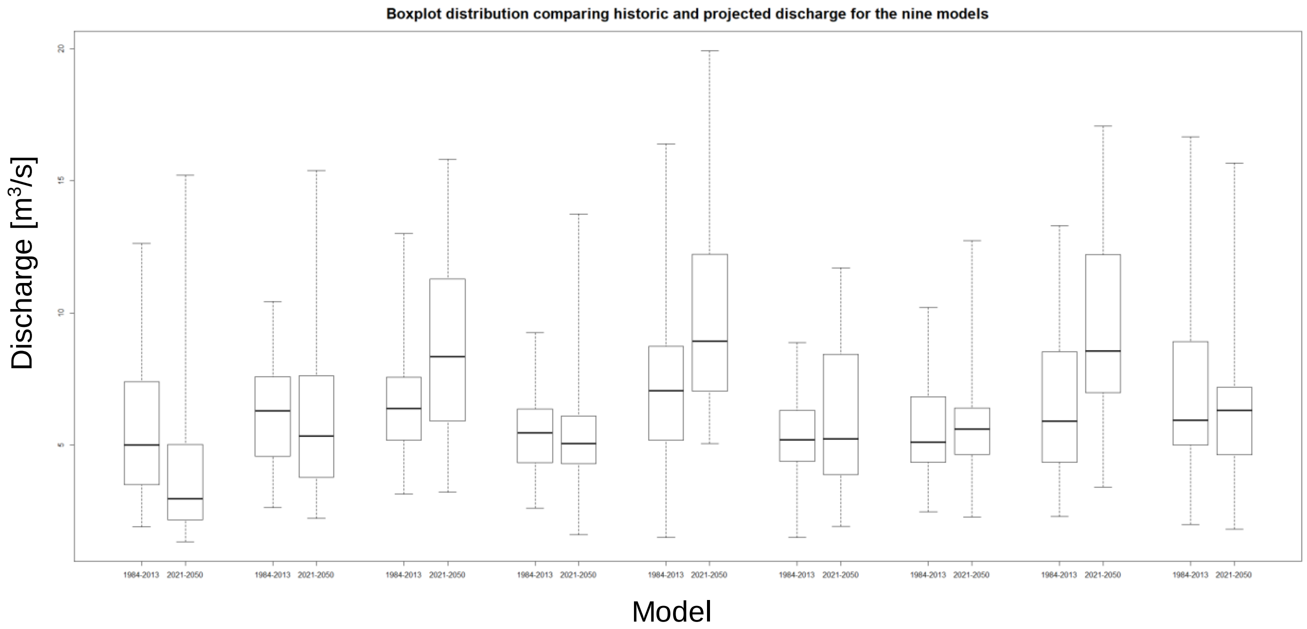

***Figure 25.** Distribution comparison for nine climate datasets for 1984-2013 and 2021-2050, presented as "pairs" with model 1 to the left with its historical and projected boxplot next to each other. Followed by the "pair" of model 2 etc.*

The monthly discharge distribution for all climate models for the years 2021-2050 and for the CFSR data between 1984 and 2013 are presented in figure 26.

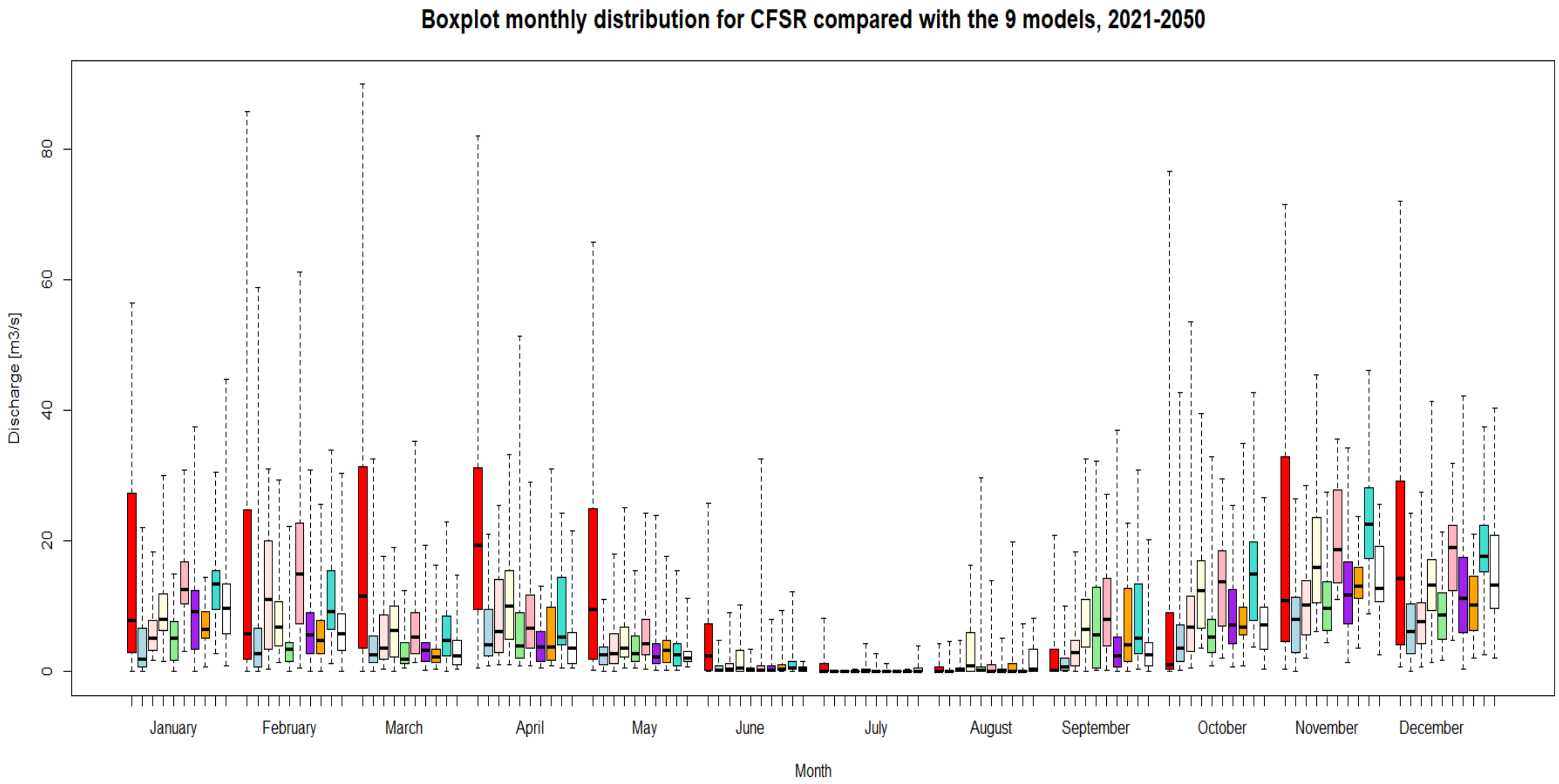

Figure 26. *The distribution for all nine climate datasets (2021-2050) and the CFSR (1984-2013) for every month. CFSR is the red box to the left of every month followed by model 1 (light blue), model 2 (peach), model 3 (yellow), etc.*

The medians for every month in figure 26 are presented in table 11.

Table 11. Values of the monthly discharge median for each climate model, 2021-2050, and for CFSR, 1984-2013, in m^3/s. For visualising see figure 26

Month	CFSR	1	2	3	4	5	6	7	8	9
Jan	7.83	1.97	5.16	7.93	5.06	12.52	9.17	6.49	13.42	9.75
Feb	5.88	2.75	11.07	6.78	3.42	14.92	5.62	4.87	9.16	5.89
Mar	11.49	2.67	3.53	6.30	1.97	5.28	3.25	2.33	4.8	2.40
Apr	19.42	4.13	6.14	10.08	3.97	6.61	3.76	3.77	5.24	3.56
May	9.54	2.63	2.75	3.62	2.71	4.30	2.32	3.26	2.64	2.06
Jun	2.37	0.27	0.35	0.54	0.28	0.25	0.25	0.40	0.5	0.35
Jul	0.10	0	0	0.02	0.02	0	0	0	0	0.06
Aug	0.04	0	0.2	0.82	0.2	0.05	0	0.1	0	0.43
Sep	0.15	0.7	2.92	6.56	5.65	8	2.46	4.05	5.13	2.64
Oct	1.15	3.62	6.83	12.43	5.36	13.7	7.17	6.86	14.94	7.17
Nov	10.81	8.07	10.17	16	9.71	18.6	11.73	13.07	22.59	12.8
Dec	14.36	6.12	7.7	13.19	8.65	19.02	11.29	10.17	17.67	13.23
Median year	6.75	3.07	5.50	8.44	5.07	9	5.33	5.61	8.61	6.28

4.4. COMPARING AND ANALYSING DATA

To evaluate if the change between the distributions of discharge simulated with the CFSR data and the climate change models, the two-sampled K-S test is used. The null hypothesis for the two-sampled K-S test is that the two compared samples are considered to have a statistically similar distribution whereas the alternative hypothesis is that they are not considered to have a similar distribution. The K-S test is based on the comparison of the ECDF of each distribution, which can be seen in figure 27, where the test is based on the maximum distance between the curve of a model and the CFSR curve.

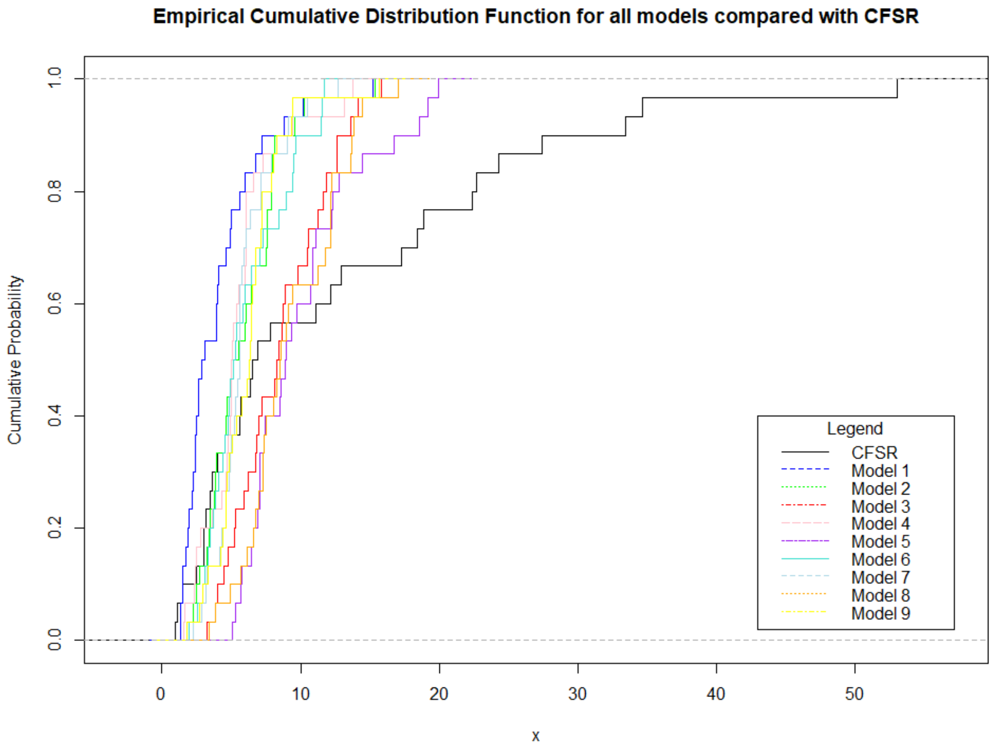

Figure 27. *Graph showing the empirical cumulative distribution function (ECDF) for the nine models and the CFSR. The maximum distance between the curve of a model and CFSR represents the K-S test. On the x-axis are the discharge values and on the y-axis the cumulative probability.*

The result of the p-values determines if the compared distributions in the K-S test are significant different or not and can be seen in table 12. Only model 3 and 8 cannot reject the null hypothesis which would indicate that model 3 and 8 share the same distribution as the CFSR. The rest of the models are supposedly not sharing the same distribution as the CFSR.

Table 12. The p-values for each model for the two-sampled K-S test

Model	p-value	Model	p-value
1	0.01564	6	0.01564
2	0.01564	7	0.01564
3	0.07089	8	0.07134
4	0.03458	9	0.01564
5	0.03458		

The Wilcoxon t-test compares the difference in mean value of the distributions between the models and CFSR. The null hypothesis says that two distributions statistically have the same mean value. By using the p-value, the result tells if the compared distribution in the Wilcoxon t-test are significant different or not. Table 13 shows the result for the test and that model 3, 5 and 8 are supposed to have the similar mean value and distribution as the CFSR data seen to the result due to a greater p-value than 0.05. The rest of the models are not sharing the same distribution due to a lower p-value than 0.05.

Table 13. The p-values for each model for the Wilcoxon t-test

Model	p-value	Model	p-value
1	5.593×10^{-5}	6	0.01966
2	0.03643	7	0.02341
3	0.3707	8	0.4161
4	0.02623	9	0.0113
5	1		

4.5. CHANGE IN IRRIGATION REQUIREMENTS

Table 14 are presenting the sum of total gross irrigation requirements every year, the irrigation requirements for both seasons, the amount of water needed for 300 ha every year and the change in irrigation need compared to today's need. For every model was the upper and lower percentile and the median value chosen.

Table 14. The sum of gross irrigation requirements for both seasons and the gross irrigation for each season for wet, median and dry years calculated with CROPWAT. A total annual need of water covering 300 ha and the change in irrigation comparing the models irrigation requirements with today's need are presented

	Type of year	Crop season	Irrigation requirements [mm/y]	For 300 ha [m^3/y]	Change [%]
Today/reference		Total	661.1	1 983 300	
		Season A	367.6		
		Season B	293.5		
Model 1	Wet	Total	1040.4	3 121 200	+57
		Season A	484.6		
		Season B	555.8		
	Median	Total	1357.2	4 071 600	+105
		Season A	650.9		
		Season B	706.3		
	Dry	Total	1028.5	3 085 500	+56
		Season A	535.4		
		Season B	493.1		
Model 2	Wet	Total	772.7	2 318 100	+17
		Season A	475.6		
		Season B	297.1		
	Median	Total	1044.3	3 132 900	+57.9
		Season A	508.8		
		Season B	535.5		
	Dry	Total	1042.8	3 128 400	+57.7
		Season A	443.8		
		Season B	599		

Model 3	Wet	Total	748.8	2 246 400	+13
		Season A	352.9		
		Season B	395.9		
	Median	Total	706	2 118 000	+6.8
		Season A	367.5		
		Season B	338.5		
	Dry	Total	886.5	2 659 500	+34
		Season A	299.9		
		Season B	586.6		
Model 4	Wet	Total	890	2 670 000	+34.6
		Season A	326.7		
		Season B	563.3		
	Median	Total	885	2 655 000	+34
		Season A	508.5		
		Season B	376.5		
	Dry	Total	906.8	2 720 400	+37
		Season A	432.9		
		Season B	473.9		
Model 5	Wet	Total	663.9	1 991 700	0
		Season A	290		
		Season B	373.9		
	Median	Total	772.5	2 317 500	+17
		Season A	466.8		
		Season B	305.7		
	Dry	Total	869.3	2 607 900	+31
		Season A	554.5		
		Season B	314.8		

Model 6	Wet	Total	905.9	2 717 700	+37
		Season A	399		
		Season B	506.9		
	Median	Total	916.6	2 749 800	+39
		Season A	457.6		
		Season B	459		
	Dry	Total	1036.1	3 108 300	+57
		Season A	481.2		
		Season B	554.9		
Model 7	Wet	Total	1007.8	3 023 400	+52
		Season A	590.6		
		Season B	417.2		
	Median	Total	860.6	2 581 800	+30
		Season A	374.3		
		Season B	486.3		
	Dry	Total	908.9	2 726 700	+37
		Season A	427.9		
		Season B	481		
Model 8	Wet	Total	757.7	2 273 100	+14.6
		Season A	291.5		
		Season B	466.2		
	Median	Total	877.9	2 633 700	+33
		Season A	343.2		
		Season B	534.7		
	Dry	Total	805.8	2 417 400	+22
		Season A	347.4		
		Season B	458.4		

Model 9	Wet	Total	920.6	2 761 800	+39
		Season A	439.7		
		Season B	480.9		
	Median	Total	879.9	2 639 700	+33
		Season A	387.6		
		Season B	492.3		
	Dry	Total	990.6	2 971 800	+50
		Season A	472.2		
		Season B	518.4		

4.5.1. Water availability for irrigation

The yearly amount of water passing through the outlet point of the watershed, calculated with discharge from table 11 and multiplied with 31 536 000, are presented in table 15. Values for the 300 ha are taken from table 14 and divided with the total amount of water volume pro year, in table 15, to get the percentage for the amount of water that is required for irrigation compared to the amount of water flowing in the river. The values are based on the median discharge value for every model and CFSR. It is presented in table 15.

Table 15. The yearly amount of water passing through the outlet of the watershed based on the median discharge from table 11. Also compared with the median amount of water needed for 300 ha irrigation according to table 14.

Climate dataset	Amount [m^3/y]	300 ha compared to total water [%]
CFSR	212 868 000	0.9
Climate model 1	96 81 520	4.2
Climate model 2	173 448 000	1.8
Climate model 3	266 163 840	0.8
Climate model 4	159 887 520	1.7
Climate model 5	283 824 000	0.8
Climate model 6	168 086 880	1.6
Climate model 7	176 916 960	1.4
Climate model 8	271 524 960	1.0
Climate model 9	198 046 080	1.3

5. DISCUSSION

5.1. CALIBRATION OF THE HYDROLOGICAL MODEL

The idea was to calibrate the hydrological model for the watershed with measured discharge data at the diversion dam, but there was very little data to be found and therefore could the model not be calibrated as planned. Instead, it had to be evaluated after the literature and studies that could be found about Africa regarding runoff and evapotranspiration. According to the study made by (Karamage, et al., 2018) shows that 16 % of the annual mean precipitation becomes runoff and the remaining percentage (84 %) becomes evapotranspiration. This study was based on the whole continent, 25 major basins and 55 countries. Looking at only Rwanda the study shows the annual precipitation is 1200 mm/year, the evapotranspiration is 900 mm/year and the runoff is 250 mm/year. This gives an ET ratio of 75 % and runoff ratio of 20.8 %. Based on data between 1901 and 2017. Since Rwanda has a big variation in both topography and climate this is only an indication on what the values should be around in general. From the statistics made by (GRID-Arendal, 2009) the average runoff in Africa is around 20 %, depending on the amount of ET.

Compared to the study from (Karamage, et al., 2018) the calibrated models shows a lower ET and a higher water yield from the precipitation into the river than average Africa. This could be because the local climate, topography and the close location to the equator of the catchment. It was difficult to get the model to give a higher evapotranspiration than 60 % which meant that a lot of water went as runoff or percolation. Settings for the SCS curve number were changed so it would adjust to a slope greater than 5 % since much of the watershed had a slope above 40 %, see figure 20. The steep slopes could be a contribution to why it is such a high runoff, but also that the elevation for the area is high which contributes to a relatively low temperature compared to, for example, Nyagatare. Also the humidity is very high, which could contribute to a lower evapotranspiration compared to the average.

The temperature of the CFSR data are about 10 % lower when compared to the collected data in Nyagatare and on that assumptions was a decision made to increase the CFSR temperature data with 10 %. This helps the hydrological model to become more realistic due to an increase of evapotranspiration and a decrease in precipitation. Regarding the precipitation, the station that are used are chosen based on table 10, where station 11303 showed a precipitation a little bit above the annual average whereas station 14303 showed a precipitation a bit lower than the annual average. It is harder to decide for the precipitation if an increase or decrease should be done to the CFSR data due to no certain pattern and no change are therefore done to the precipitation data of the two chosen stations. The other two stations are so excessive in the precipitation compared to the annual average precipitation that they are not used as source points in the model, even if one of them are in the watershed. This means that the model is estimating a precipitation for the catchment regarding the two chosen stations.

Because the lack of validation data, it is hard to determine how accurate the model is compared to reality, however according to the only discharge data collected through

RSSP, the discharge in the river is 16.6 m^3/s which is in the range of the distribution for the discharge output of CFSR data. The average discharge data for March and April collected from the output says that the discharge is 11.5-19.4 m^3/s. That is the only data existing for the river according to RSSP which also makes it questionable to why there are no records of discharge data and when and where this was measured. It would have been good to at least have some discharge data for sporadic time intervals over the year to see if the model follows the same pattern. Assumptions are however made that the model gives a satisfactory result with regard to the limitations that exist.

5.2. ASSESSMENT OF THE CLIMATE MODELS

By analysing the boxplots between the years 1984 and 2013 an indication can be given on how well the climate models represents the hydrology of the region through the hydrological model. Since CFSR data are chosen to represent todays discharge in Muvumba river the other models are compared to the median of CFSR's median. The distribution of the CFSR discharge have higher extreme values which could be because of the DBS bias correction made on the climate data. Looking at the medians, they all are quite similar which indicates that they represent the hydrology in the region satisfactory enough to be used.

5.3. EVOLUTION OF THE DISCHARGE OVER THE NEXT 30 YEARS

A comparison between the CFSR and the climate models projected boxplots were made, but also and a comparison between the climate models historical and projected boxplots. Both types of comparisons have uncertainties but when comparing to the CFSR a more general change are compared since the CFSR are a more "fixed point" and a general change can be seen from that. However when comparing the climate models with themselves could give an idea of how the models project the change in extremes or width of the distribution due to the fact that they have the same correction factors in both the past and in the future. Due to the correction the climate models have no outliers.

When looking at the median for the nine models between the years 2021 and 2050 and comparing it with the median of the CFSR data, see figure 24, there is a change in discharge since the models medians are more dispersed compared the models medians for the past, seen in figure 23. This indicates that the climate change will have an effect on the amount of water that ends up in the outlet of the watershed. Comparing with CFSR, only three out of nine models have a discharge greater than the CFSR median which would indicate that the median discharge in Muvumba river are going to decreased in comparison to today's discharge.

Since the climate models have DBS corrected data is it difficult to compare the distribution change between the models and the CFSR data. Therefore are comparison made between the models own historical and projected boxplots. Looking at figure 25 it shows an increase in discharge. Since both boxplots have the same bias-correction the comparison in this case can be made on how the distribution of the discharge changes from the past to the future. More than half of the models have a greater distribution compared to the historical distribution. The density for almost half of the projected boxplots increase, i.e. a smaller box, which could indicate a better precision on the predicted discharge since the box represents 50 % of the discharge values. However there when looking at model 1 and 4 the box is smaller for the projected boxplots but the distribution are greater compared to the historical. This could indicate that the concentration of discharge values are higher around fewer discharge values but some years are going to have greater extreme flows. So in general when comparing the models with themselves the results indicates that the discharge change will in general have a greater distribution which means that a higher variety and more extreme (both high and low) will occur but that almost half of the models will have a higher density of the box. Which indicates a higher concentration of values around certain discharges. The projection of the future climate is difficult and uncertain and since the climate data is DBS corrected is it more relevant to compare the position of the medians rather than the extreme values. Therefore are this study focusing on the result of figure 24.

Looking at the median for the monthly distribution, see figure 26, it shows that in general will be a longer dry season between May and August, but already from March the discharge show a tendency to become drier than normal. This assumption is based on median comparison with the CFSR every month. The change in season means that the need for irrigation probably are going to increase during the long drier period since less rain will come and the crops still need sufficient water. Whereas for the period between September and November will be wetter.

The change in discharge in terms of increase or decrease could depend on how the precipitation are occurring. Is it the same amount of rainy day but more or less rainfall each time? Or is it the same amount of rain that comes but just during a few days which would show a general decrease in flow because all the water comes at the same time and the rest of the month is dry? It cannot be answered in this study but is to take into consideration.

5.4. COMPARING AND ANALYSING DATA

To evaluate if the change between the discharge distributions for the CFSR and the projected climate models are significant, the two-sampled K-S test is used. The result showed that 6 out of 8 models are significant different. This means that almost all models do not have a statistical similar distribution with CFSR. Since the CFSR have a greater distribution than the climate models it would be reasonable to assume that none of the models share a distribution with CFSR and that it would be more reasonable to compare between the models historical and projected distributions. However since the result of this study is based on the comparison between CFSR and climate models are the K-S test performed between them. In the K-S test are the differences in location and the shape of ECDF compared, which means that the median are compared for instance. Seen to the K-S graph the frequency of the low discharges are greater than the higher because of the steep curve that places most of the lowest values inside 80 % of the discharge distribution.

Compared to the CFSR curve, that has a higher frequency of values up to about 50 % and thereafter are the distribution more scattered.

The Wilcoxon t-test analyses if two dependent samples mean differ. The result presented in table 13, shows that model 3, 5 and 8 are significant with the CFSR whereas the rest of the models are significant different. Because the test compares the mean score, it is possible to say that a change in climate has occurred because of a differences in mean value. However it would have been interesting to do a Wilcoxon t-test between CFSR and the historical climate models. This to see if there would have been a difference in amount of significant models and in that way show another indication for climate change.

5.5. CHANGE IN IRRIGATION REQUIREMENTS

Data given by different organizations or associations regarding the crops are hard to know if they are reliably due to the fact that they differ much from each other or have unrealistic values. Therefore had a lot of information, used in CROPWAT, be collected (mainly) from FAO to complete the gaps for missing data. It does not give a perfect picture of the local conditions but gives a general picture of the crop conditions in the area.

There are different meaning about how much the first reservoir covers. According to the official report and the Water User Association the reservoir covers 5-5.9 ha whereas RSSP are saying that it covers about 300 ha. Since there are only three reservoirs for storing water and the whole cropping area is 1 750 ha, would 300 ha be a more reasonable area. 300 ha represents 17 % of the total area whereas 5 ha represent barely 0.3 % of the total area. Since there are only three reservoirs installed to cover the fields in case of a water deficiency, assumptions are made that the first reservoir covers 300 ha.

For every model is the irrigation requirements for rice calculated for both season A and B, see table 14. The seasons started in mid-July and mid-January which both are supposed to be in the dry season and are most likely therefore requiring irrigation from the beginning. However being on the field in March showed that the farmers where harvesting at that time and started growing new plants in April, i.e. almost at once. This means that the start of the season does not seem to be the same every year, however a general start have been made to be the 15th of July respective 15th of January like the farmer intend it to be according to the MP8RGCO agronomist. Both season A and B are supposed to have rain season and part of dry season since rain season generally are between March to May and September to November. Irrigation requirements are calculated assuming that the whole field grow rice, as that is the purpose of the marshland.

Since figure 26 indicates that the dry seasons are getting longer, which means less rain, the need for irrigation is going to increase. That will increase the demand of water from the river and if it would become an insufficient water level in the river a more sustainable way would probably be to start using the reservoirs to collect water. This should be done when there are good access to water, like the wet season, and irrigate with the collected water during dry season. There are different parameters that varies the irrigation requirement, such as the crop stage, humidity, temperature and precipitation. It is also hard to say how much the reservoir are losing water due to evaporation, leakage or seepage since no data can be found regarding the reservoir. Model one gives the biggest increase of water requirements (105 %) which is about double the amount of water than what is required today. This without taking into account of losses in the channels etc. The amount of water taken from the river also have to be more than the gross irrigation to compensate for the loss of water transported in the channels and on the fields. Biggest part of the main channel was earthen which has a greater water loss than e.g. channels made of masonry. Losses are e.g. through evapotranspiration, leakages or seepage which increases the total water amount. When investigating the channels could a lot of vegetation be seen in the channels which can increase the water loss from the channels since roots could increase seepage. Presence of roots can also mature and die which creates a food supply for animals such as worms, ants and beetles who increases the seepage, especially in the banks (Kahlown & Kemper (2004). Sedimentation in the channels was also a known problem which decreases the capacity of the system.

For all models the irrigation requirements are increasing in the future when comparing to today's need even if some of the models are indicating that more water would exit the watershed in the future compared to the CFSR. This could be because of the uneven distribution of the seasons. It could also do with the fact that the climate are so varying over a very small area in Rwanda and that even if the precipitation in the catchment increases, Nyagatare can get a more drier and warmer climate which requires more irrigation. The temperature and precipitation data used in CROPWAT to predict the future irrigation requirements are collected from the sub-basin that are at the outlet to give a more representable picture of the Nyagatares future climate. This might explain why a drier year, are in less need of irrigation than a wet year because the climate in Nyagatare might not be reflecting the discharge at all. It could also do, as mentioned before, with how the precipitation are distributed over the month. When looking at the need for irrigation a total requirement is presented, but also each season separately to show that even if the seasons are supposed to contain both part of a rainy season and a dry season can the season have big differences in irrigation requirements. For example the wet year for model 2 and the dry year for model 3 shows a big difference between irrigation requirements for season A and B. An understanding in climate differences between the watershed and Nyagatare is important to be able to estimate when it is good to store water or irrigate directly from the river.

Another aspect due to irrigation and climate is that Nyagatare might not face the problem of water deficiency but too high temperatures for rice crops to grow in good conditions. If the temperature rises above 30 ºC, the climate might not be favourable and the rice yield could decrease.

5.5.1. Water availability for irrigation

Assumptions are made that this is the water required when a good distribution of water are made on the field and that the irrigation scheme has the capacity to manage the water.

After doing some field studies on the marshland the impression was that the farmers barely used water from reservoir no.1 but always took water directly from the channel. They did not take any consideration on which season it was or the water level in the river but always took sufficient with water to the rice crops. If there is water deficiency on the field it would be because of the farmer's poor distribution of water according to RSSP. This might not be a problem now and they might have enough water all year round for many years to come. Looking at table 15 the amount of water taken from the river during a year to cover 300 ha is not many percentage and will probably not affect the river too much, however this would also mean taking water in a sustainable way. To withdraw water from the river when, according to calculations, none or a very small amount of water are exiting the watershed might not be a problem to cover the irrigation requirements for that moment. However it can become a problem downstream that too much water is extracted from the river which will not be sufficient for farmers living after the diversion dam. Problem can occur when more water demanding user are increasing their demand or more users are created both upstream and downstream which are putting pressure on the water source. This study does not evaluate the change of land use in the watershed that with an increasing population might also increase the farmland in the watershed, which also needs more water. This can contribute to a smaller discharge in the river. Now are only the amount of water to cover 300 ha calculated due to the limitation of the project. It would probably be more if the water demand for the whole marshland would be calculated, including compensation for the loss of water in the irrigation scheme.

6. CONCLUSIONS

In the 30 years to come the water resources availability will in general decrease when comparing nine climate models with the Climate Forecast System Ranalysis (CFSR). There is an indication of change in season with a dryer and longer dry season between June and August and an increased precipitation during the rainy season between September and November.

All the models show an increase in need for irrigation in the future, regardless if the models show an increase or decrease in discharge. Calculations show that irrigation requirements could increase with more than 100 %.

Today the irrigation scheme works as a complement in the absence of precipitation. It has a natural fall because of elevation difference which can transport water from the diversion dam to the end of the marshland. However it does not work completely as intended, because the farmers barely use the reservoirs but always irrigate directly from the river, regardless season. There are also a problems with sedimentation in both the channels and the reservoirs which was not taken into account when designing the construction.

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8. APPENDIX

Additional information that might not suit the contents of the report but are still relevant.

8.1. SOIL PARAMETERS EQUATIONS

Saturated hydraulic conductivity:

$$K_S = 1930(\Theta_s - \Theta_{33})^{(3-\lambda)} \qquad [8]$$

Where KS is saturated conductivity, ΘS and Θ33 are moisture parameters for normal density [% volume] and λ is the slope of logarithmic tension-moisture curve. All parameters used to calculate Ks had their own equations to be calculated (Saxton & Rawls, 2006).

Organic matter content:

$$OM = 1.72 \times orgC \qquad [9]$$

where orgC is the organic carbon content of the layer [%] ((SWAT), 2012). Organic matter was needed to get a more correct calculation of the saturated hydraulic conductivity.

8.2.WEATHER DATA

8.2.1. Temperature and precipitation comparison

The average temperature in each table are taken between year 2010 and 2014. Compared to the years 2011-2013 both 2010 and 2014 have average or total values based on not complete years. Comparison for temperature are done on all the years but for precipitation are only 2011-2013 compared to give a more accurate value. Red marked column in all tables represents the chosen stations that are compared with Nyagatare station.

Table 16. The average maximum temperature [°C] 2010-2014. For location of the stations see figure 15 under section 3.4.3.

Year	Nyagatare	11300	11303	14300	14303
2010	27.97090909	23.81179636	24.08222909	22.28477091	24.46732
2011	26.96630137	20.67633425	25.19932877	19.61202466	24.50606575
2012	27.32240437	20.99696175	25.50838525	20.02071311	24.97709016
2013	27.69461078	20.95236164	25.71518904	19.86221644	25.03037808
2014	27.39833333	21.67656667	26.432425	20.38121667	25.68196667
Average	27.44691781	21.48141784	25.29468276	20.32846211	24.83753588

Table 17. The average minimum temperature [ºC] 2010-2014. For location of the stations see figure 15 under section 3.4.3.

Year	Nyagatare	11300	11303	14300	14303
2010	14.77345455	14.58898909	15.39248364	13.66779636	15.19737455
2011	15.09608434	12.01451233	13.6693726	11.1118	12.85983836
2012	14.93551913	11.59381694	13.44987978	10.79739071	12.75739891
2013	15.07694611	11.98270959	13.63312329	11.1351589	12.84027945
2014	15.80166667	11.798225	13.465025	10.87063333	12.87186667
Average	15.04758234	12.36088665	13.90798323	11.49235748	13.26200738

Table 18. The average temperature [°C] 2010-2014. For location of the stations see figure 15 under section 3.4.3.

Year	Nyagatare	11300	11303	14300	14303
2010	21.37218182	19.20039273	19.73735636	17.97628364	19.83234727
2011	21.54808219	16.34542329	19.43435068	15.36191233	18.68295205
2012	21.12896175	16.29538934	19.47913251	15.40905191	18.86724454
2013	21.38577844	16.46753562	19.67415616	15.49868767	18.93532877
2014	21.6	16.73739583	19.948725	15.625925	19.27691667
Average	21.37702055	16.92115225	19.601333	15.91040979	19.04977163

Table 19. The total amount of precipitation [mm] 2010-2014. Average value are only based on the complete years, i.e. 2011-2013, to give a more correct comparison. For location of the stations see figure 15 under section 3.4.3.

Year	Nyagatare	11300	11303	14300	14303
2010	472.4	2055.928	2611.284	2633.995	1431.606
2011	824.4	4861.793	1189.407	5213.621	1000.103
2012	887.3	4314.338	1125.858	4698.132	916.7233
2013	581.2	4307.672	960.538	4703.046	771.6711
2014	275.2	1221.297	300.3061	1448.195	263.1312
Average	764.3	4494.601	1091.935	4871.599	896.1657

8.2.2. Nyagatare 1954-2017

Due to lack of data in the dataset between 1954 and 2017 it is not used but the variation is presented in this section to compare.

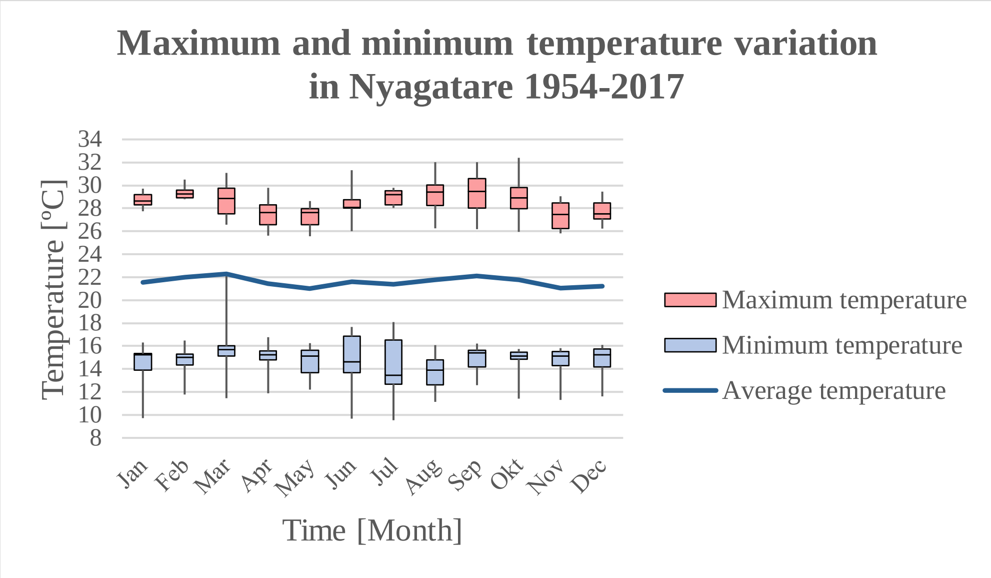

Figure 28. *The variation of maximum and minimum temperature for the whole collected dataset between 1954 and 2017.*

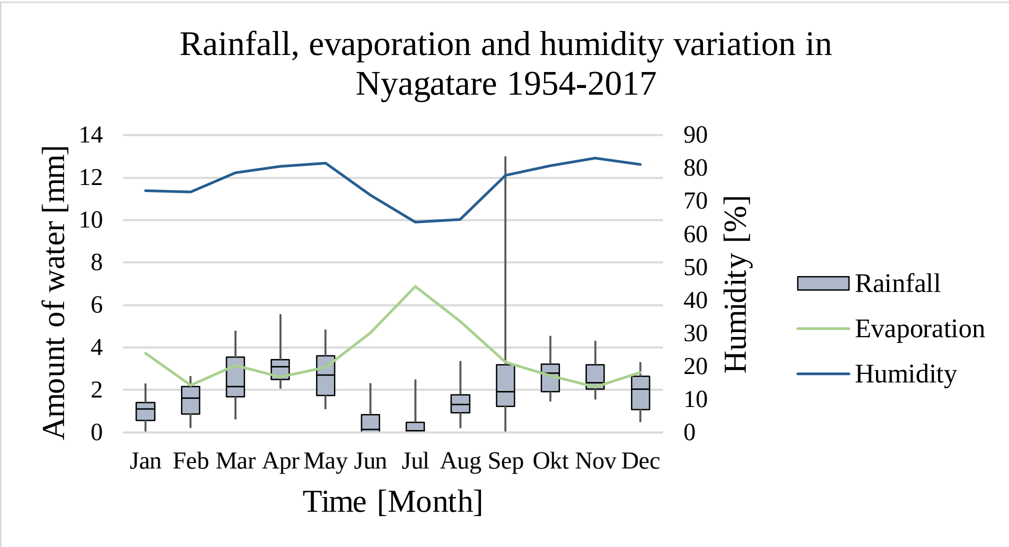

Figure 29. *The variation of humidity and evaporation and the distribution of rainfall per day between 1954 and 2017.*

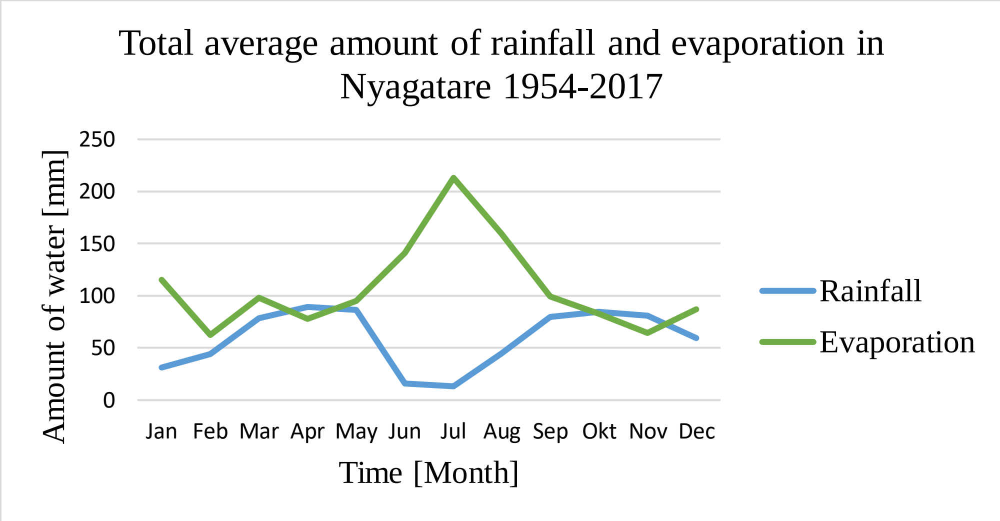

Figure 30. *The variation of rainfall and evaporation between 1954 and 2017.*

8.3. FAOSTAT 2017

These tables are the support for the choice of Generic land cover for the reclassification of land use.

Table 20. Harvested area of agricultural commodity in Rwanda. Source: FAOSTAT 2017

Rank	Crop	Harvest area [ha]	Annual or perennial crop
1	Beans, dry	549 411	Annual
2	Bananas	464 862	Perennial
3	Maize	297 447	Annual
4	Sweet potato	184 609	Annual
5	Sorghum	143 490	Annual
6	Cassava	120 000	Annual

Table 21. Harvested area of agricultural commodity in Uganda. Source: FAOSTAT 2017

Rank	Crop	Harvest area [ha]	Annual or perennial crop
1	Cassava	1 187 900	Annual
2	Maize	1 185 006	Annual
3	Plantains and other	755 962	Perennial
4	Beans, dry	633 226	Annual
5	Sorghum	419 521	Annual
6	Groundnuts	408 408	Annual

8.4. SLOPE COMPARISON AND WATERSHED BOUNDARY

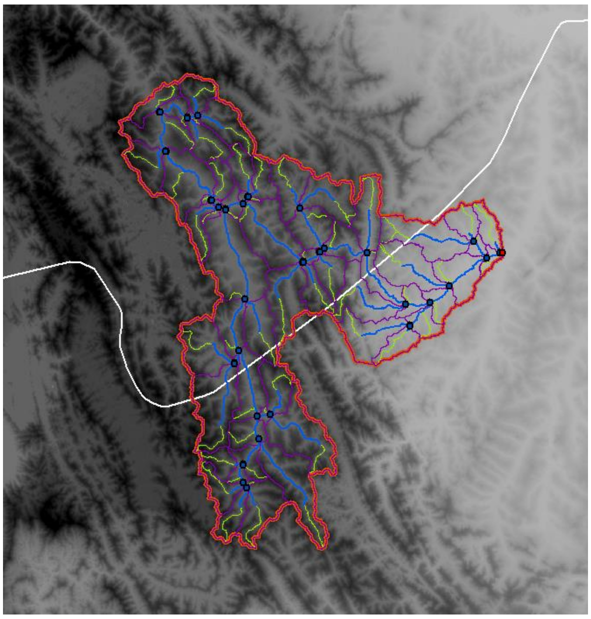

Figure 31. *The watershed that is created with an outlet point at the red dot.*

By analysing the slope intervals a suitable slope definition could be produced. This was done by analysing different slope maps and determine which intervals suited the model best.

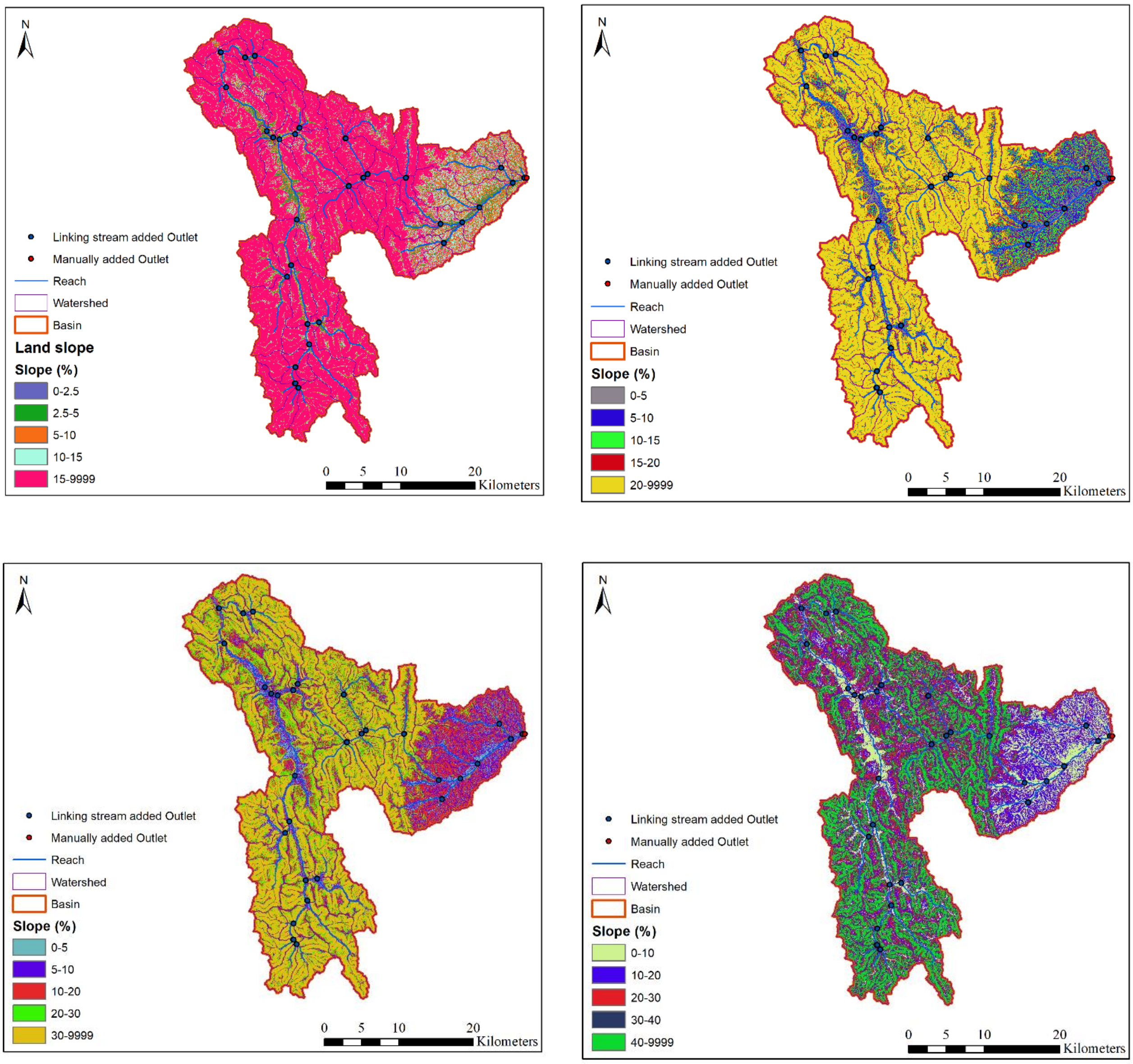

Figure 32. *The different slope intervals.*