Evaluation of the accuracy of TAMSAT weather data on Rwanda for improved maize yield simulation with APSIM

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Evaluation of the accuracy of TAMSAT weather data on Rwanda for improved maize yield simulation with APSIM

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DECLARATION

Student's declaration

I declare that this Dissertation contains my own work except where specifically acknowledged.

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Declaration by Supervisors

This work has been submitted with our approval as supervisors

Dr. Pascal RUSHEMUKA Date

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Mr. Alain Ndoli (MSc, PhD candidate) Date

International Maize and Wheat Improvement Center (CIMMYT)

DEDICATION

This thesis is dedicated to my loving God.

I also dedicate this thesis to my wife Sandrine Ugiriweneza, who has been a great source of motivation and inspiration all along my courses and thesis writing, to my daughter Cassidy Akaliza, and to my entire family and friends for their encouragement.

Finally, this thesis is dedicated to all those who believe in the richness of learning.

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Also to my other friends, colleagues and relatives who contributed in many ways to make sure that I could make it to the end. I can never thank you enough as it may be hard to mention each person by name. MAY GOD BLESS YOU ALL.

ABSTRACT

Across Rwanda, the raingauge network is extremely sparse and it often takes many months before raingauge records are accessible to the wider community. However, rainfall information is very critical to predict yields and inform food security early warning system of the country. TAMSAT provides a gridded daily rainfall map at a resolution of 4 km and this gives around 1,646 pixels for Rwanda. Since Rwanda has not such distribution of raingauge, the use of TAMSAT data can be of high importance. TAMSAT rainfall estimates can be used in APSIM to predict maize crop yield. This study attempt to provide information on the reliability of spacio-temporal satellite rainfall data to alleviate the scarcity of rainfall data in Rwanda. In addition, the study highlights the importance of such data in simulating crop yields with APSIM. TAMSAT rainfall data from 30th June 2013 to 30th June 2015 were downloaded for the volcanic highland and Bugesera AEZ using GPS coordinates corresponding to the ground location of weather stations. These data were compared to the recorded data on the stations and were both used in APSIM for maize yield simulation. The simulated maize stover and grain yields were compared to the values observed in the field experiments during season 2014A and 2014B in both the volcanic highland and Bugesera AEZ. Results showed that in Bugesera AEZ, TAMSAT slightly underestimated the total rainfall (1,310.0 mm) as compared to the actual rainfall (1,518.9 mm). This slight difference may be due to lack of one-off local calibration. However, the cumulated daily rainfalls estimated by TAMSAT was strongly correlated (R^2 = 99%) to the ones recorded by the weather station in Bugesera. In the humid volcanic highland AEZ, results showed a broad agreement in the trends of both TAMSAT rainfall and weather station records but TAMSAT significantly underestimated the rainfall. In the whole study period, the latter estimated the total rainfall to be 1,418 mm while the actual rainfall received was 2,427.2 mm. This is due to the intricate topography of the volcanic highland which receives complex local rainfall variations and occurrence of non-convective rainfall while TAMSAT mainly predicts the convective rainfall. This is probably the reason why TAMSAT better estimated rainfall in Bugesera AEZ (slightly flat with round hills) than in the volcanic highland AEZ (very hilly). The APSIM-Maize model performed well in the simulation of maize stover and grain yields for both Bugesera and Volcanic Highland AEZ. As expected, the simulated maize stover and grain yields were higher in the volcanic highland than in the Bugesera AEZ. The simulations also showed that there were significantly ($p<0.05$) higher maize grain yields in season A (2014A) than in season B (2014B) due to differences observed in the rainfalls. Results showed that there were no difference in the outputs of the simulations while using TAMSAT rainfall instead of the station rainfall in the metfile of APSIM module. This obviously shows that APSIM can simulate maize stover and grain yields with almost no noise coming from TAMSAT rainfall data and hence recommendable for places with limited raingauge records. Based on the findings of this study, TAMSAT offers good estimations particularly in the semi-arid regions of Rwanda with less hilly topography. It can be used successfully to identify periods with well below or well above average rainfall even over highland areas, and is therefore useful for providing good APSIM simulations and hence inform food security early warnings.

LIST OF SYMBOLS AND ACRONYMS

AEZ	Agro-ecological zone
APSIM	Agricultural Production Systems Simulator
BD	Bulk density
C	Carbon
CCD	Cold Cloud Duration
CERES	Crop Environment Resource Synthesis
DAP	Di-ammonium Phosphate
DSSAT	Decision Support System for Agrotechnology Transfer
DUL	Field capacity
Ha	Hectare
ITCZ	Tropical Convergence Zone
IUSS	International Union of Soil Sciences
Kg	Kilogram
MINAGRI	Ministry of Agriculture and Animal Resources
MINECOFIN	Ministry of Finance and Economic Planning
Mt	Metric ton
N	Nitrogen
NISR	National Institute of Statistics of Rwanda
P	Phosphorus
pH	Hydrong potential
R^2	Coefficient of determination
TAMSAT	Tropical Applications of Meteorology using SATellite
WHO	World Health Organization
WRB	World Reference Base (for soil resources)

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CHAPTER 1

1. Introduction

1.0 Background information

Rapid population growth rate averaging 2.6% (NISR 2014) threatens Rwanda's future especially by its negative consequence on physical and natural resources. The rural population density has steadily increased from 121 inhabitants km^{-2} in 1960 to 415 in 2014 inducing the decline of farm size from 3 ha to less than 1 ha in the same period (NISR, 2014). The increased population pressure on available land and water resources has led to land degradation, and resulted in the loss of productivity of arable lands and increased food insecurity (Bidogeza, 2011). This makes Rwanda one of the challenged countries as agriculture contributes to more than 30% of the GDP and over 70 % of the population is employed in agriculture (NISR 2015). Poor crop yields are also due to hard biophysical conditions such as soil acidity (pH<5.2) in the West, erratic rainfall in the East and steep slopes (erosion risk-prone) all over the country.

Maize is world's one of the three most popular cereal crops. Worldwide, the average yield losses in maize crops due to drought can be high, particularly in the tropics (Srinivasan et al. 2004). Maize is particularly susceptible to water stress at the flowering stage when yield potential is being set (Birch et al. 2008 Srinivasan et al. 2004). It has become the leading crop in production and ranks first among pulse and grain crop production in Rwanda (NISR, 2013). In Rwanda, maize is essentially rain fed crop. The poor distribution and low total rainfall in agricultural seasons significantly reduce maize yield in the semi-arid eastern region of Rwanda.

Crop yield information is very crucial for monitoring and predicting progress on agricultural programs of countries. Crop simulation models are used in USA and in Europe by farmers, private agencies, and policy makers to a greater extent for decision making (Murthy et al, 2004). However, these models are not yet widely used in Africa. In many African countries including Rwanda, weather records for over 50 years are scarce. In crop modeling, the use of meteorological data has assumed a paramount importance. There is a need for high precision and accuracy of the rainfall data. The data obtained from surface observatories has proved to be of good quality. It gained the confidence of the people across the globe for decades (Murthy et al, 2004).

The Agricultural Production Systems Simulator (APSIM) is a modular modeling framework that has been developed by the Agricultural Production Systems Research Unit in Australia. APSIM was used to simulate biophysical process in farming systems, in particular where there is interest in the economic and ecological outcomes of management practice in the face of climatic risk (Keating et al. 2005). APSIM has been used in a broad range of applications in Africa. This includes support for on-farm decision making, farming systems design for production or resource management objectives, assessment of the value of seasonal climate forecasting, analysis of supply chain issues in agribusiness activities, development of management guidelines, risk assessment for government policy making and as a guide to research and education activity (Keating et al. 2005). Crop models including APSIM require a number of data for calibration and evaluation before running different simulations. One of the most important dataset required by crop models is the daily rainfall. The standard way to measure rainfall is using a raingauge; this provides a reliable pin-point measurement of how much rain has fallen. However, across most of Africa the raingauge network is extremely sparse and it often takes many months before raingauge records are accessible to the wider community. In Rwanda, long-term datasets of rainfalls are very scarce and in most cases with wider gaps in time and space. TAMSAT is a research group based at the University of Reading, UK. TAMSAT stands for 'Tropical Applications of Meteorology using SATellite and ground-based observations'. TAMSAT uses Cold Cloud Duration (CCD) method to estimate rainfall. It is known that rainfall in Africa typically comes from tall, convective systems characterized by cold cloud tops (Grimes et al., 1999). Using thermal infra-red (TIR) imagery therefore allows to identify and monitor such cold cloud tops which in turn allow to estimate rainfall. The TAMSAT rainfall estimation algorithm provides rainfall estimates using cloud top temperature; it does not directly measure the rainfall (Milford et al., 1996), hence the need to assess its accuracy and precision in Rwandan context (e.g high altitude with hilly topography).

1.1 Problem statement

Evidence based agricultural decision making for development necessitates good yield records and capacity to simulate possible scenarios in crop production. The National Institute of Statistics of Rwanda (NISR) produces yearly comprehensive agricultural statistics but tools to use such yield observations to simulate best and worst scenarios in crop production are still unexploited. While APSIM can help in this, quality long-term rainfall records are still missing. Given the high spatial variability of rainfall across Rwanda, the raingauge network is still very sparse and it often takes many months before raingauge records are accessible to the wider community (e.g researchers, leaders and farmers). For instance, Rwanda accounts for only 21 automated weather stations installed in 2013 by meteo services while few other stations are regularly monitored for quality data. However, rainfall information is critical to predict yields in crop models including APSIM. The results from modeling can inform food security early warning system of the country. TAMSAT provides a gridded daily rainfall map at a resolution of 4 km and this gives around 1,646 pixels for Rwanda. Since Rwanda doesn't have such distribution of raingauge (4 stations per sector or 1,646 weather stations across the country), the use of TAMSAT data can be of high importance to cover areas with no raingauges records. The problem that this thesis is solving is to provide information on the reliability of special and temporal satellite rainfall data to alleviate the scarcity of rainfall data in Rwanda. In addition, this thesis will highlight the utility of such data in simulating crop yields with crop model to inform the food security early warning system.

1.2 Research objective

1.2.1 General objective

The general objective of this study is to evaluate the usefulness of satellite rainfall data (e.g TAMSAT) in simulating crop performance with APSIM.

1.2.2 Specific objective

The specific objective can be subdivided into 3 sub objectives:

- To assess the accuracy of TAMSAT rainfall data in humid and semi-arid regions of Rwanda by comparing it with data from weather stations on ground;
- To simulate maize yields with APSIM using TAMSAT rainfall data and data from on-site weather stations;
- To assess the maize yield predictive capacity of APSIM and evaluate the importance of yield errors that may arise from using satellite weather data.

1.3 Research hypothesis

The central hypothesis in this research is that TAMSAT satellite weather data are precise and accurate to be used by APSIM to adequately predict maize yields.

1.4 Justification of the study

Rwandan's land resources are finite, while the population that the land must support continues to grow rapidly. This creates a major problem for agriculture. The productivity must be increased to meet rapidly growing demands while natural resources are protected. Innovative agricultural research is needed to supply information to farmers and policy makers on how to achieve sustainable agriculture over the broad variations in climate around the country. In this regard, explanation and prediction of growth of major food security crops such as maize in response to climate and soil-related factors are increasingly important as objectives of research. As part of this effort, intensively monitored field experimentation was conducted to evaluate APSIM's predictive performance for maize based cropping systems in Rwanda. Since precise and region specific weather data are scarce, results from this study will present whether APSIM could adequately simulate maize yields using TAMSAT data freely available online to support the decision making and planning in agriculture.

CHAPTER 2

2.0 Literature Review

2.1 General overview of Rwandan agriculture

Rwanda is highly populated with current population of 10,718,379 inhabitants over 26,338 km^2 of land. This means 406 inhabitants per km^2 on average mostly located in rural areas and involved in agriculture sector for their livelihood. The country is characterized by a high rapid growth of population with growth rate of 2.6% (average of 2002-2012. NISR 2014). Arable land is 1,371,958 ha where 0.7 ha/ household is an average area of agriculture production (NISR, 2015). Agriculture of Rwanda is divided in industrial crops (tea, coffee and pyrethrum) covering 3% of agricultural land and food crops which include mainly maize (12.4%), sorghum (1.2%), potatoes (3.6%), bananas (22.9%), cassava (21.5%), beans (19.8%), and rice (1.2%). The country also produces a variety of fruits and vegetables such as avocados, mango, passion fruits, pineapples, papaya, apples and oranges all covering 1.5% of the total crop land (NISR 2015).

Large number of rural farmers practice subsistence agriculture and sell the surplus (World Bank, 2007, Diao et al, 2010). Rwandan agriculture is still characterized by old methods and traditional tools like hoes and machetes while very few farmers use power tillers. The diversity in climatic conditions allows an important diversification from crops suited for tropical areas to crops adapted to temperate climatic conditions. The favorable temperature regime allows three agricultural seasons yearly. Two of these seasons correspond with the two rainy seasons. From June to September, a third harvest is possible of crops cultivated in the imperfectly to poorly drained valleys (Verdoot and van Ranst, 2003).

Rwanda has made remarkable development especially in Agriculture, after the genocide of 1994, where different assets had been destroyed by the war; like protection of soil erosion strategies, land consolidation program and increment in production (MINECOFIN, 2002). The government has set ambitious development goals, and a strategy for reducing poverty and stimulating higher and sustainable economic growth is laid out in Vision 2020 (MINECOFIN 2002). In order to contribute to the achievement of the Vision 2020, the government of Rwanda through MINAGRI has adopted different growth strategies such as stimulating productivity growth in staple food, scaling up sustainable development of land and water resources (irrigation and terracing), strengthening research and extension systems, building capacity in producer organizations, promoting export growth and diversification, improving performance of agricultural markets and improving access to rural financial services (MINAGRI, 2007). Cereals, especially rice and maize, are among the high priorities for the government with 50% subsidies on fertilizer and seeds (MINAGRI, 2009). Figure 2.1 shows the increment in food crop production from 1998 up to 2010, mostly cereal have a rapid growth compared to other food commodities due to the new policies supporting more cereals for food security than tubers.

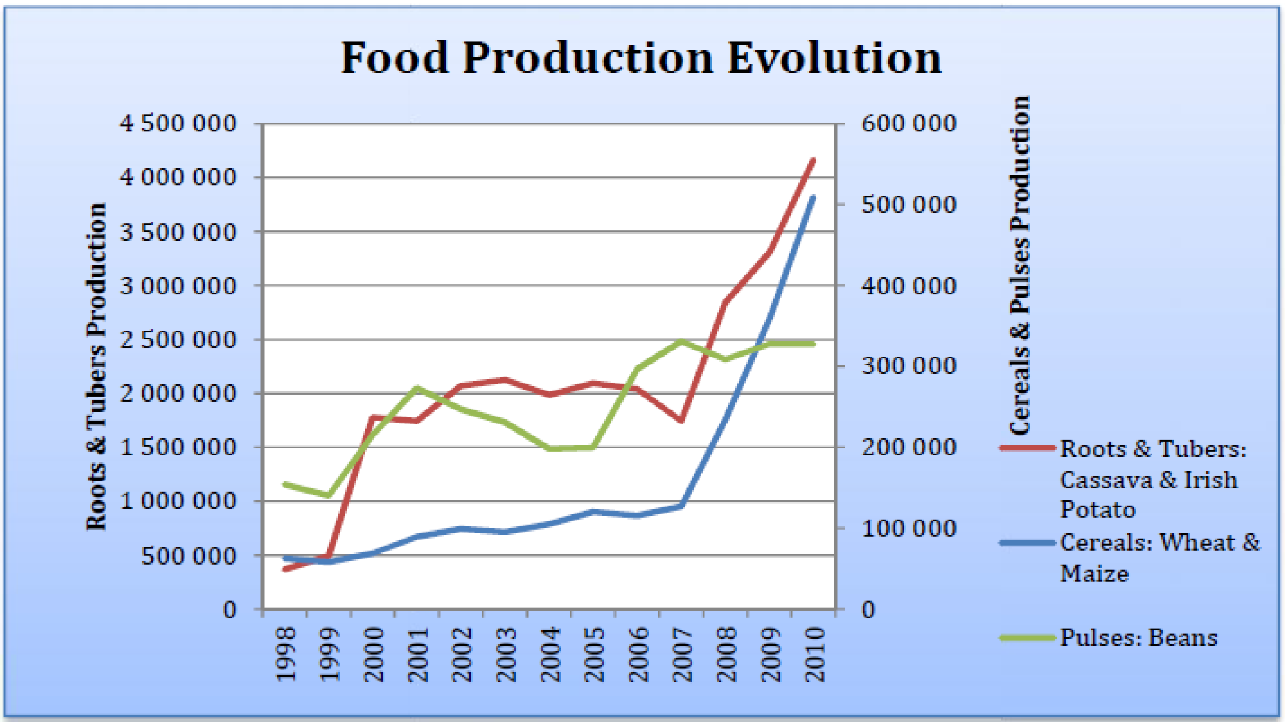

Figure 2- 1 Rwandan Crop production growth in (Mt) from 1998-2010

(Source: MINAGRI 2011)

2.2 Maize production in Rwanda

Maize (*Zea mays*) is a major staple food crop in Sub-Saharan Africa. Its importance is comparable to rice in Southeast Asia or wheat in Middle East. Maize is used largely for direct human consumption in many African countries, unfortunately with low productivity of 1-1.5 ton/ha (Hughes and Odu, 2001, FAO stat 2014).

Maize was introduced in Rwanda around 1957's, during the colonial period. The production had increased consistently since 1962, although the upward trends began to level off in the last decades;

the decline was caused by long period of drought and population fairs to produce. Before 1996, maize was only important in highlands (Buberuka and volcanic) where it constituted the staple crop, but from 1996, it expanded in other ecologies of Rwanda especially in moist mid-altitudes (Ntabakirabose et al., 2015). The shift of interest from other crops such as sweet potato to maize, was multiple uses and easy conservation of maize, and its ability to grow in diverse ecologies in Rwanda. Furthermore, the encouragement to grow maize was to constitute cereal reserves to face unexpected hunger periods through the crop intensification program (Ngaboyisonga, 2010). Currently, maize has become leading crop in production and ranks first among pulse and grain crop production in Rwanda (NISR, 2013).

2.3 Climate variability

In the last 100 years, the world warmed by approximately 0.75°C, with a much higher rate in the last 25 years (0.18°C every 10 years), partly because, the rate of GHG emissions is much higher than the absorption rate. It is considered that heat waves have become more frequent over most land areas; the frequency of heavy precipitation events has increased over most areas including Africa (WHO, 2010). African societies are dependent on rainfall for agricultural and other water-dependent activities, yet rainfall is extremely variable in both space and time and reoccurring water shocks, such as drought, can have considerable social and economic impacts (Maidment et al, 2014).

Because of the high altitude in Rwanda ranging between 970 and 4,507 m, this equatorial country is characterized by a sub-equatorial climate (Verdoot and van Ranst, 2003). Temperature in Rwanda varies throughout the year with two maxima and two minima. The low maximum temperature occurs in February while the high maximum temperature occurs in August. The two minima occur respectively in June and in November. The average temperature for Rwanda is around 20°C and varies with the topography. The warmest annual average temperatures are found in the eastern plateau (20°C - 21°C) and south-eastern valley of Rusizi (23°C - 24°C), and cooler temperatures are found in higher elevations of the central plateau (17.5°C - 19°C) and highlands (<17°C).

Annual rainfall varies across the country, with the highest totals in the western part and the high elevated north-western part (>1200 mm) and then diminishing towards the eastern plateau (<900 mm). The country experiences two rainy seasons in a year associated with the North-South oscillating migration of the Inter- Tropical Convergence Zone (ITCZ) of trade winds. The period of March, April and May corresponds to the long rainy season when the ITCZ moves to the North and the period of October, November and December to the short rainy season when the ITCZ returns to the South. A short dry season occurs from January to February and a long dry season from June to September (Bonfils, 2012). In the last decades, there has been clear indication that climate change has occurred in Rwanda and statistically significant abrupt changes and trends have been detected (Bonfils, 2012).

2.4 TAMSAT weather data

TAMSAT is a research group based at the University of Reading, UK. TAMSAT stands for 'Tropical Applications of Meteorology using SATellite and ground-based observations'. Our main aim is to provide reliable and timely rainfall estimates for sub-Saharan Africa using satellite imagery. TAMSAT uses thermal infra-red (TIR) imagery in the 10.8 μm band from the Meteosat satellite. At this wavelength, the satellite is essentially measuring the temperature of the surface in view. Since temperature decreases with height, we can use temperature as a proxy for height when looking at clouds. We know that rainfall in Africa typically comes from tall, convective systems characterized by cold cloud tops. Using TIR imagery therefore allows us to identify and monitor such cold cloud tops which in turn allow us to estimate rainfall.

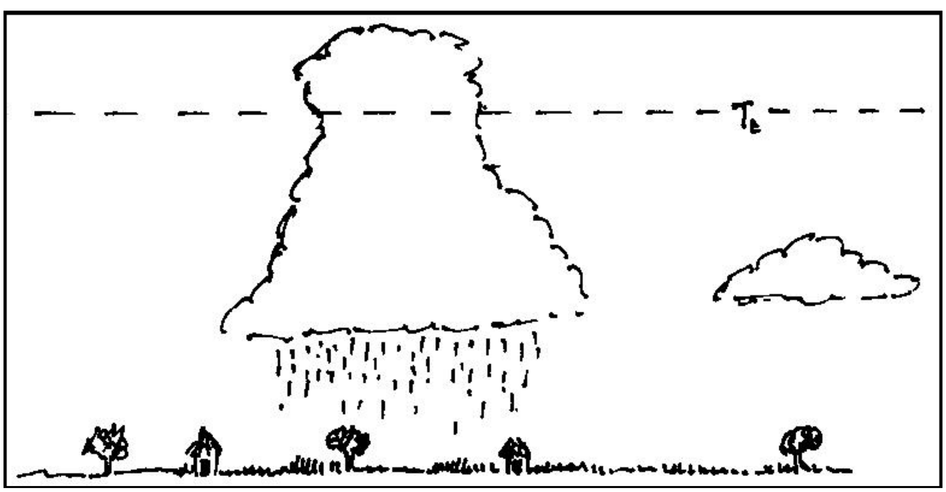

Figure 2- 2 Schematic indicating the optimum temperature threshold. ***Clouds with tops colder than the given temperature threshold Tt are assumed to be raining. Clouds with tops warmer than Tt are assumed not to be raining.***

The basic methodology of the cold-Cloud statistics procedures is simple. It has been set out more fully elsewhere (Barrett, 1980), and is briefly summarized by Milford et al (1996) as follows. Local seasonally varying temperature thresholds are used to discriminate between precipitating and nonprecipitating clouds of convective origin are determined. Simple linear regressions of rainfall per hour of "cold cloud" are applied to calculate the period rainfall. The operational details follow.

Firstly, al1 available Meteosat TIR dots are used. Where more than ten lines are missing the image is rejected. The preceding image is repeated to substitute for a single missing image. Infilling from each side covers longer gaps. If more than six consecutive hours of data are lost no estimate of rainfall is made for that day for operational purposes and users are advised accordingly. If decadal (10-days period) data are needed for climatological purposes a missing day is represented by the average of the other nine days. Time and space averaging considerations interact. In TAMSAT, al1 data processing is carried out on the original METEOSAT pixels at full resolution, with reprojection (which inevitably loses some resolution) left to the last possible stage. Rainfall estimates are made pixel by pixel on a decadal basis: the clouds have already produced a reasonably smooth field so that general smoothing is not necessary. However, to avoid discontinuities smoothing is applied at the boundary between two calibration zones, using linear interpolation across a band of 20 lines or pixels on either side of the boundary. This interpolation is applied to the threshold calibration. This also represents a meteorological/ climatological transition zone.

The type of regression used by TAMSAT has so far simply been linear in rainfall against CCD (Cold Cloud Duration), considering non-zero CCD values only. It is an important proviso that zero CCD is always equated to zero rainfall. During calibration, the rainfall values are grouped according to 2.5-hour bands of CCD and the regression performed on the median rainfall in each class (see Milford& Dugdale, 1990 for more detail). To provide a significant number of classes each containing a sensible population, a minimum of 100 data pairs has been recommended. As more become available they can be used to improve the statistical significance of existing calibrations or to subdivide the calibration areas. The next consideration is the way in which an area should be divided up for calibration purposes. The calibrations are also time-dependent, and those from TAMSAT have so far been related to individual months of the year.

Finally, some reference should be made to the raingauge data which are essential to the whole procedure. For the majority of purposes such as drought and agricultural monitoring, decadal rainfall data are suitable, and any sources available have been used, including FA0 and national records. Daily data, as required for hydrological purposes, may come from data transmitted over the Wh40 Global Telecommunications System, or from national meteorological services. Some reservations over the accuracy of measured rainfall are justified when, for instance, decadal rainfall from two sources show only 38 % of the decades in agreement with 8 % having a difference greater than 10 mm. Quality control of the data at Reading has been minimal except to compare supposedly identical sets reaching here by different routes, and, very occasionally, to shift daily records by one day where a station shows a consistent displacement of major rainfalls either from neighboring stations or from satellite records of Cloud (Milford et al, 1996).

2.5 APSIM use for maize yield simulation

A model is a set of mathematical equations describing a bio-physical system (in this case soil–plant–atmosphere). Crop models predict the response of crops to weather, soil, and management by simulating the growth and development of plant organs such as leaves, roots, stems and grains. Thus, a crop growth simulation model not only predicts the final state of total biomass or harvestable yield, but also contains quantitative information about major processes involved in the growth and development of a plant. Changes in climatic conditions influence soil moisture availability, nutrients and water uptake by plant root. The phenology of the crop is also affected and, depending on the growth stage of a plant, unfavorable climatic conditions can result in large losses in crop yield or total crop failure. In recent years, crop growth models have become state-of the art research tools and are an important component of agriculture-related decision-support systems (Jame and Cutforth, 1996; Stephens and Middleton, 2002).

Agricultural Production Systems Simulator (APSIM) is a modeling framework that allows individual modules of key components of the farming system (defined by model developer and selected by model user) to be 'plugged in' (Mc Cown et al., 1996). The initial stimulus to develop APSIM came from a perceived need for modelling tools that provided accurate predictions of crop production in relation to climate, genotype, soil and management factors, whilst addressing long-term resource management issues in farming systems. APSIM was designed at the outset as a farming systems' simulator that sought to combine accurate yield estimation in response to management with prediction of the long-term consequences of farming practice on the soil resource such as soil organic matter dynamics, erosion and acidification (Keating et al. 2005).

In APSIM, any logical combination of modules can be simply specified by the user "plugging in" required modules and "pulling out" any modules no longer required. APSIM can simulate more than 20 crops and forests (e.g., alfalfa, eucalyptus, cowpea, pigeonpea, peanuts, cotton, lupin, maize, wheat, barley, sunflower, sugarcane, chickpea, tomato). APSIM outputs can be used for spatial studies by linking with geographic information systems (GIS). It is a powerful tool for exploring agronomic adaptations such as changes in planting dates, cultivar types, fertilizer/irrigation management, etc. The key outputs are changes in crop and pasture yields, yield components, soil erosion losses, for different climate change scenarios (Keating et al. 2005).

2.6 Factors affecting maize growth, development and yield

A number of factors are known to affect maize growth, development and yield. These factors can be classified under two broad categories, namely crop genetic factors and environmental factors.

2.6.1 Genetic factors

The rate of development and yield potential of crops such as maize is determined by the genetic makeup of the crop. The increase in grain yield of maize observed over the years is a result of improved cultivars, open pollinated as well as hybrids. Other characteristics such as quality, disease resistance, and drought resistance are determined by the genetic makeup of the crop. The type of cultivar affects the yield component of maize. In a study carried out by Costa et al. (2002) to evaluate the effect of N rates on maize genotypes, it was observed that genotype 3905 consistently yielded best (12.4 and 10.3 t ha-1 in 1997 and 1998, respectively), while the NLRS hybrid performed worst; however, the genotypic grain yield ranking varied between sites. Overall, the yields of cultivar LRS exceeded its conventional counterpart (P3979) by 12 % at one site and by 26 % at another. Similarly, Kogbe and Adediran (2003) conducted an experiment to test the effect of five N rates (0, 50, 100, 150 and 200 kg N ha-1) on three hybrids (8516-12, 8321-18 and 8329-15) and two open-pollinated maize varieties (TZSR-Y and TZSR-W) in Nigeria. They reported that hybrid maize produced higher yields with high N-use efficiency compared to the open-pollinated varieties. They concluded that hybrid 8516-12 had a higher N use efficiency than the other varieties, and all hybrids responded up to 150 and 200 kg N ha^{-1}. In a similar study, D’Andrea et al. (2006) conducted experiments in Argentina to analyze the response of morpho-physiological traits to different N rates of 12 maize inbred lines from different origins (USA and Argentina) and breeding eras (from 1952 onward). Traits considered included canopy structure, light interception, shoot biomass production, yield components and grain yield. Significant differences in these parameters among the genotypes were reported.

2.6.2 Environmental factors

A number of environmental factors affect growth and development of maize. The most important ones are temperature, moisture availability, solar radiation, soil structure, soil reaction, biotic factors and supply of nutrients.

Temperature directly affects photosynthesis, respiration and transpiration (loss of water, absorption of water and nutrients). The rate of these processes increases with an increase in temperature and is different for different crops. The temperature of the soil affects the rate of uptake of water and nutrients from the soil. Water is essential for all plant growth and development and is an integral part of living systems. Crop growth is limited by water stress. Oldeman and Suardi (1977) stated that maize crops need an average monthly precipitation of 100 to 140 mm. They basically take 3 to 3.5 months for optimum growth and will need an average of 300-500 mm of precipitation during this period.

Light is an important environmental factor that affects crop growth and development. It is necessary for photosynthesis and is also a factor of changes in day length needed (photoperiod-sensitive plants) for physiological processes such as growth and which takes place only when a certain number of daylight is assured (Kyei-Baffour 2006).

CHAPTER 3

3.1 Materials and Methods

3.1.1 Rwanda biophysical environment description

Rwanda is endowed with a variety of topography, soils, biodiversity and ecological regions. It is a hilly country with altitudes ranging between 970 and 2,500 m and this confer it a sub- equatorial climate. Temperature is relatively stable during the year, and ranges between 15 and 25 °C depending on the altitude. The highlands also receive more rainfall (> 2,000 mm annually) than do the lowlands, where the annual rainfall totals drop below 1,000 mm. These biophysical characteristics favor a variety of crop production (Verdoot and van Ranst, 2003). Delepierre (1974) delimited 12 agricultural zones in Rwanda, based on differences in altitude, rainfall regime and soil properties. An updated map with agricultural zones is presented below (Figure 3.1). A brief description of the climatic, topographic and edaphic characteristics of these zones has been given below.

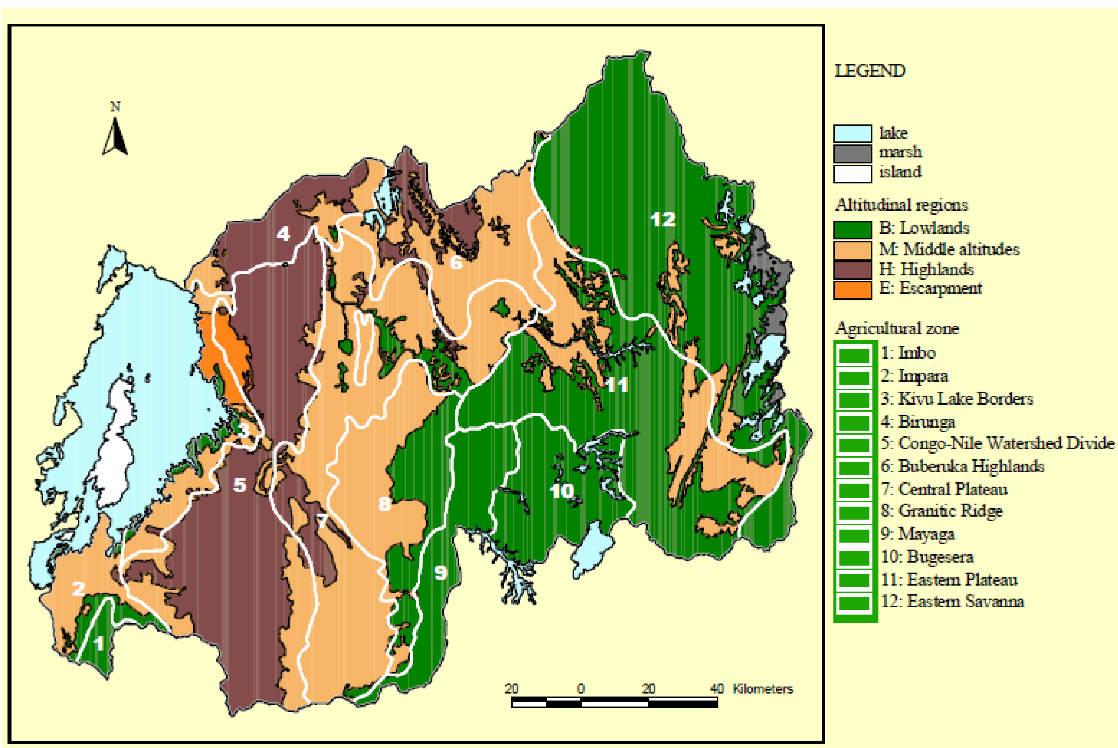

Figure 3- 1 Agro-ecological zones (AEZ) of Rwanda with their altitudinal regions: source: Verdoot and van Ranst, 2003.

Table 3-1 shows the characteristics of the agricultural zones of Rwanda with a qualitative indication of their agricultural values.

Table 3- 1 Characteristics of the agricultural zones of Rwanda (Verdoot and van Ranst, 2003).

Zone	**Altitude**			**Rainfall**			**Soils**	**Agricultural value**
	min	**avg**	**max**	**min**	**avg**	**max**		
1. Imbo	970	1,100	1,400	1,050	1,200	1,600	Alluvial	Excellent
2. Impala	1,400	1,700	1,900	1,300	1,400	2,000	Very fine, red, < basalt	Good
3. Kivu lake borders	1,460	1,600	1,900	1,150	1,200	1,300	Shallow, clay loam	Excellent-good
4. Birunga	1,600	2,200	2,500	1,300	1,500	1,600	Volcanic	Excellent
5.Congo-Nile Watershed Divide	1,900	2,100	2,500	1,300	1,600	2,000	Humiferous, acid	Moderate
6.Buberuka highland	1,900	2,000	2,300	1,100	1,200	1,300	Laterite soil	Good
7. Central Plateau	1,500	1,700	1,900	1,100	1,200	1,300	Humiferous	Good
8. Granitic ridge	1,400	1,600	1,700	1,050	1,100	1,200	Coarse, gravely	Moderate
9. Mayaga	1,350	1,450	1,500	1,000	1,050	1,200	Clayey, < schists	Very good
10. Bugesera	1,300	1,400	1,500	850	900	1,000	Strongly weathered	Poor
11. Eastern plateau	1,400	1,500	1,800	900	950	1,000	Laterite soil	Moderate-good

12.	Eastern savanna	1,250	1,400	1,600	800	850	900	Strongly weathered	Very poor

3.2 Study area

This study was carried out in Bugesera and Birunga agro-ecological zones.

3.2.1 Site in Bugesera

Bugesera is a large plateau located at an altitude of 1,300 to 1,500 m and bordered by the fluvial depositions of the Nyabarongo. A more recent erosion cycle superimposed a new drainage system and resulted in a landscape of smaller isolated plateaus with deep strongly weathered soils, intersected by dry valleys with very gentle slopes. From a climatic viewpoint, this agricultural zone is dry and warm, characterized by an annual rainfall varying between 850 and 1,000 mm, a dry season lasting for three months and an average temperature of about 21 °C . The Bugesera AEZ was described by Verdoot and van Ranst (2003).

The experimental site was in the Bugesera agro-ecological zone on latitude of 09739863N; longitude of 00529455E and the elevation of 1397 m above sea level. The site is bimodal, with primary and secondary peaks in April and November; average daily temperature of 21ºC. A short dry season: January to mid-march, Long rainy season: mid-march to June, Long dry season: mid-June to September, and a short rainy season: mid-October to December. The selected site was formerly farmed with maize or sorghum and bush beans in rotation. Soils at Bugesera are humic and haplic Ferralsols with depth ranging from 100-200 cm.

3.2.2 Site in the Volcanic Highland (Birunga)

The AEZ of the Birunga groups the volcanic soils that descend from the limit of the national park at an altitude of 2,500 m to an altitude of 1.900 m near Musanze district and even below 1,600 m near Rubavu district. Regularly distributed rainfall, varying between 1,300 and 1,600 mm and fertile soils create favorable conditions for agricultural production. The experimental site was is in the southern part Birunga AEZ (latitude, 09814126N; longitude, 00428135E; elevation, 1946 m) near Gishwati forest. Mean annual rainfall at Gishwati is 1,400 mm and has a bimodal rain pattern, with primary and secondary peaks in April and November; average daily temperature of 16ºC. The fields was previously farmed with 2 cropping seasons under maize and climbing beans or potatoes in rotation before being selected for the present study. The soils in this site are dominated by mollic

Andosol and humic Cambisol derived from volcanic materials. Soil depth ranges from 100 to 150 cm in farmer's fields (Verdoot and van Ranst, 2003).

3.3. Establishment of field experiments

Trials was established in August 2014 in farmers' fields. Three replicates per site were followed until harvest. Plots of 10 x10 m were used and effort was made to select replicates having identical soils and historical management. Fertilizers' application has followed farmers' practice; 100kg of DAP per ha at planting and 50kg of Urea/ha for topdressing. In Bugesera, the maize used is an open pollinated variety called ZM607 while in the volcanic highlands, a hybrid named PAN691 was used.Cultivar ZM607 is a late maturing maize population with white, mixed dent and flint kernels adapted to mid altitude environments while PAN691 is a hybrid adapted to humid high altitude of Rwanda.

Maize was grown for 2 consecutive seasons (1 year). Maize was grown at a spacing of 0.4 m within rows and 0.8 m between rows. The first and second maize crop was grown in 2014 short rains (September-February) and in 2015 long rain season (February-June) respectively.

3.4.Soil moisture

Access tubes of 1 m deep were permanently installed in the middle of all maize plots. Profile probe (PR2 type) were used to measure soil moisture at depth of 100, 200, 300, 400, 600 and 1000 mm at the interval of 30 days throughout the maize growing season. Three readings in each tube were taken by rotating the probe through 120° each time; the three small screw heads were used for this purpose. The calibrated conversion formulae for mineral soils, supplied by the manufacturer, were used to obtain volumetric soil moisture from the millivolt data recorded by the sensors. The recorded soil moisture was used in APSIM simulations.

3.5.Maize harvest

Biomass and grain yield at maturity were determined for each plot. Cob number and shoot and grain dry weight was determined in each plot. Plant number per plot was determined before cutting the plants at ground level. Cobs and stover and was weighed separately. Cobs weighing 500 g were sampled and placed in labeled bags and dried at 60ºC for one week.

Grain dry weight was determined after shelling the cobs. Total grain dry weight for all plants in each plot was determined by multiplying the grain dry weight: cob fresh weight ratio for the sub-sample by the total fresh weight of cobs from all plants in the same plot. Stover fresh weight was determined in each plot before taking a 500 g sample for drying at 60ºC for one week. Total stover dry weight per plot was determined by multiplying the dry: fresh weight ratio for the sample by total fresh biomass for the same plot.

3.6.Soils analysis

Soil sample was taken from all the 3 farmer's fields in each site and was analyzed from the soil and plant laboratory of the University of Rwanda.

3.6.1. Soil pH

A total of 20 g (two replicates of 10 g each) of dried and pestled material of each soil sample (P10-13) was weighed in a 60 milli-liter (ml) bottle then 25mL distilled water (for pH water) was added with a dispenser. The mixture was stirred for 10 minutes, allowed to stand for 30 minutes (min) and stirred again for 2 min. The pH_{H2O} (active acidity) value was then measured using a glass electrode PT 100 for 30 to 60 seconds until the values remained constant (Okalebo *et al*., 2002). The electrode was then removed from the bottle, rinsed with distilled water before introducing it to the next sample. Similar procedures was again used but this time using KCl 1 M as extractant to determine the pH KCl which is a measure of potential or reserve acidity in soil extracts.

3.6.2. Total Nitrogen

Air-dried soil material was sieved through < 2 mm sieve and ground into fine powder and then sieved <0.25mm (60 mesh). A sample of 0.3 g of this soil was weighed into a labelled, dry and clean digestion tube and 2.5 ml of a digestion mixture (salicylic acid dissolved in sulphuric acid-selenium mixture) was added to each tube and the reagent blanks for each batch of samples. They was then digested at 110^0C for 1 hour, left to cool and added three successive 1ml portions of hydrogen peroxide before raising the temperature to 330^0C.

When the solution turned colourless and the remaining sand white, it was allowed to cool and 25 ml distilled water was added to it and mixed until no more sediment dissolved.

Total N was then determined in the digests through distillation whereby free ammonia was liberated from solution by steam distillation in the presence of excess alkali (Na0H). The distillate was collected in a conical flask containing excess boric acid with drops of mixed indicator. Titration of the distillate was then carried out using N/140 HCl until colour changed from green to pink. The total ml of N/140 HCl used was recorded and used to determine total N using the formula in Appendix 2. The total P and K determination of 5.0 ml sample for each was carried out by colorimetric without pH adjustment using ascorbic acid in a colorimetric measurement and total N was calculated as recommended by Okalebo *et al.*, (2002).

3.6.3. Available Phosphorus

Two grams of soil was weighed into a 50 mL Erlenmeyer flask, tapping the scoop on the flask to remove all of the soil from the scoop. Twenty mL of extracting solution (reagent-grade ammonium fluoride (NH_4F) mixed with distilled water and 250 mL of previously standardized 1M HCl was added to each flask and shaken at 200 rpm or more for 5 minutes at a room temperature (24 to 27^0 C). Extracts was filtered using Whatman No. 42 filter paper. Phosphorus was then analyzed by colorimetry using a blank and standards prepared in the Bray P-1 extracting solution (Bray and Kurtz, 1945).

3.6.4. Soil organic Carbon

Organic carbon in soils was determined by the sulphuric acid and aqueous potassium dichromate ($K_2Cr_2O_7$) mixture. A sample of 0.30 g of ground soil (<0.5mm) was weighted out into a clean labelled 100 ml digestion tube and added 2ml of distilled water. Ten ml 5% of Potassium dichromate solution was added and it was allowed to completely wet the soil and standards was prepared (Sucrose Carbon stock 50mg/ml used to make 20, 15, 10, 5 and 0 mg C standards). Slowly and carefully, 5 ml H_2SO_4 from a slow burette was added and the mixture was gently swirled to mix. It was then digested at 150^0C for 30 min and allowed to cool after which 50 ml of 0.4% barium chloride was added. It was swirled to mix thoroughly, then brought to 100 ml mark by distilled water and allowed to settle overnight so as to leave a clear supernatant solution.

An aliquot of the supernatant solution was transferred into a cuvette, and measurement of absorbance of the standards, the sample and the blank at 600 mm was performed. The content of total organic carbon in air dry soil expressed in %C was then calculated by the pilot program as described by Okalebo *et al*., (2002).

3.6.5. Bulk density

Bulk density was determined using a bulk density ring to take soil samples. Samples were then oven dried at 105 °C for 24 hours, and the dried weight recorded. Bulk density was calculated by dividing the oven-dried soil mass by volume of the cylinder (Landon, 1991).

Bulk density ℓb (g cm $^{-3}$) = $(M_2 – M_1)/ V$

Where M_2: Mass of the core cylinder + oven dried soil

M_1: Mass of empty core cylinder

V : Volume of core cylinder (πr^2h).

3.6.6. Soil particle size analysis

A sample of 50 g of air dry <2 mm soil was weighed out into a 400 ml beaker and was saturated with distilled water before adding 10 ml of 10% calgon solution. The suspension was transferred to the dispersing cup and about 300 ml of tap water added to it. The suspension was mixed for two minutes with an electric high speed stirrer then transferred into a graduated cylinder. The cylinder was covered with a tight-fitting rubber band and the suspension was mixed by inverting the cylinder carefully ten times. The time was noted and 2-3 drops of amyl alcohol was quickly added in order to remove froth and after 20 seconds the hydrometer was gently placed into the column. The hydrometer readings and thermometer measurements at 40 seconds was recorded. The cylinder was covered again with a tight-fitting rubber band and the suspension was mixed by inverting the cylinder ten times and then allowed to stand undisturbed for 2 hours after which both hydrometer and temperature readings was taken. The % sand, silt and clay was then calculated as described by Okalebo *et al*., (2002).

3.7. Measurements of weather and Acquisition of TAMSAT weather data

The rainfall was measured using an integrated sensor suit of Davis weather station installed in less than 1 km from the experimental site. The station will automatically log data each hour from the beginning to the end of the experiment. The data logged includes: Rainfall, temperature, relative humidity, wind speed and direction as well as solar radiation. TAMSAT daily rainfall data was downloaded from the TAMSAT website using tamsat data extractor. Csv files will then be downloaded and analyzed. This is done using time series selection per pixel and choosing the GPS coordinates matching with the location of the weather data on ground to be able to compare satellite and ground station data.

3.8. Simulation techniques with APSIM

Crop simulation models are state-of the-art technology that enables users or researchers to estimate the growth, development and yield of crops using management strategies and environmental factors as input parameters (Mavromatis et al., 2001). A framework is provided by the model that uses a range of component modules. These modules, which are plugged into one main model (e.g., APSIM, CropSyst, CERES and DSSAT) engine, can be managerial or biological, environmental and economic (Jones et al., 2001; Keating et al., 2003). The models are built such that they use in-built algorithms that express the correlation between plant growth processes (transpiration, photosynthesis, physiological development, biomass growth and partitioning, and nutrient and water uptake) and environmental driving forces (e.g., daily temperature, photoperiod and available soil water). In the APSIM model, there is integration of cultivar-specific genetic coefficients which estimate growth and development on daily basis and response of plants to environmental factors such as weather, soil and management practices (Boote et al., 1998).

The Maize module has 11 crop stages and 9 phases (time between stages). Commencement of each stage is determined by accumulation of thermal time except during the sowing to germination period which is driven by soil moisture. The phase between emergence and floral initiation is composed of a cultivar-specific period of fixed thermal time, commonly called the basic vegetative or juvenile phase. Between the end of the juvenile phase and floral initiation the thermal development rate is sensitive if the cultivar is photoperiod sensitive (for further details see the documentation of APSIM Maize under http://www.apsim.info/Wiki/Maize.ashx.

Field data on soil moisture in different depths, soil chemical parameters, weather data and the management practices were used in the module of continuous maize to build a simulation tree. The dataset generated from field work was used to evaluating the performance of APSIM to simulate the complex of climate (data from satellite and data from weather stations on site), soil and plant interactions and effects on crop growth and yield. The comparison of APSIM simulations with observed data was conducted. Different APSIM runs using two different weather files was compared to analyze the differences in simulated yields.

3.9.Sensitivity analysis of APSIM

Sensitivity analysis is done on a model to determine how sensitive the output of the model is to changes in the input parameters in order to understand the comportment of the model. If a small change in an input parameter results in relatively large changes in the output, then the outputs are said to be sensitive to that parameter. This implies that the particular parameter concerned has to be determined more accurately. Sensitivity analysis helps the user to determine, in order of priority, the parameters that show the highest contribution to the output variability (Lenhart et al., 2002).
Models in general have several parameters, and the user has to parameterize the model by adjusting the parameter based on certain criteria to obtain a best fit between the model output and measured data. Knowing the input parameters in the environmental module (temperature, rainfall and radiation) that are sensitive to the model output, the focus was on these parameters during simulations to produce outputs using weather station data and TAMSAT data while maintaining similar parameters in Biologic and Management modules of APSIM.

3.10. Model evaluation

To evaluate the APSIM model, data from the experiments for model evaluation for both long and short rainy seasons were used. The model was run for two sites for each season. For the site Bugesera, soil type used in the model was clay deep with medium fertility from Africa-generic soil module. This was fairly corresponding to the Humic Ferralsol in the experimental site. For Birunga site, soil type used in the model was sandy deep with high fertility from Africa-generic soil module as well. It was also fairly comparable to the Mollic Andosol on the site.

Sowing density was 4.4 plants m^{-2} and sowing done on 23rd September 2013 (Season 2014A) and on 27th February 2014 (Season 2014B) for Bugesera. Sowing density for Birunga was 4.4 plants m^{-2} and sawing done on 20th September 2013 (Season 2014A) and on 25th March 2014 (Season 2014B). During the model evaluation process, measured data on maturity date for maize grain yield and Stover biomass were compared with simulated values.

For the Mollic Andosol in the volcanic highland AEZ of Rwanda, soils characteristics used in APSIM simulations were from the built-in Generic Soil Profile Database (Koo and Dimes, 2010) called Sand_HF_111mm. This default file was modified by replacing some default soil properties by data from soil analysis. For the Humic Ferralsol in the Bugesera AEZ, soil properties used in APSIM simulations were also from the same source but called Loam_Deep_MF (Koo and Dimes, 2010).

3.11. Statistical analysis

The results were analyzed by Analysis of Variance using Genstat (4th edition) software. Pair-wise comparison, one to one lines and other statistical tests were used. Model validity was tested using three goodness of fit indicators, the root mean square error (RMSE) (Kobayashi and Salam, 2000), the mean absolute error (MAE), and the index of agreement (d) (Willmott et al., 1985). Their formulae are the followings:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Yi - \hat{Y}i\right)^2}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|Yi - \hat{Y}i|$$

$$d = 1 - \frac{\sum_{i=1}^{N}|Yi-\hat{Y}i|}{\sum_{i=1}^{N}(|\hat{Y}i-\bar{Y}|+|Yi-\bar{Y}|)}$$

Where Yi and $\hat{Y}i$ are the observed and predicted Y values, respectively, and $\bar{Y}$ is the mean of the entire N of observed Y values. Low values of RMSE and MAE illustrate high accuracy whereas high d indicates high accuracy.

CHAPTER 4

4.0 Results and discussions

4.1 TAMSAT rainfall estimates

With the help of data extractor, daily rainfall data from 30th June 2013 to 30th June 2015 were extracted for the pixel in Rubavu district (Birunga AEZ, latitude: -1.6482, longitude: 29.3828) Figure 4-1 shows the daily rainfall from August 2013 to June 2015 while Figure 4-2 shows the cumulated rainfall in the same period.

4.1.1 TAMSAT rainfall in the Birunga AEZ (humid highland)

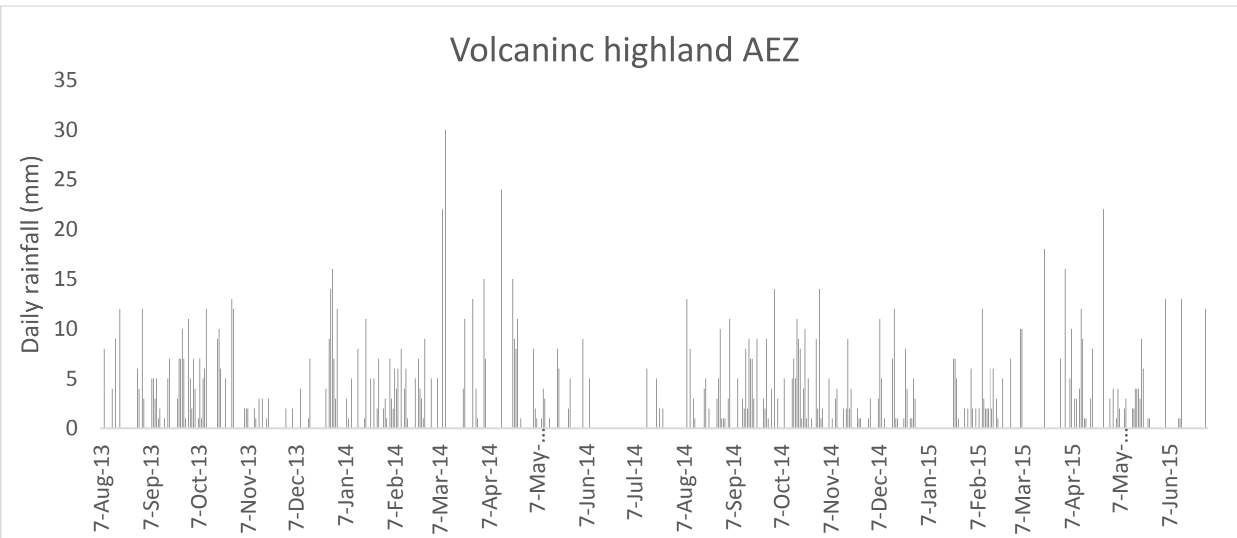

Figure 4- 1 TAMSAT daily rainfall in the Birunga AEZ of Rwanda

Figure 4-1 shows that maximum daily rainfall in each year is received between March and June (agricultural season B) but the daily distribution of rain throughout the months is very scattered than in season A which goes from September to February.

4.1.2 TAMSAT rainfall in Bugesera AEZ (semi-arid mid-altitude)

With the help of data extractor, daily rainfall data from 30th June 2013 to 30th June 2015 were extracted for the pixel in Bugesera AEZ (Bugesera AEZ, latitude: -2.3535, latitude: 30.2649). Figure 4-2 shows the daily rainfall in the above mentioned period. It highlights that maximum daily rainfall is reached in March of each year.

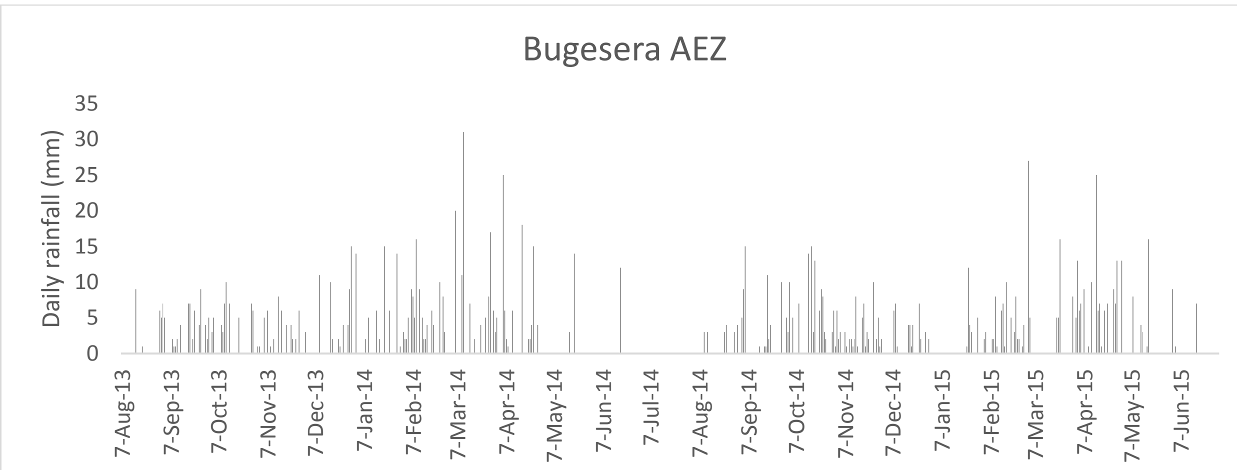

Figure 4- 2 TAMSAT daily rainfall in the Bugesera AEZ of Rwanda

Figure 4-3 shows concurrent increase of rainfall in both humid highland and semi-arid lowland. However, these TAMSAT data show higher rainfall in the Birunga than in Bugesera AEZ. For a period of 2 years, total rainfall in the Birunga is reported to be 1,424 mm while it is about 1,311 mm in Bugesera AEZ. Data indicate that the dry spell period elongates from May to August. Daily rainfall is well distributed in the A agricultural season (September to February) while steep slopes are found in the B agricultural season that goes from end February to early June.

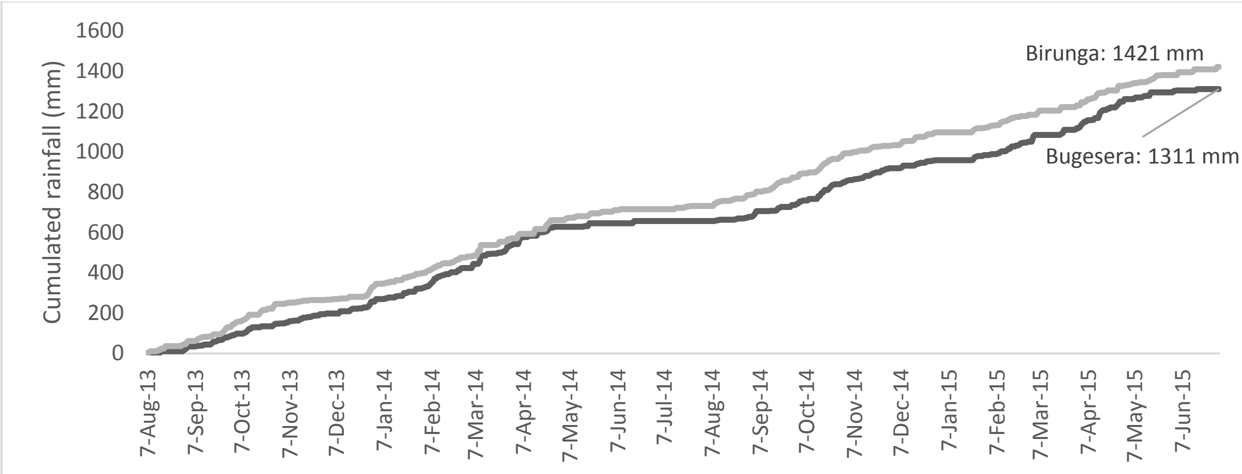

Figure 4- 3 Comparison of the cumulated daily rainfall in the Birunga and in Bugesera AEZ.

4.2 Rainfall records from weather stations

4.2.1 Weather station rainfall in Birunga AEZ

Weather station installed in the Birunga AEZ (latitude: -1.6482, longitude: 29.3828, altitude: 1,946 m) recorded hourly rainfall. Figure 4.4 shows the daily rainfall from August 2013 to June 2015.

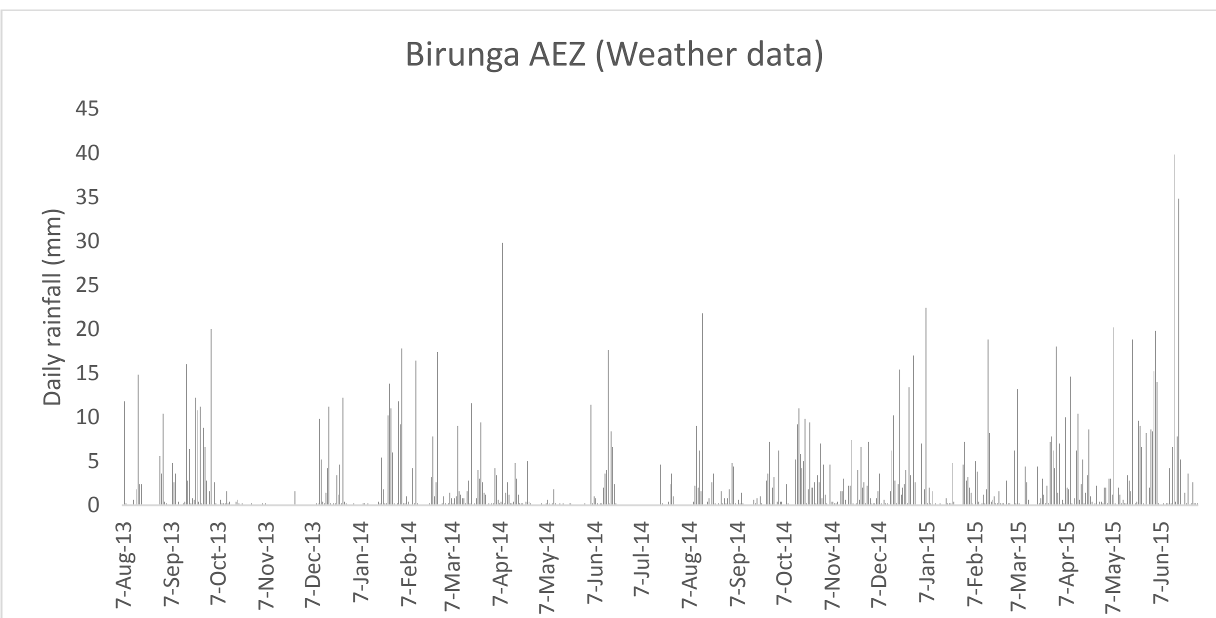

Figure 4- 4 Weather station daily rainfall in the Birunga AEZ of Rwanda

4.2.2 Weather station rainfall in semi-arid lowlands

Figure 4.7 presents the daily rainfall recorded by weather station from August 2013 to June 2015. The month of July and August had almost no rainfall in this semi-arid region.

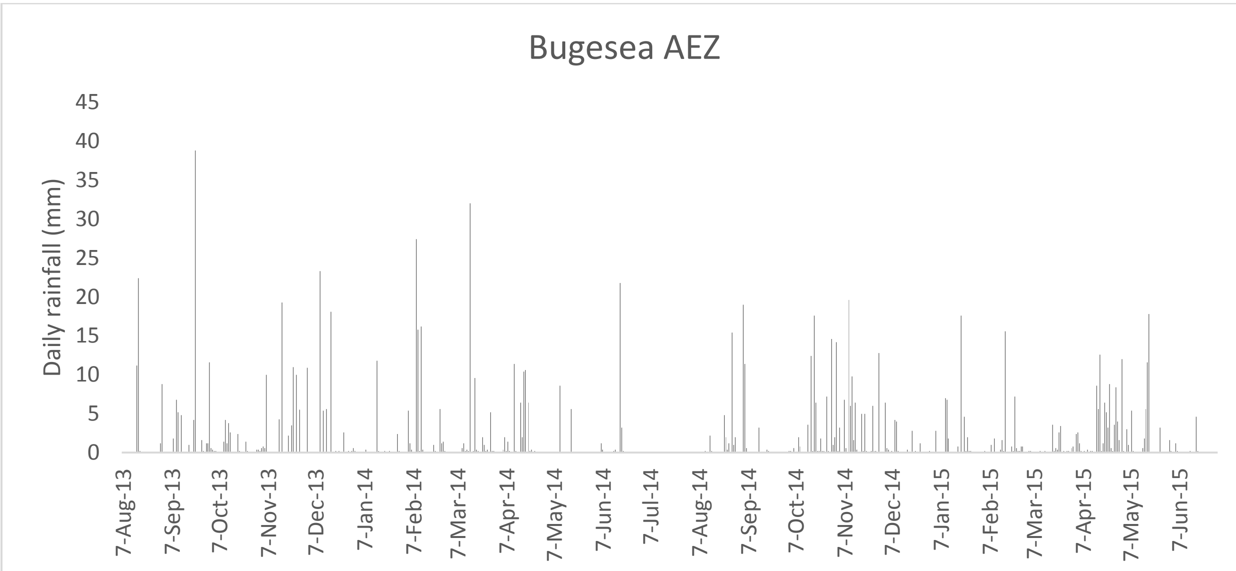

Figure 4- 5 Daily rainfall recorded on Bugesera weather station

Figure 4-6 compares the rainfall recorded in the Birunga and in the Bugesera AEZ. Curves show higher rainfall in the Birunga than in Bugesera AEZ as expected.

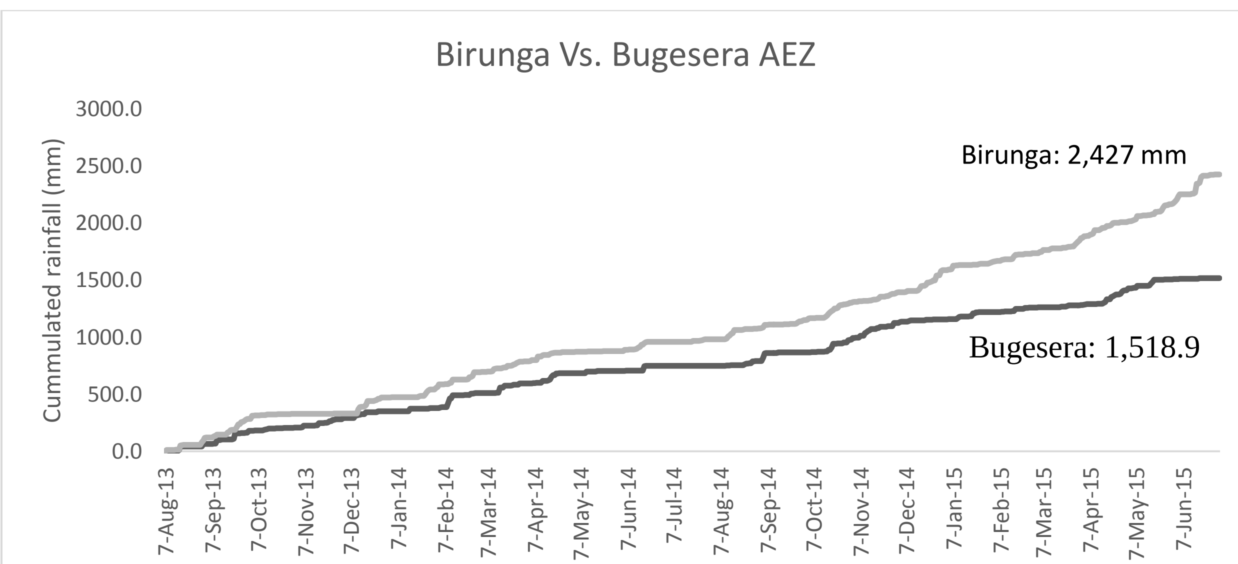

Figure 4- 6 cumulative daily rainfall recorded in the Birungas and in Bugesera AEZ

The above figure shows a fairly good distribution of rainfall throughout the year as no steep slopes are remarkably seen on the curves. However, it shows that in the Birunga AEZ, there was a shortage of rainfall during the agricultural season 2014 A (September 2013 to February 2014) which was comparable to the dry spell in August. During the 2 years investigated, TAMSAT data stipulates that after season 2014A, rainfall in the semi-arid (Bugesera AEZ) rose to almost the same total amount of rainfall with the humid highland (Birunga AEZ).

4.3 TAMASAT rainfall accuracy testing in Bugesera AEZ

Figure 4-7 and Figure 4-8 compares results from TAMSAT rainfall estimates and those from weather stations in Bugesera AEZ.

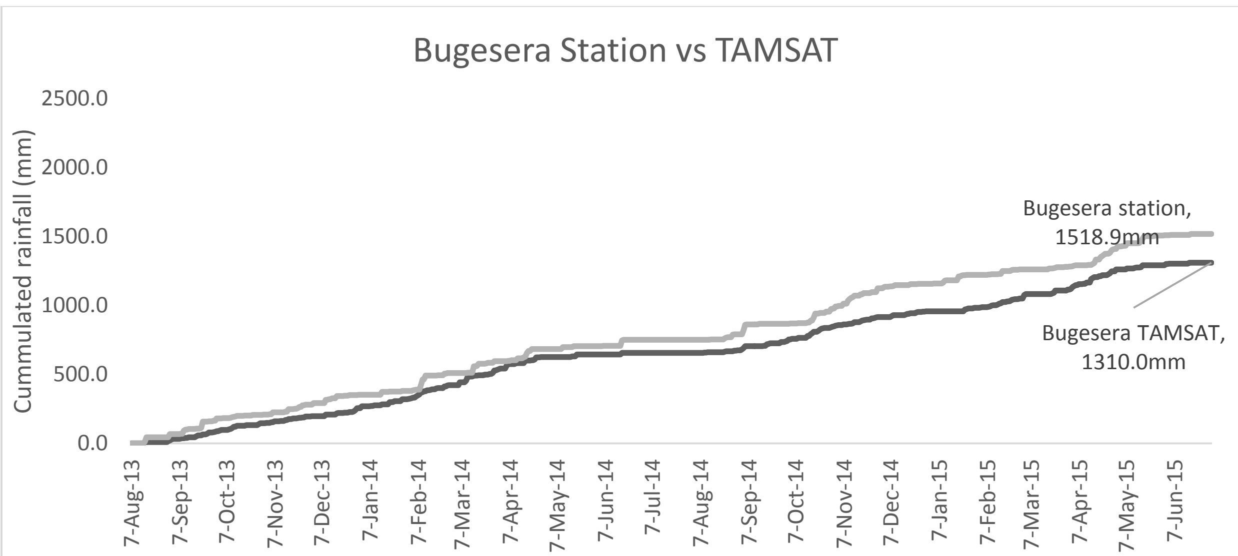

Figure 4- 7 Cumulative daily rainfall recorded on weather station vs estimates from TAMSAT in Bugesera AEZ

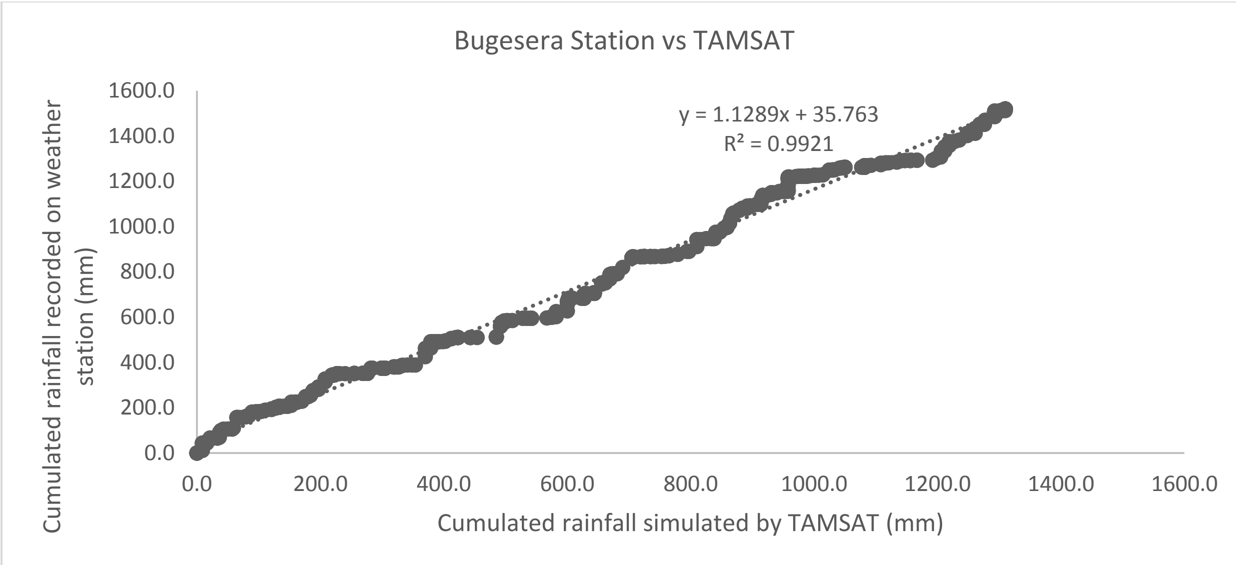

Figure 4- 8 Cumulated daily rainfall using data from TAMSAT vs weather station in Bugesera AEZ

TAMSAT slightly underestimated the rainfall received in Bugesera AEZ (semi-arid). TAMSAT estimated the total rainfall in the study period to be 1,310.0 mm while the actual rainfall received was 1,518.9 mm (Figure 4.10). This slight difference may be due to lack of one-off local calibration to account for variations with geographic location, time of year, character of season, topography and local storm climatology. However, the cumulated daily rainfall estimated by TAMSAT is strongly correlated (R^2 = 99%) to the one recorded by the weather station in Bugesera. This indicates that the model (Figure 4.11) explains almost all the variability of the response data around its mean.

Though there was no validation experiments in Rwanda for TAMSAT data, the comparison of downloaded daily rainfall estimates and the observed values demonstrates that the TAMSAT algorithm performs very well in the semi-arid (Bugesera AEZ) region of Rwanda. In their validation experiments Dinku et al., (2007) in Ethiopia and Jobard et al. (2007) in the Sahel and Thorne et al., (2001) in South Africa found that the TAMSAT algorithm was performing consistently. This may be due to the fact that TAMSAT algorithm is only suitable if the rainfall is convective in nature while it is known that rainfall in Africa typically comes from tall, convective systems characterized by cold cloud tops.

Figure 4-9 presents a 1 to 1 comparison of daily rainfall as estimated by TAMSAT and the daily rainfall recorded by on ground weather station in Bugesera.

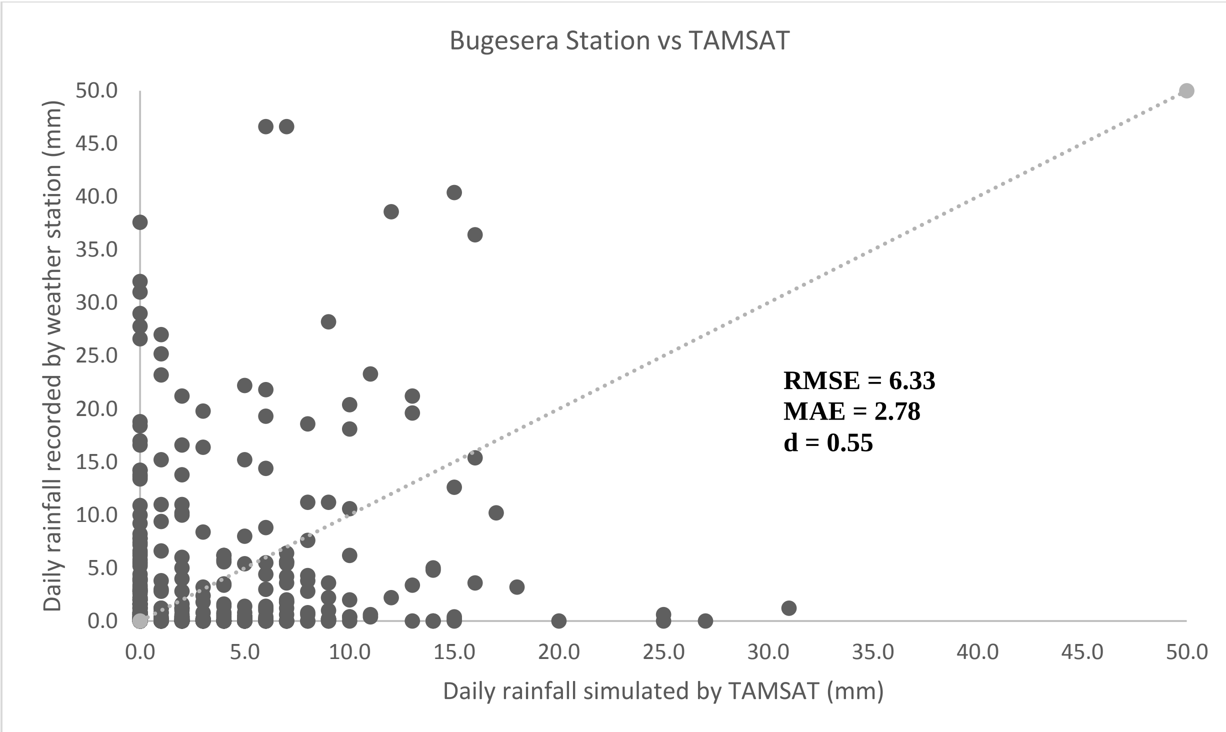

Figure 4- 9 Scatter plot of measured versus estimated daily rainfall together with one on one line in Bugesera AEZ. RMSE, MAE and d indicates root mean square error, mean absolute error and index of agreement respectively.

The key factor for testing model performance is the difference between the simulated (estimated) values of the model, and measured values. A simple way to analyze model performance is to make a scatter plot of model predictions and measurements. Such a scatter graph provides an immediate general impression of how closely predictions and observations cluster around the 1:1 line of perfect correspondence. For the TAMSAT estimated daily rainfall versus measurements (Figure 4.12), TAMSAT seems to perform reasonably well in the semi-arid region (Bugesera AEZ).

Root mean square error of 6.33 and mean absolute error of 2.75 seem enough low for rainfall estimation, suggesting that the rainfall estimated by TAMSAT is closer to the real rainfall recorded on weather station. Normally an index of agreement of 0 means little or no agreement while an index less than 0.5 might suggest greater diversity, inconsistence and spread among predicted observations.

In the case of Bugesera AEZ, the index of agreement (d) calculated was 0.55 and high enough to conclude that TAMSAT rainfall estimation is satisfactory in this zone even though the estimation could be furthermore improved by local calibration.

4.4 TAMASAT rainfall accuracy testing in the Birunga AEZ

Figure 4-10 and Figure 4-11 compares results from TAMSAT rainfall estimates and those from weather station in the Birunga AEZ.

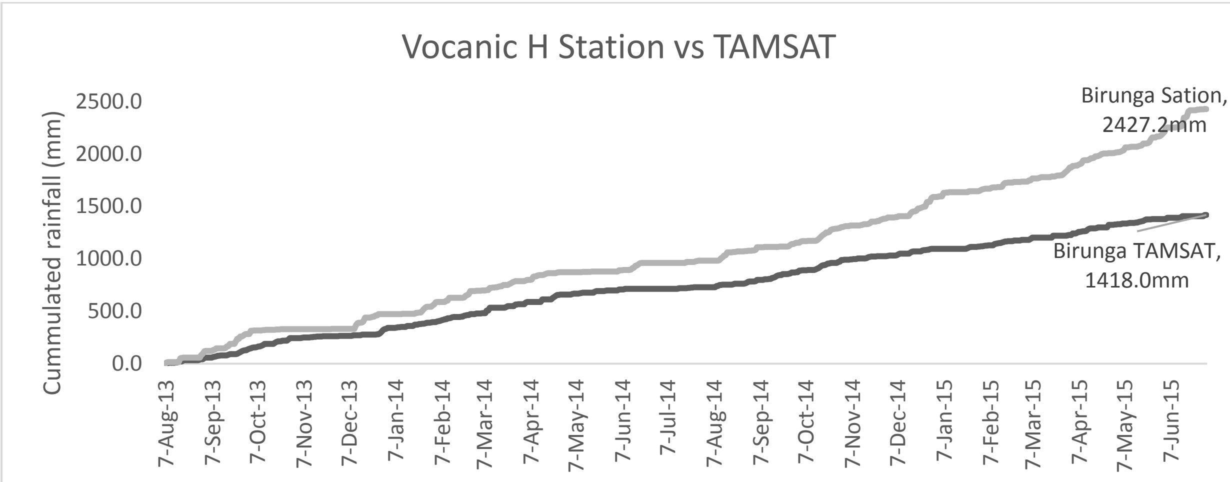

Figure 4- 10 Cumulative daily rainfall recorded on weather station vs estimates from TAMSAT in the Birunga AEZ

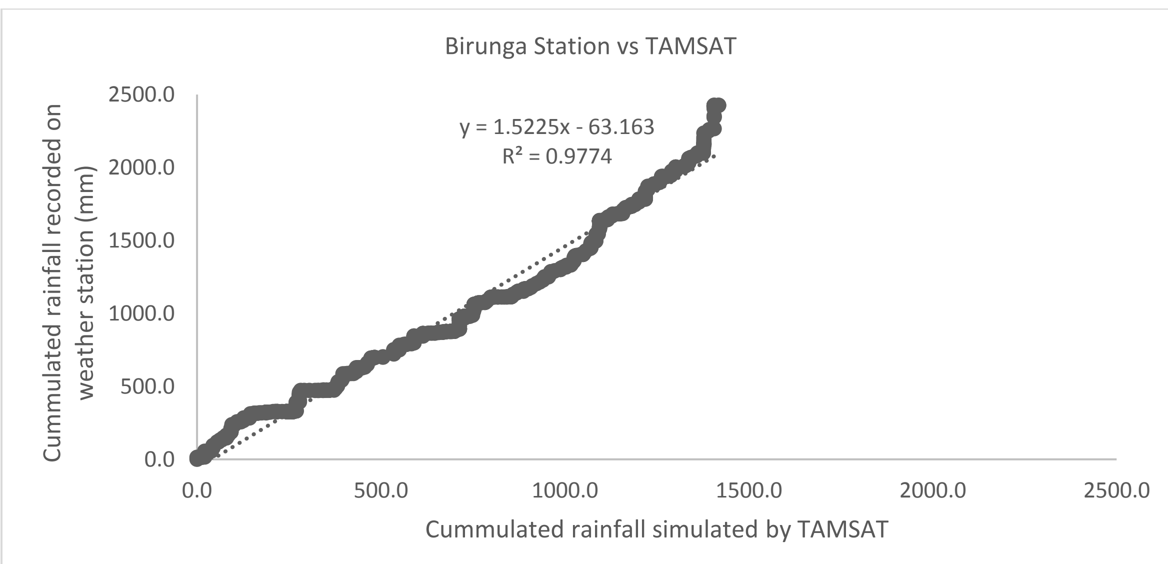

Figure 4- 11 Cumulated daily rainfall using data from TAMSAT vs weather station in the Birunga AEZ

Despite the concurrent growth and similar trend of both TAMSAT estimates and weather station measurements of the cumulated daily rainfall, TAMSAT significantly underestimated the rainfall in the humid highlands (Birunga AEZ). In the whole study period, the latter estimated the total rainfall to be 1,418 mm while the actual rainfall received (recorded on station) was 2,427.2 mm (Figure 4-10). The regression equation presented in Figure 4.14 shows that it can highly explains variability of data but when rainfall is cumulated for long period, the estimations diverge from the real measured values.

Figure 4-12 presents the Scatter plot of measured daily rainfall against the TAMSAT estimated daily rainfall in the humid highland of Rwanda (Birunga AEZ).

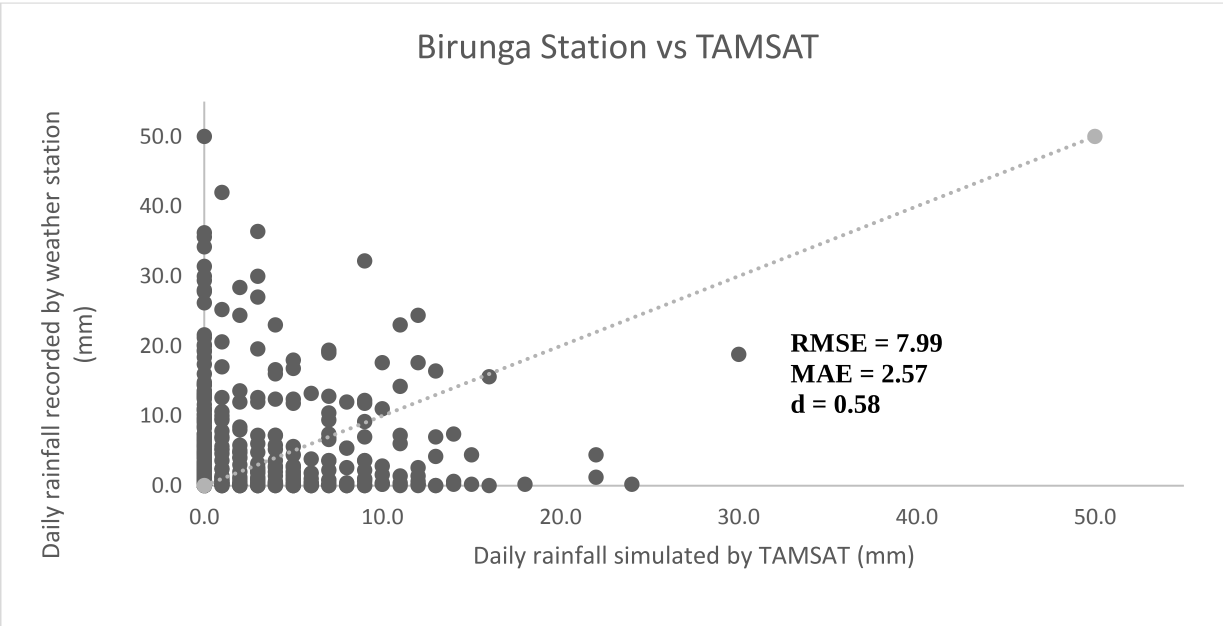

Figure 4- 12 Scatter plot of measured versus estimated daily rainfall together with one on one line in the Birunga AEZ. RMSE, MAE and d mean root mean square error, mean absolute error and index of agreement respectively.

Figure 4-12 shows that more points are above the one on one line which implies that TAMSAT underestimated the daily rainfall in the Birunga.

Root mean square error of 7.99 and mean absolute error of 2.57 were low but suggesting a wider skewness in under prediction. However, the index of agreement (d) of 0.58 calculated shows that most of the times when rainfall was recorded, it was concurrently predicted by TAMSAT despite the inequalities in the amount of rainfalls.

It is know that tropical highland areas, especially those with complex topography such as the Birunga AEZ, have presented a considerable challenge to users of satellite rainfall estimation methods because of complex local rainfall variations and the occurrence of non-convective rainfall. It is to be recalled that TAMSAT assumes both that the significant rainfall in the monitored area is convective and that there is a linear relationship between the length of time that convective clouds are present and the amount of rain that falls. This generally restricts the method to the tropical and sub-tropical regions with less mountains where convective rainfall predominates over frontal or orographic rainfall. This is probably the reason why TAMSAT better estimated rainfall in Bugesera AEZ (slightly flat with round hills) than in the Birunga AEZ (very hilly). In their studies, Tucker et al., (2001) found that TAMSAT estimated better the rainfall in the arid and semi-arid regions of northern Kenya but poorly in the more humid western Kenya and very poorly in the eastern highlands from Nairobi northwards.

4.5 Initial soil properties

Table 4.1 presents soil chemical and physical properties from two sites in the selected agro-ecological zones (Birunga and Bugesera AEZ) at the onset of the field experiment during the short rain season of 2014A.

Table 4- 1 Soil chemical and physical properties at the beginning of the field experiment (Season 2014 A)

Site (AEZ)	Depth (cm)	pH (water)	% C	% SOM	% N	P avail. (ppm)	Bulk Density (g/cm^3)	% clay	% silt	% sand
Birunga	0-20	5.90±0.01	4.27±0.48	7.36±0.82	0.52±0.02	1.71±0.13	1.58	9	25	66
Birunga	20-40	5.87±0.03	4.83±0.05	8.33±0.09	0.46±0.02	2.37±0.31	1.58	9	25	66
Birunga	40-60	6.00±0.01	4.35±0.39	7.49±0.67	0.46±0.05	1.95±0.55	1.59	9	25	66
Bugesera	0-20	5.70±0.02	1.84±0.19	3.17±0.33	0.08±0.00	9.02±0.84	1.41	17	15	68
Bugesera	20-40	5.09±0.02	1.73±0.24	2.98±0.41	0.06±0.01	5.00±0.21	1.40	25	9	66
Bugesera	40-60	4.79±0.02	1.42±0.11	2.45±0.19	0.07±0.00	6.11±0.32	1.40	29	7	64

The site in the Birunga AEZ was sandy loam. As expected, the mollic andosol from the Birunga had a medium pH. The parent material is a volcanic rock (igneous rock), a mafic basalt rich in base minerals such as pyroxene and calcium-rich feldspar. For this reason, the pH of deepest soil horizon was slightly higher than the overlying horizons. This type of soil develops on volcanic glasses and ejecta, mainly ash, but also tuff, pumice and cinders. The environment where this soil develop is in undulating to mountainous, humid regions such as in the Birunga of Rwanda.

Results showed that soil in the Birunga had a medium range of organic carbon (4.27% to 4.83%), around double of the amount found in the humic ferralsol of Bugesera. In these mollic andosols, rapid weathering of porous volcanic ejecta or glasses results in accumulation of stable organo-mineral complexes or short-range-order minerals such as allophane, imogolite and ferrihydrite (IUSS Working Group WRB, 2006). According to the interpretation norms of Landon et al., (1991), the total nitrogen was also high (0.46% to 0.52%) and this was probably due to the relatively high fertilizer use in this region compared to the rest of the country (Kelly et al., 2002).

In addition, the higher soil organic matter would explain the higher total nitrogen found in these soils. Available soil phosphorus in the andosol of the Birunga was very low (1.71 ppm to 2.37 ppm) according to the interpretation norms of Mutwewingabo and Rutunga (1987). This may be due to the strong phosphate fixation of andosols caused by active Al and Fe (IUSS Working Group

WRB, 2006). Ameliorative measures to reduce this effect may include application of lime, organic material, and phosphate fertilizer.

The site in Bugesera AEZ had a sandy clay loam soil. The soil in the experimental site is humic ferralsol with a lower pH especially in the deeper horizons. Deep and intensive weathering has resulted in a residual concentration of resistant primary minerals (e.g. quartz) alongside sesquioxides and kaolinite. This mineralogy enhance the relatively low pH and explain the stable microstructure (pseudo-sand) and yellowish (goethite) or reddish (hematite) soil colors (IUSS Working Group WRB, 2006). The soil had low content of organic carbon (2.45% to 3.17%)

It is know that ferralsols are normally low in total nitrogen, however, the site in bugesera had an extremely low total nitrogen (0.06% to 0.08%). This may be due to the longtime continuous cultivation of the fields without fertilizing. The available soil phosphorus was low (5.00 ppm to 9.02 ppm) in Bugesera and this may be due to the strong retention or fixing of phosphorus of the ferralsols. Slow release phosphate (phosphate rock) should be applied at a rate of several tonnes per hectare to eliminate P deficiency and for a quick fix, much more soluble double or triple superphosphate should be used.

4.6 Field experiment maize yields

Figure 4-13 and Figure 4-14 presents maize stover and maize grain yields respectively. Results presented concern the 2014 A and 2014 B agricultural seasons in both Bugesera and Birunga AEZ of Rwanda.

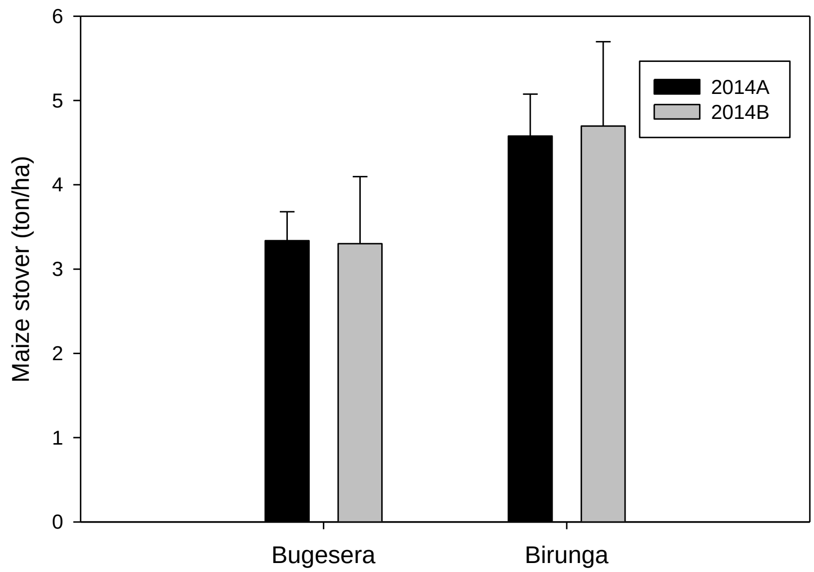

Figure 4- 13 Maize stover in Bugesera and Birunga AEZ during the short and long rain seasons of 2014. Data are means of three replicates ± S.D.

In Bugesera, maize stover was lower than in the Birunga for both agricultural seasons (2014A and B). However, there was no significant difference of maize stover yields among seasons. The higher maize stover yields in the Birunga may be due to the hybrid variety (PAN 691) which is known to have more robust stalks than the open pollinated variety (ZM607) used in Bugesera AEZ. In addition, the mollic andosols in the Birungas had higher fertility than the humic ferralsol in the Bugesera AEZ.

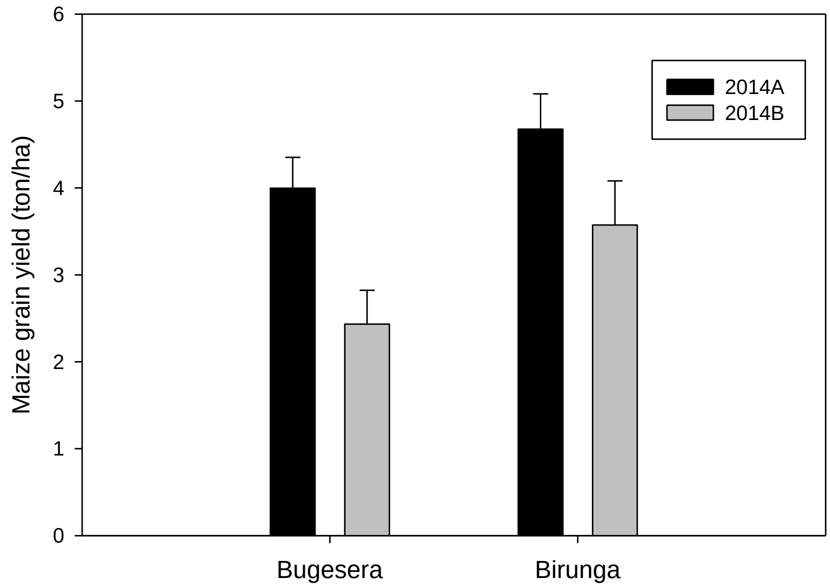

Figure 4- 14 Maize grain yield in Bugesera and Birunga AEZ during the short and long rain seasons of 2014. Data are means of three replicates ± S.D.

Maize grain yield was higher in the Birunga than in Bugesera AEZ (Figure 4-14). This is due to the high performance of the highland maize hybrid (PAN 691) compared to the open pollinated maize variety (ZM607) used in Bugesera AEZ. Furthermore, the mollic andosol in the Birunga had higher pH, organic carbon and total N than the humic ferralsol in Bugesera AEZ (Table 4.1). Higher rainfall with good distribution throughout the season in the Birunga than in Bugesera AEZ would also justify the difference in the maize grain yields.

Season 2014A gave consistently higher grain yields than season 2014B. This is due to the fact that season A had generally higher and prolonged rainfall than season B. In season B, rainfall usually stops in May in Bugesera and usually cause maize abortion. Similarly, rainfall strongly reduces around July in the Birunga while the full season hybrid (PAN691) is still in the silking stage. This is the reason why maize stover may not vary among seasons but maize grain yields are found to be significantly ($p<0.05$) lower in season B than in season A.

4.7 Maize yield simulation with APSIM

Figure 4-15 and Figure 4-16 presents the simulated maize stover and grain yields in both Bugesera and Birunga of Rwanda for the short and long agricultural seasons of 2014.

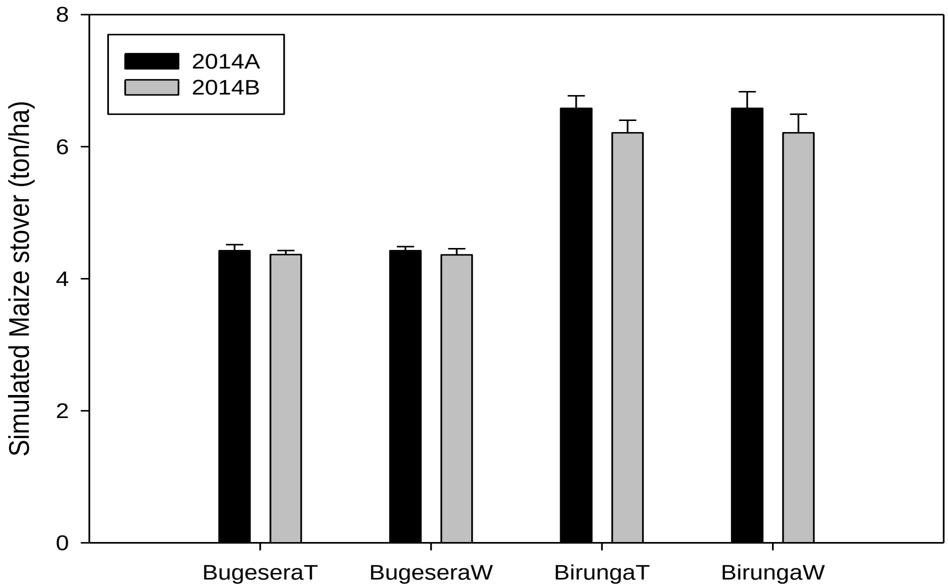

Figure 4- 15. Simulated maize stover yield using TAMSAT and weather station in both Bugesera and Birunga AEZ. Data are means of three replicates ± S.D.

BugeseraT: TAMSAT metfile used, BugeseraW: station metfile used, BirungaT: TAMSAT metfile used and BirungaW: station metfile used.

With closer values to the field experiment observations (Figure 4.16), APSIM simulated well the maize stover and showed a significant difference across the sites. It also showed no significant difference among the seasons (Figure 4.18).

A very interesting finding here is that while simulating maize stover using TAMSAT rainfall, it did not give different outputs as compared to when weather station rainfall data is used in the metfile module of APSIM. This implies that in the absence of consistent weather station data, TAMSAT rainfall can be used to accurately simulate maize stover in the studied AEZ of Rwanda.

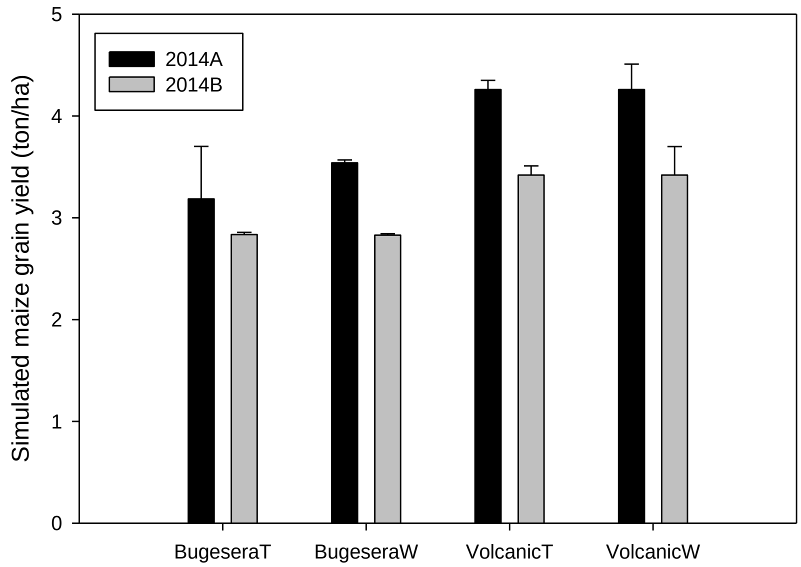

Figure 4- 16 Simulated maize grain yield using TAMSAT and weather station in both Bugesera and Birunga AEZ. Data are means of three replicates ± S.D.

BugeseraT: TAMSAT metfile used, BugeseraW: station metfile used, BirungaT: TAMSAT metfile used and BirungaW: station metfile used.

The APSIM-Maize model performed well in simulation of maize grain yield (Figure 4-16) for both Bugesera and Birunga AEZ. Similarly to what was observed in the field experiment (Figure 4-14), the simulated maize grain yield was higher in the Birunga than in the Bugesera AEZ. The simulations also showed that there were significantly ($p<0.05$) higher maize grain yields in season A (2014A) than in season B (2014B).

It is also very important to highlight that there were no differences in the outputs of the simulations when using TAMSAT rainfall instead of the station rainfall in the metfile of APSIM. This clearly shows that APSIM can simulate maize grain yields with almost no noise coming from TAMSAT rainfall data. It should be recalled that TAMSAT provides a resolution of 4 km and this gives around 1,646 pixels for Rwanda. Since Rwanda doesn't have such distribution of raingauge (4 stations per sector or 1,646 weather stations across the country), the use of TAMSAT data can be of high importance to cover areas with no raingauges records.

CHAPTER 5

5.0 Conclusion and recommendations

5.1 Conclusions

The first objective of the study was to assess the accuracy of TAMSAT rainfall data in humid and semi-arid regions of Rwanda by comparing it with data from weather stations on ground. TAMSAT slightly underestimated the rainfall received in Bugesera AEZ (semi-arid). The slight difference may be due to lack of one-off local calibration to account for variations with geographic location, time of year, character of season, topography and local storm climatology. However, the cumulated daily rainfall estimated by TAMSAT was strongly correlated (R^2 = 99%) to the one recorded by the weather station in Bugesera.

In spite of the simultaneous growth and broad agreement in trends of both TAMSAT estimates and weather station records of the cumulated daily rainfall, TAMSAT significantly underestimated the rainfall in the humid highlands (Birunga AEZ). This is due to the intricate topography of the Birunga which receives complex local rainfall variations and occurrence of non-convective rainfall while TAMSAT mainly predicts the convective rainfall. This generally restricts the method to the tropical and sub-tropical regions with less mountains where convective rainfall predominates over frontal or orographic rainfall. This is probably the reason why TAMSAT better estimated rainfall in Bugesera AEZ (slightly flat with round hills) than in the Birunga AEZ (very hilly).

The second objective was to simulate maize yields with APSIM using TAMSAT rainfall data and data from on-site weather stations. The APSIM-Maize model performed well in the simulation of maize stover and grain yields for both Bugesera and Birunga AEZ. The simulated maize stover and grain yields were higher in the Birunga than in the Bugesera AEZ. The simulations also showed that there were significantly ($p<0.05$) higher maize grain yields in season A (2014A) than in season B (2014B) due to differences observed in the rainfalls.

The third objective was to assess the maize yield predictive capacity of APSIM and evaluate the importance of yield errors that may arise from using satellite weather data. Results showed that there were no differences in the outputs of the simulations when using TAMSAT rainfall instead of the station rainfall in the metfile of APSIM module.

This clearly shows that APSIM can simulate maize stover and grain yields with almost no noise coming from TAMSAT rainfall data and hence recommendable for places with limited raingauge records.

5.2 Recommendations

Based on the findings of this study, TAMSAT provides good estimations especially in the semi-arid regions with less hilly topography. It can be used successfully to identify periods with well below or well above average rainfall even over highland areas, and is therefore useful for providing good APSIM simulations and hence inform food security early warnings. TAMSAT provides a resolution of 4 km giving around 1,646 pixels for Rwanda and since the country doesn't have such distribution of raingauges (4 stations per sector or 1,646 weather stations across the country), the use of TAMSAT data can be of high importance to cover areas with no raingauge records. The TAMSAT rainfall estimations in a pixel with no available raingauge would give more accurate data than using a "so called" nearby weather station.

This study, nevertheless, didn't cover all the related gaps due to limitations of time and resources. More research, therefore, needs to be carried out in other agro-ecological zones of Rwanda using big datasets for a prolonged duration of at least 15 years or more since TAMSAT can provide data from 1982. In addition, local calibration can be used to derive a relationship between rainfall amount and number of hours colder than threshold temperature (CCD) and hence significantly increase the accuracy of TAMSAT data on Rwanda. The meteorology services in Rwanda would benefit from sharing data from the 22 automated weather stations (sending online data every 5 min) and the newly installed weather radar (located in Bugesera district) with the TAMSAT team at the University of Reading to help in calibrations. Rwanda would in turn receive more accurate rainfall maps and this would even improve the country weather forecasting capacity. Though the temperature and radiation does not vary much within a season in Rwandan context, there is a need to research on APSIM simulations using satellite estimates of temperature and radiation to provide a metfile fully downloaded from satellites estimates.

REFERENCES

Barrett *C.G.;* (1989) - Satellite remote sensing of rainfall. In *Applications of remote sensing in agriculture.* Ed. E Toselli, Kluwer, Dordrecht.

Bidogeza, J. C. (2011). *Bio-economic farm modelling to analyse agricultural land productivity in Rwanda.* (Proefschrift Wageningen), s.n.], [S.l. Retrieved from http://edepot.wur.nl/169076

Birch, C.J., Stephen. K., McLean. G.. Doherty. A.. Hammer. G.L., Robertson. M.J. (2008). Reliability of production of quick to medium marurity maize in areas of variable rainfall in north—east Australia. *Australian Journal of Experiinental Agriculture* 48: 326-334

Bonfils, S. (2012). Trend analysis of the mean annual temperature in Rwanda during the last fifty two years. *Journal of Environmental Protection*, *2012*.

Clay, D. C., & Lewis, L. A. (1996). Land use, soil loss, and sustainable agriculture in Rwanda. In *Case Studies in Human Ecology* (pp. 271-287). Springer US.

Costa, C., Dwyer, L. M., Zhou, X., Dutilleul, P., Hamel, C., Reid, L. M., & Smith, D. L. (2002). Root morphology of contrasting maize genotypes. *Agronomy Journal*, *94*(1), 96-101.

D'Andrea, K. E., Otegui, M. E., Cirilo, A. G., & Eyherabide, G. (2006). Genotypic variability in morphological and physiological traits among maize inbred lines—nitrogen responses. *Crop science*, *46*(3), 1266-1276.

Delepierre, G. (1974). Les Regions Agricoles du Rwanda. Note technique 13. ISAR, Butare.

Dinku, T, Ceccato, P, Grover-Kopec, E.; Lemma, M., Connor. S.J.; Ropelewsk C.F., (2007); Validation of satellite rainfall products over East Africa's complex topography. *Int. J. Rem. Sensing*, 28(7), 1503-1526.

Grimes, D. I. F., Pardo-Iguzquiza, E. & Bonifacio, R. (1999). Optimal areal rainfall estimation using raingauges and satellite data. *J. Hydrology*.

Hughes, d'A. J., Odu, B., (2001). Plant virology in Sub-Saharan Africa: Proceedings of a Conference organized by IITA. Ibadan Nigeria. Available online < http://books.google.nl/books?id=NbLlvMhVxxsC&pg=PA165&dq=maize++in+rwanda&hl=en&sa=X&ei=UurzT5nPEs7a0QXi-

NStBw&redir_esc=y#v=onepage&q=maize%20%20in%20rwanda&f=false> [Accessed on 27th July 2015]

Inter-Academy Council. (2004). Analyiss of the potential for agroforestry in Africa and the Hunger Task Forse report to the General Assembly of the United Nations: Inter-Academy Council and World Agroforestry Centre.

IUSS Working Group WRB (2006): World reference base for soil resources, World Soil Resources Reports, 103, Food and Agriculture Organization of the United Nations, Rome, Italy.

Jame YW and Cutforth HW (1996) Crop growth models for decision support systems. Can. J. Plant Sci. 76: 9–19

Jobard, I.M., Chopin, F., Berges, J.C., Ali, A., Lebel, T., Desbois, M., (2007): Presentation of the EPSAT-SG method and comparison with other satellite precipitation estimations in the frame of Precip-AMMA *EGU Vienna 15-20 April 2007.*

Keating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, Huth NI, Hargreaves JNG, Meinke H, Hochman Z, McLean G, Verburg K, Snow V, Dimes JP, Silburn M, Wang E, Brown S, Bristow KL, Asseng S, Chapman S, McCown RL, Freebairn DM, Smith CJ (2003) An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267-288.

Kelly, V. A., Mpyisi, E., Murekezi, A., Neven, D., & Shingiro, E. (2002). Fertilizer consumption in Rwanda. *Past Trends, Future Potential, and Determinants. Rwanda Food Security Research Project, Michigan State University, East Lansing, MI. Available on-line (June 2005): http://www. aec. msu. edu/agecon/fs2/Rwanda/fertilizerconsumption. pdf*

Kogbe, J. O. S and JA Adediran. (2003). Influence of N and P application on yield of maize in Savanna zone of Nigeria. *Afri. J. of Biotec*, *2*(10), 345-349.

Koo, Jawoo; Dimes, John, (2010), "HC27 Generic Soil Profile Database", http://hdl.handle.net/1902.1/20299 International Food Policy Research Institute [Distributor] V1 [Version]

Krishna-Murthy, V. R. "Crop growth modeling and its applications in agricultural." *Satellite Remote Sensing and GIS Applications in Agricultural Meteorology. World Meteorological Organization* (2003): 235-261.

Kobayashi, K., Salam, M.U. (2000). Comparing simulated and measured values using mean

squared deviation and its components. *Agronomy Journal* 92, 345–352.
Kyei-Baffour O (2006) Factors affecting plant growth http://www.wmo.int/pages/prog/wcp/agm/gamp/documents/chap13C-draft.pdf cited on 26th, August 2015.
Landon J.R., (1991). *Booker Tropical soil Manual. A handbook for soil survey and Agricultural land evaluation in the tropics and subtropics.* Longman, Booker Tate limited, Oxon, UK. 474p.
Maidment, R. I., D. Grimes, R. P. Allan, E. Tarnavsky, M. Stringer, T. Hewison, R. Roebeling, and E. Black (2014), The 30 year TAMSAT African Rainfall Climatology And Time series (TARCAT) data set, J. Geophys. Res. Atmos., 119, 10,619–10,644 doi:10.1002/ 2014JD021927.
Mc Cown, R.L., G.L. Hammer, J.N.G. Hargreaves, D.P. Holzworth, and D.M. Freebairn. (1996). APSIM: A novel software system for model development, model testing and simulation in agricultural systems research. *Agricultural Systems* 50:255-271.
MILFORD J.&R. D UGDALGE., (1990) - Estimation of rainfall using geostationary satellite data. In *Applications of remote sensing in agriculture.* Ed. J.A. Clark & M.D. Steven, London, Buttenvorth.
Milford, J. R., V. D. McDougall, and G. Dugdale (1996), Rainfall estimation from cold cloud duration: Experience of the TAMSAT group in West Africa, in Colloques et Seminaires. Validation Problems of Rainfall Estimation Methods by Satellite in Intertropical Africa. Proceedings of the Niamey Workshop (1994), ORSTROM.
MINAGRI, 2007. Ministry of Agriculture. Crop Intensification Program. Kigali. Rwanda
MINAGRI, 2010. Ministry of Agriculture. Crop Production data2007-2010. Kigali. Rwanda
MINAGRI, 2011. Ministry of Agriculture. Annual report 2010-2011. Kigali, Rwanda
MINECOFIN, 2002. Ministry of Finance. Poverty reduction Strategic Paper. Kigali, Rwanda
MUTWEWINGABO B. et RUTUNGA V., (1987). *Etude des sols des stations d'essais du projet PIA-Gikongoro,* Série n°1 MINAGRI-PIA.nationale pour le developpement et la gestion des petits marais.
Murthy, V. R. K. (2004). Crop growth modeling and its applications in agricultural meteorology. *satellite remote sensing and GIS applications in agricultural meteorology. Ed. Sivakumar,*

MV K, 235-261.

Ngaboyisonga, C., (2010). Promotion and utilization of new maize varieties for improving livelihood of smallholder farm families in Rwanda. ISAR Butare;

Ntabakirabose, G., Mbabazize, M., Shukla, J., (2015) An Analytical Study of the Factors Influencing Maize Production in Rwanda: A case study of Gatsibo District. *The International Journal of Business & Management.* 3 (10).

Oldeman, L. R., & Suardi, D. (1977). Climatic determinants in relation to cropping patterns. In *Symposium on Cropping Systems Research and Development for the Asian Rice Farmer* (p. 61). Int. Rice Res. Inst..

Rwanda NISR. (2014). Fourth Population and Housing Census, Rwanda. Kigali: NISR.

NISR (2010) National agricultural survey 2008.Results of final data analysis. National Institute of Statistics of Rwanda, Kigali

NISR (2013). National Agriculture Survey 2013. National Institute of Statistics in Rwanda, Kigali.

Paul, W. H. and Wilfred, M., (1996). Fertilizer Use and Maize Production in Sub Saharan Africa. CIMMYT Economics Working. Mexico

Salami, A. , Abdul, B. , Kimaran, B., & Zuzana, B. , (2010). Smallholder agriculture in East Africa:Trends, constraints and opportunities. In A. D. Bank (Ed.), *working paper series no. 105*.

Srinivasan. G., Zaidi P. H.. Singh. N. N.. Sanchez, C. (2004). *Increasing productivity through genetic*

improvement for tolerance to drought and excess—moisture stress in Maize (Zea maïs L.).Seng.

V.. Craswell, E.. Fukai. S. and Fischer. K. eds. Australian Centre for International Agricultural

Research Canberra. pp. 227-239.

Stephens W and Middleton T (2002) Why has the uptake of decision support systems been so poor? In: Matthews, R. and Stephens W. (Ed.) Crop-soil simulation models. 129-147. CAB International, Wallingford, UK, pp. 129-147

Thorne, V., Coakley, P., Grimes, D.I.F. & Dugdale, G., (2001): Comparison of TAMSAT and CPC rainfall estimates with rainfall, for southern Africa. *Int. J.Remote Sensing, 2001, Vol*

22, No.10, pp1951-1974.

Tucker, M. R., & Sear, C. B. (2001). A comparison of Meteosat rainfall estimation techniques in Kenya. *Meteorological Applications*, *8*(1), 107-117

Verdoodt, Ann, & Ranst, Eric Van. (2006). Environmental assessment tools for multi-scale land resources information systems: A case study of Rwanda. *Agriculture, Ecosystems & Environment, 114*(2–4), 170-184. doi: http://dx.doi.org/10.1016/j.agee.2005.10.006

Verdoot, A., and Van Ranst, E. (2003): Land Evaluation for Agricultural Production in the Topics A Large-Scale Land Suitability Classification for Rwanda", Ghent University, Laboratory of Soil Science, Belgium.

WHO (2010) Essential Public Health package to Enhance Climate Change Resilience in Developing Countries. Report on the Consultative Meeting on September 7-8, 2010. Geneva.

Willmott, C.J., Ackleson, S.G., Davis, R.E., Feddema, J.J., Klink, D.R., Legates, K.M., O'Donnell, J., Rowe, C.M. (1985). Statistics for the evaluation and comparison of models. *Journal of Geophysical Research* 90, 8995–9005.

World Bank (2007) World Development Report 2008 Overview: Agriculture for development. Washington DC: International Bank for Reconstruction and Development/World Bank.