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Projections of precipitation, air temperature and potential evapotranspiration in Rwanda under changing climate conditions

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Precipitation and air temperature records from 6 sites in Rwanda in the period from 1964 to 2010 are used for past/present climate assessment. Future climate projections (2010-2099) based on 3 general circulation models and 2 emission scenarios (A2 and B1) are used for climate projections. Precipitation, air temperature, and potential evapotranspiration based on ccma_cgcm3_1.1; miroc3_2medres and mpi_echam5.1 models are used in the analysis. Observed air temperatures suggested warming pattern over the past 40 years at an average of 0.35°C per decade. Rainfall records show no significant trend in the considered period. The potential evapotranspiration has an increasing trend and exceeds the precipitation in the months of June to September. Climate projections indicate trend towards a warmer and wetter climate. Increases in mean temperature are projected under all models and scenarios, while all models also indicate increases in annual rainfall totals. Despite of the projected wetter climate, the increase in potential evapotranspiration will overrule during the 21st century resulting in deficit in water availability for the rainfed agriculture. Deficit periods in which potential evapotranspiration exceeds precipitation will be extended to 10 months at some parts in the country instead of 4 months at present.

Key words: Climate change, Rwanda, hillside irrigation, air temperature, precipitation, potential evapotranspiration.

INTRODUCTION

Climate change can be defined as the change in statistical properties of the climate system over extended periods of time regardless of the causes of this change. Earth is warming up, and there is now overwhelming scientific consensus that warming is happening and it is human-induced (Finnis et al., 2015). The Intergovernmental Panel on Climate Change (IPCC, 2014) provides startling details of the devastating impact climate change could have on development in different sectors namely agriculture, water resources, human health, ecosystem and biodiversity. Understanding the spatial and temporal variation of climate within a zone or region, and their relationship with other factors is important in activities related to climate change and the

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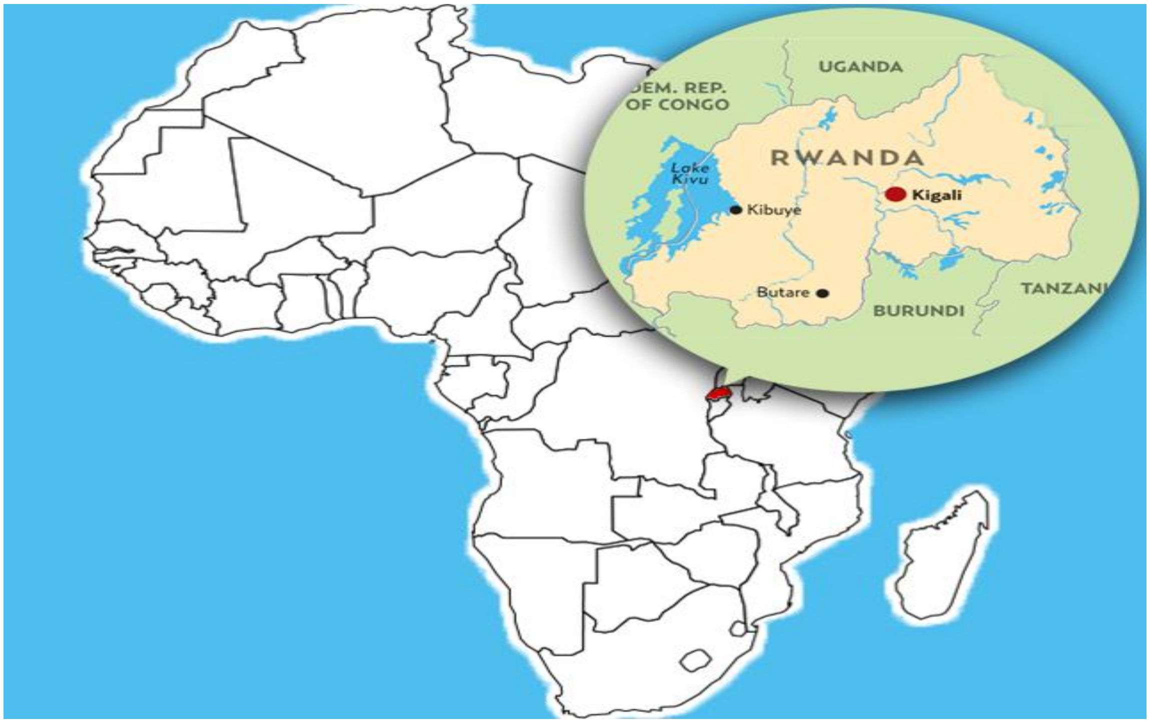

Figure 1. Location of Rwanda in the center of Africa.

management of the natural resources, such as environmental planning, land use planning, water resources planning, agriculture and irrigation.

The countries of Eastern Africa are prone to extreme climatic events such as droughts and floods. In the past, these events have had severe negative impacts on key socioeconomic sectors of the economies of most countries in the region. In the late seventies and eighties, droughts caused widespread famine and economic hardships in many countries of the region. There is evidence that future climate change may lead to a change in the frequency or severity of such extreme weather events, potentially worsening these impacts. In addition, future climate change will lead to increases in average mean temperature, and changes in annual and seasonal rainfall. These will have potentially important effects across all economic and social sectors, possibly affecting agricultural production, health status, water availability, energy use, biodiversity and ecosystem services.

Changing climate patterns will have important implications for water availability in Africa. According to the IPCC (2014), by 2030 an additional of 75 to 250 million people in Africa are projected to be exposed to an increased water stress due to climate change. The most important pressure on renewable water resources is linked to the agricultural sector in which irrigation represent the maximum demands (Valipour, 2014a, b). The population growth triggers the need for additional resources to satisfy the increasing food and living requirements. Valipour (2015a) estimated the ratio of area equipped for irrigated to cultivated area in Africa in 2035 and 2060. The results show an increasing trend of irrigated areas in different parts of Africa from 0.3 to 49.5% and 16.5 to 83.2% from 2011 to 2035 and 2060, respectively. Rao et al. (2015) shows that the areas suitable for agriculture, the length of growing seasons and the potential yield of food staples are all projected to decline with some African countries could see agricultural yields decrease by 50% by 2050 and crop net revenues could fall by as much as 90% by 2100.

This paper focus on investigating past/present climate conditions and future climate projections in some potential hillside irrigation sites in Rwanda. Rwanda is a landlocked country located in central east Africa (Figure 1). It is surrounded by four neighboring countries: Uganda to the north, Tanzania to the east, Burundi to the south and the Democratic Republic of Congo to the west. Rwanda is highly dependent on natural resources and agricultural growth is critical for pro-poor growth. Climate change is likely to add to existing pressures including change in precipitation pattern, increased temperature, etc.

Results of regional historical climate trends from stations in Rwanda, Kenya and Tanzania, indicate that during the 20th century, the trend of daily maximum temperature is not significantly different from zero. However, daily minimum temperature suggests an accelerating temperature rise (Christy et al., 2009). A further study looking at day and night temperatures concluded that the northern part of East Africa region generally indicated nighttime warming and daytime cooling in recent years. The trend patterns were, however, reversed at coastal and lake areas.

There were thus large geographical and temporal variations in the observed trends, with some neighboring locations at times indicating opposite trends. Air masses arising from the seasonal shift of the intertropical convergence zone that are transported between the anti-cyclones of the northern and southern hemispheres shape Rwanda’s climate (Henninger, 2013). Henninger (2009) analyzed the observed air temperature at Kigali using 3 meteorological stations maintained by the by the “Service Meteo du Rwanda” in the period from 1971 to 2008. The data indicated an increasing annual mean temperature of 2.6°C for a period of nearly 40 years. Mainly, for the last 10 years from 1998 to 2008, a warming in Kigali is evident and could be attributed to global warming and to the ongoing urbanization. Schreck and Semazzi (2004) showed that during the 20th century, the region of eastern Africa has been experienced an intensifying dipole rainfall pattern on the decadal time-scale. The dipole is characterized by increasing rainfall over the northern sector and declining amounts over the southern sector. East Africa has suffered both excessive and deficient rainfall in recent years (Webster et al., 1999). In particular, the frequency of anomalously strong rainfall causing floods has increased. Shongwe van Oldenborgh and Aalst (2009) report that their analysis of data from the international Disaster Database (EM-DAT shows that there has been an increase in the number of reported hydrometeorological disasters in the region, from an average of less than 3 events per year in the 1980s to over 7 events per year in the 1990s and 10 events per year from 2000 to 2006, with a particular increase in floods.

Agriculture is the backbone of Rwanda’s economy, accounting for about 43% of GDP (CIA, 2010), and 63% of foreign exchange earnings. It also provides 90% of the country’s food needs and 80% of the country’s labor force is engaged in agriculture. Total arable land in Rwanda is slightly above 1.5 million ha, 90% of which is found on hillsides. Land husbandry water harvesting and hillside irrigation, is a mean for improvement of rural productivity and diversification of market-oriented agricultural commodities. Considering the agriculture input to Rwandan GDP and the percentage of Hillside arable land, water harvesting and hillside irrigation is one of the key government tools for poverty alleviation in Rwanda and makes the investigation of the potential impacts of climate change on this sector is a prerequisite.

Climate change due to global warming might impact the agriculture development plans in this small country by imposing increased air temperature, seasonal variation of precipitation, flooding and drought, soil erosion, spread of water borne diseases (e.g. Malaria), etc. Valipour (2015b) analyzed the status of irrigated and rained agriculture at wide scale, it is found that major portion of the cultivated areas are not suitable for rainfed agriculture because of climate changes and other meteorological conditions. Potential uncertain effects from warming still need to be investigated for regional agricultural adaptation to climate change (Valibour, 2015c).

Drought and floods are other direct impacts of warming; in 2002 heavy rains caused by unusually high temperatures over the Indian Ocean killed more than 112 people in East Africa. Floods and mudslides forced tens of thousands of people to leave their homes in the sub region with Rwanda suffered the heaviest toll (Douglas et al., 2008). Global climatic change is expected to increase the incidence of vector-borne diseases, especially malaria (Tanser et al., 2003). Some studies assessed the contribution of climate to a malaria epidemic in Rwanda, proving the correlation between malaria incidence and climatic variables (Loevinsohn, 1994; Hay et al., 2002).

In this paper, 3 climatological parameters are assessed (precipitation, surface air temperature and potential evapotranspiration). Such parameters are the most important to assess the impact of climate change on hydrological conditions, water availability, and agriculture productivity. Six sites with potential hillside irrigation are considered for detailed analysis and all are located within the Nile basin part in Rwanda that represent 67% of the country total area and provide 90% of the country’s water resources.

Study area

Rwanda is located in Central Africa between latitude 1°4’ and 2°51’ South of the equator and between longitude 28°45’ and 31°15 East (Figure 1). Its total area is 26.338 km^2 with land occupying 24,666 km^2; while the rest occupied by water. Rwanda has mountainous and sloppy landscape with altitude varying from 900 to 4,507 m over a territory of about 400 km wide. Rwanda has dense hydrological network with a stream density of 2 km/km^2. It is split up into 2 basins by a water divide line called “Congo-Nile Ridge”: at the east of divide is the Nile Basin covering 67% of the national territory and at the west is the Congo Basin (Figure 2). The former comprises many small lakes and drains 90% of national waters through two major rivers, Nyabarongo and Akagera. The Congo Basin, covering 33% of Rwanda, drains 10% of national water resources towards Lake Kivu (102,800 ha on Rwanda side). Average surface water flow rates measured at major hydrological stations are 78 m^3/s for Nyabarongo at Kigali; 100 m^3/s for Nyabarongo at Kanzenze, 232 m^3/s for Akagera at Rusumo, and 256 m^3/s for Akagera at Kagitumba (MINIRENA, 2012).

Because Rwanda lies near the equator, Rwandan territory belongs to the inner or moist tropics. The regional climate in Rwanda can be classified following Köppen and Geiger climate classification (Prioul, 1981).

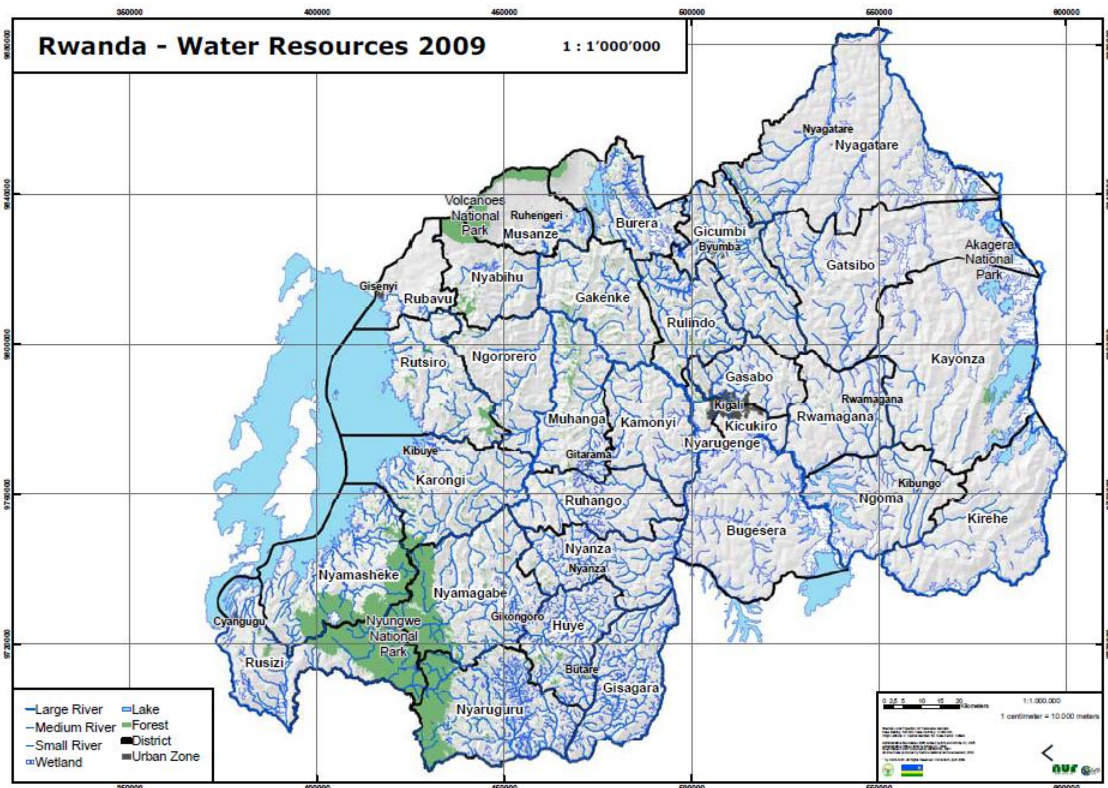

Figure 2. Rwanda's water resources network in 2009 (MINIRENA, 2009).

The hilly nature of Rwanda controls the windward and lee locations clearly influencing the country's rainfall and how it is distributed. The amount of rainfall varies between 1000 and 1500 mm (Bamusananire et al., 2006). An analysis of rainwater potential revealed that at the national level Rwanda receives about 28 km^3 of annual rainfall. About 4.3 km^3 are generated as runoff water, 9.5 km^3 are lost to evaporation, 5.3 km^3 are transpired by all vegetation, and 4.8 km^3 for other uses while 4.3 km^3 percolate into the groundwater system (Malesu et al., 2010). In 2000 the estimated total annual water consumption was 150 million m^3. Agriculture accounted for 68%, domestic needs 24%, and industry 8% of total consumption. Although located only two degrees south of the Equator, Rwanda's high elevation makes the climate temperate. The average daily temperature near Lake Kivu, at an altitude of 1463 m is 23°C. During the two rainy seasons (February-May and September-December), heavy downpours occur almost daily, alternating with sunny weather. Annual rainfall averages 800 mm but is generally heavier in the western and north-western mountains than in the eastern savannas.

Rwanda possesses abundant water resources, however, these resources are not evenly distributed, and the quantity and quality may not be adequate. The conditions are critical in the hilly agricultural land, particularly in the eastern regions where rainfall is scarce. According to the Food and Agriculture Organization (FAO, 2007), Rwanda's irrigation potential is 165,000 ha of which only 7000 ha is currently irrigated that is only 4% of the country's potential (LWH03, 2008). The prevalent method of irrigation is flood irrigation system, which is used in the marsh lands in the country. Moreover, the eastern province of the country with crops that are not drought resistant could not be cultivated without supplementary irrigation. Such lack of water in the dry seasons for the hillside agriculture has drastically affected productivity of the perennial agricultural crops especially pineapple and plantain on which livelihoods of the country and district community depends.

MATERIALS AND METHODS

Potential hillside irrigation sites

Rwandan irrigation potential indicates that the country has a potential of about 589,713 ha, taking into consideration runoff, river, lake, groundwater, small reservoirs and marshland domains (Malesu et al., 2010). Following the keenness of the Government of Rwanda to transform the irrigation potential into reality in order to achieve food security, a number of interventions have to be initiated to develop short, medium, and long-term strategic irrigation plans. The potential hillside irrigation sites in Rwanda that subject to this study are shown in Figure 3. Sites are Gastibo 8 and 32, Kayonza 15, and Bugesera 3 and 4, and Nyanza 23 located in Gastibo,

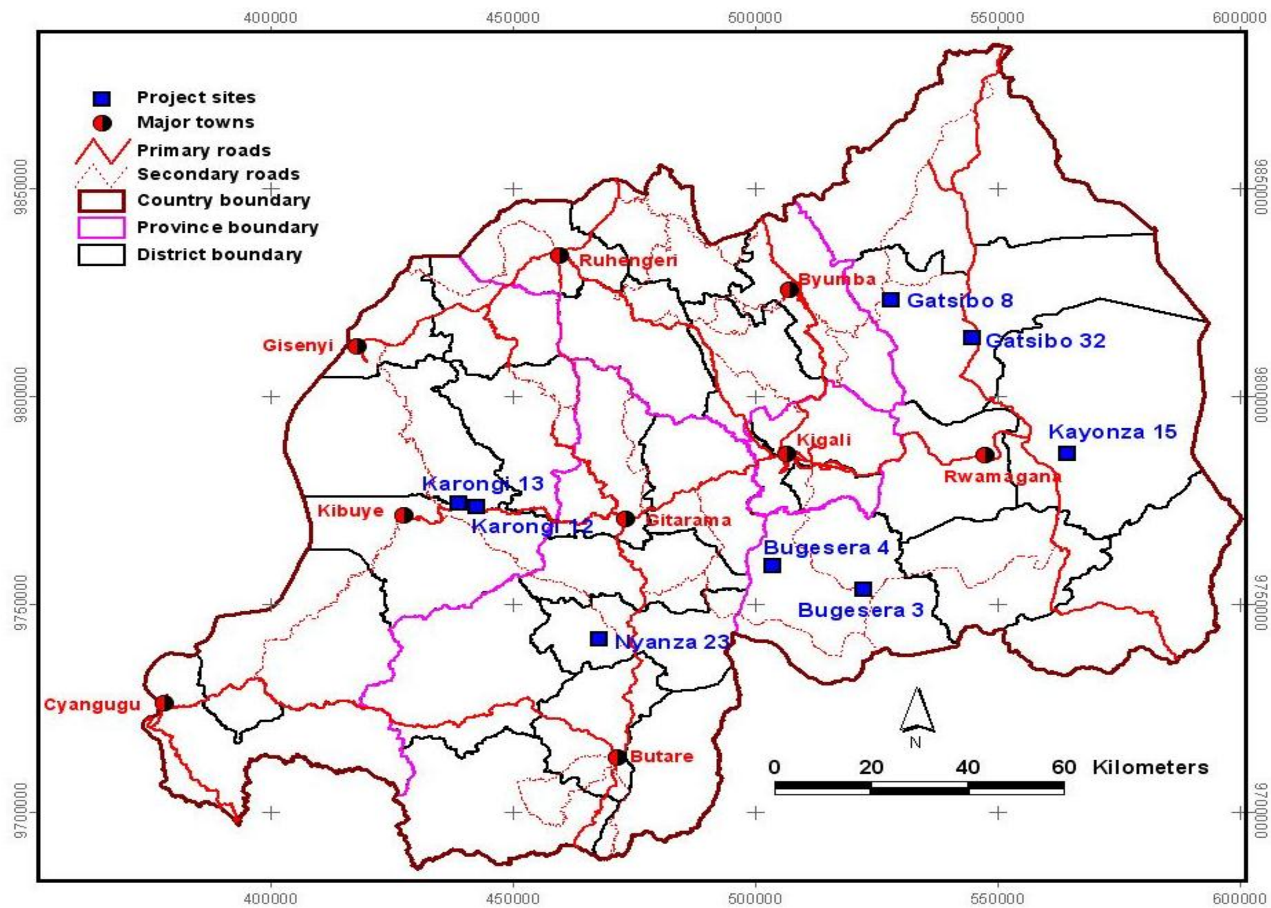

Figure 3. Map of the potential hillside irrigation sites in Rwanda (Source: LWH32; 2008).

Kayonza, Bugesera and Nyanza districts, respectively, and all are located in the eastern part of the country that belongs to the Nile Basin.

Observation datasets and gap filling

Because of the history of the civil war and genocidein Rwanda, hydrometeorological records are incomplete with extended periods of data gaps. Kigali Airport meteorological station provides almost complete and continuous record from 1964 to 2010 and it is selected to be the reference rain gauge in filling missing data at other rainfall gauges in the study area. Precipitation and air temperature records from six potential hillside irrigation sites (Nyanza 23, Bugesera 03, Bugesera 04, Kayonza 15, Gatsibo 32 and Gatsibo 08) are collected and checked against gaps and other types of noise. The period from 1964 to 2010 is decided to be the reference for analysis of observations because of the availability of the full record at Kigali airport station.

Global climate datasets and emission scenarios

Climate projections are obtained from 3 GCMs and 2 emissions scenarios (A2 and B1). Each scenario presents different atmospheric concentrations of future greenhouse gases. While A2 does not represent the highest CO_2 emissions (at least through 2100) of the SRES scenarios (IPCC, 2007), 21st century emissions to date appear to be above this projection (Raupach et al., 2007). A2 emission scenario used to be the highest emission scenario for which most modelling groups have completed simulations. B1 emission scenario generally represents the best case of the SRES scenarios through the 21st century (IPCC, 2001). All data are obtained from the World Climate Research Programme's (WCRP's) Coupled Model Inter-comparison (CMIP3) multi-model dataset (Meehl et al., 2007). These data were downscaled as described by Maurer et al. (2010) using the bias-correction/spatial downscaling method (Wood et al., 2004) to a 0.5° grid, based on 1950-1999 gridded observations of Adam and Lettenmaier (Yang et al., 2005).

Temperature and precipitation data corresponding to A2 and B1 for 3 GCMs namely Canadian ccma_cgcm3_1.1; Japanese miroc3_2medres and German mpi_echam5.1models are used for future projection analysis. Delta approach is used to apply or transfer changes relative to twentieth century (20 cm^3) baseline on site level. As an alternative of calculating a single percentage change for precipitation or a single addition/subtraction value for temperature for the whole period, we used periods (2010-2039, 2040-2069, and 2070-2099) relative to the reference period (1960-1990). The change in every month from the A2 or B1 scenarios relative to the same month in the run of the twentieth century (20 cm^3) is multiplied or added to the observed time series of precipitation or temperature. For instance having 5% as the percentage change for January 2010 to 2039 in the A2 scenario relative to January 1960 to 1990 of the run of the twentieth century, mean that the value of precipitation for January 2010 to 2039 will be 1.05 the observed value for January 1960 to 1990.

Regression analysis

A linear relationship is established between Kigali Airport rainfall station (reference station) and other rainfall stations. A linear equation is established to calculate the least squares fit for a line, Equation (1):

$$y = mx + b \qquad (1)$$

Where m is the slope and b is the intercept.

Once the equation representing the best fit between the reference station and the station of interest with missing data is established, the same equation is then used to generate the missing data.

Generated data verification

The generated data are checked and verified usingPearson correlation coefficient (r) and coefficient of determination (R^2) in addition to Z-test.Pearson correlation coefficient, like the covariance, is the measure of the extent to which two measured variables ''vary together''. Unlike the covariance, Pearson correlation coefficient is scaled so that its value is independent of the units in which the two measured values are expressed. The Formula for correlation coefficient if expressed by Equation (2):

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \qquad (2)$$

Where: x = observed value, y = predicted value, $\bar{X}$ = the average of observed value, and $\bar{y}$ = the average of predicted value.

Z test is a statistical procedure used to test the hypotheses concerning the mean in a single population with a known variance. A population mean is greater than (>), less than (<), or not equal (≠) to the value stated in a null hypothesis. The alternative hypothesis determines which tail of a sampling distribution to place the level of significance. Z is considered significant if the difference is more than roughly two standard deviations above or below zero (or more precisely, |Z| > 1.96)" Collins and Morris (2008). The Z measure is calculated as:

Z = (x - m) / SE

Where x is the mean sample to be standardized, m is the population mean and SE is the standard error of the mean, that is, SE = s / SQRT (n) where s is the population standard deviation and n is the sample size. The z value is then looked up in a z-table. A negative z value means it is below the population mean. For comparing the mean of two variables, Equation (3) is used for data similarity condition:

$$Z = \frac{(\bar{X}_1 - \bar{X}_2) - (\mu_1 - \mu_2)}{\sqrt{\frac{\sigma_1^2}{n_1} x \frac{\sigma_2^2}{n_2}}} \quad |Z| \le 1.96 \qquad (3)$$

Where: n1 = sample 1 size; n_2 = sample 2 size; $\bar{X}$ = sample mean; μ_0 = hypothesized population mean, μ_1 = population 1 mean; μ_2 = population 2 mean; σ = population standard deviation; and σ^2 = population variance.

Precipitation disaggregation

Based on the fact that the area of interest of this study is relatively small resulting in proximity of rainfall stations to each other, we assumed that the daily rainfall distribution at all rainfall gauges will be the same. Based on that, we constructed synthesis daily rainfall time series at any station by disaggregating its total monthly rainfall at such station based on the daily rainfall record observed at Kigali. Mathematically, this can be expressed by assuming the daily rainfall depth at Kigali station is k_i, i with day order ranges from 1 to 31 in a specific month. The total monthly-accumulated rainfall depth in this month at Kigali is given by Equation (4):

$$K_{total} = \sum_{i=1}^{31} k_i \qquad (4)$$

By assuming that the daily rainfall depth at any other station is S_i , where i refers to day order, the total monthly-accumulated rainfall depth in a certain month at this station is expressed by Equation (5), and the daily rainfall at S_i can be expressed by Equation (6).

$$S_{total} = \sum_{i=1}^{31} S_i \qquad (5)$$

$$S_i = k_i \frac{S_{total}}{K_{total}} \quad , i = 1,2,..,31 \qquad (6)$$

Potential evapotranspiration calculation

Precise estimation of evapotranspiration is obtained using lysimeters or imaging techniques at relatively high cost. Instead, it is possible to calculate the actual evapotranspiration using crop coefficients and potential evapotranspiration. The most commonly applied technique for the estimation of potential evapotranspiration, in various regions of the world, is the FAO Penman-Monteith method (Allen et al., 1998), however this method needs many meteorological parameters to estimate the potential crop evapotranspiration. Due to the scarcity of weather data in Rwanda, we could not use the FAO Penman-Monteith method, hence other experimental methods with limited weather data requirements could be used instead. Valipour (2014c, d, e; 2015d, e) provided an inventory for different evapotranspiration methods applicable for regions with limited weather data availability. The different methods include mass transfer, radiation, temperature, and pan evaporation-based models.

In this study, Thornthwaite method (Thornthwaite, 1948) which is a temperature based method and gives estimates of potential evapotranspiration (PET) on a monthly basis is used (Equation 7).

$$PET = 16La\left(\frac{10\bar{T}}{I_t}\right)^a \qquad (7)$$

Where: PET: Monthly potential evapotranspiration in mm, La: Monthly Adjustment factor for the number of hours of daylight, related to the latitude of the place, $\bar{T}$: mean monthly air temperature (°C) I_t: The heat index for the year $= \sum_1^{12} i$, and

$i = \left(\frac{\bar{T}}{5}\right)^{1.514}$, a is an empirical constant given by Equation (8).

$$a = 6.75t10^{-7} \times I_t^3 - 7.71 \times 10^{-5} \times I_t^2 + 1.792h10^{-2} \times I_t + 0.49239 \qquad (8)$$

Table 1. Summary of gap filling and data generation (R^2, R and Z test).

Station name	Station available data relationship with the base station data		Comparison with TRMM data	
	Equation	R^2	Z	R
Butare (Nyanza23)	$y^* = 0.99x^{**} + 19.23$	0.62	-1.66	0.85
Ngarama(Gastibo8)	*y = 0.971x + 5.537*	0.60	-1.42	0.96
Bicumbi(Kayonza15)	y = 0.755x + 17.44	0.61	-1.67	0.96
Nyamata(Bugesera4)	y = 0.840x + 14.82	0.60	-0.72	0.96
Karama(Bugesera3)	y = 0.755x + 17.44	0.61	-0.15	0.93
Kiziguro(Gastibo32)	y = 0.840x + 14.82	0.60	-0.65	0.99
Kigali airport	-	-	-0.30	0.95

*y is the missing value at a given rainfall station; **x is the corresponding value at Kigali.

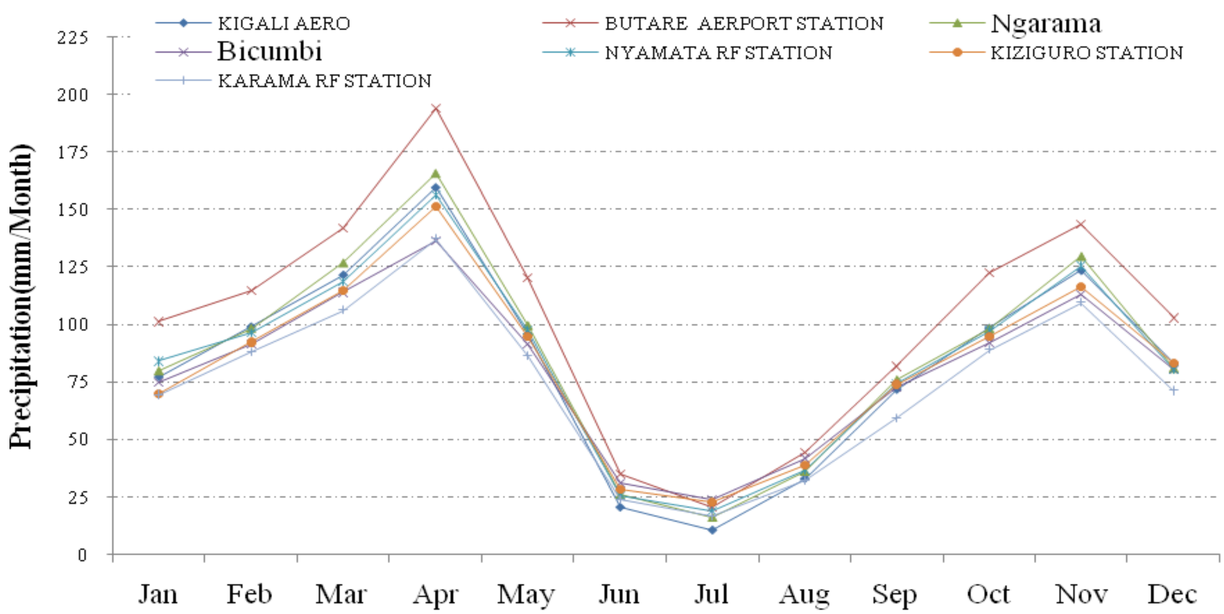

Figure 4. Average monthly precipitation at LWH sites in Nile basin and Kigali station from 1971-2010.

For the past PET calculation, observed air temperature at Kigarama, Rubona and Karama meteorological stations were used as the temperature input, while for future projection of PET, GCM temperature fields at the same locations as GCMs are used.

For verification purposes, CROPWAT 8.0 model for PET estimation, which is based on Penman equation is used to get corresponding PET values. Since some meteorological parameters needed for Penman equation are not available in Rwandan meteorological data office, instead we used FAO database which is built-in CROPWAT8.0.

RESULTS AND DISCUSSION

Observed precipitation

Table 1 presents the linear best fit relationships established between Kigali rain gauge and other rain gauges. Filled and generated data were compared to TRMM rainfall observations using Pearson correlation coefficient and Z test. The correlation with TRMM varies from R= 0.85 to 0.99 at Butare and Kiziguro stations, respectively, while Z test is varying from |Z|= 0.15 to 1.67 at the same stations. This implies that there's no significant difference between the two data sources. TRMM data proves to be usable when observed rainfall data are unavailable. The lowest correlation with TRMM data is found at Butare station, nearest to Congo Basin, and the highest correlation at Kizuguro station, farthest from the Congo Basin. Figure 4 shows the annual trend of rainfall season in Rwanda based on the average monthly rainfall record from 1964 to 2010. The rainfall season can be subdivided into four parts:

1. Long rainy season (March-May) with peak in April when the rain is heavy and persistent. Average monthly rainfall is between 110 and 160 mm/month, except for Nyanza site where it reaches 190 mm/month. April is the

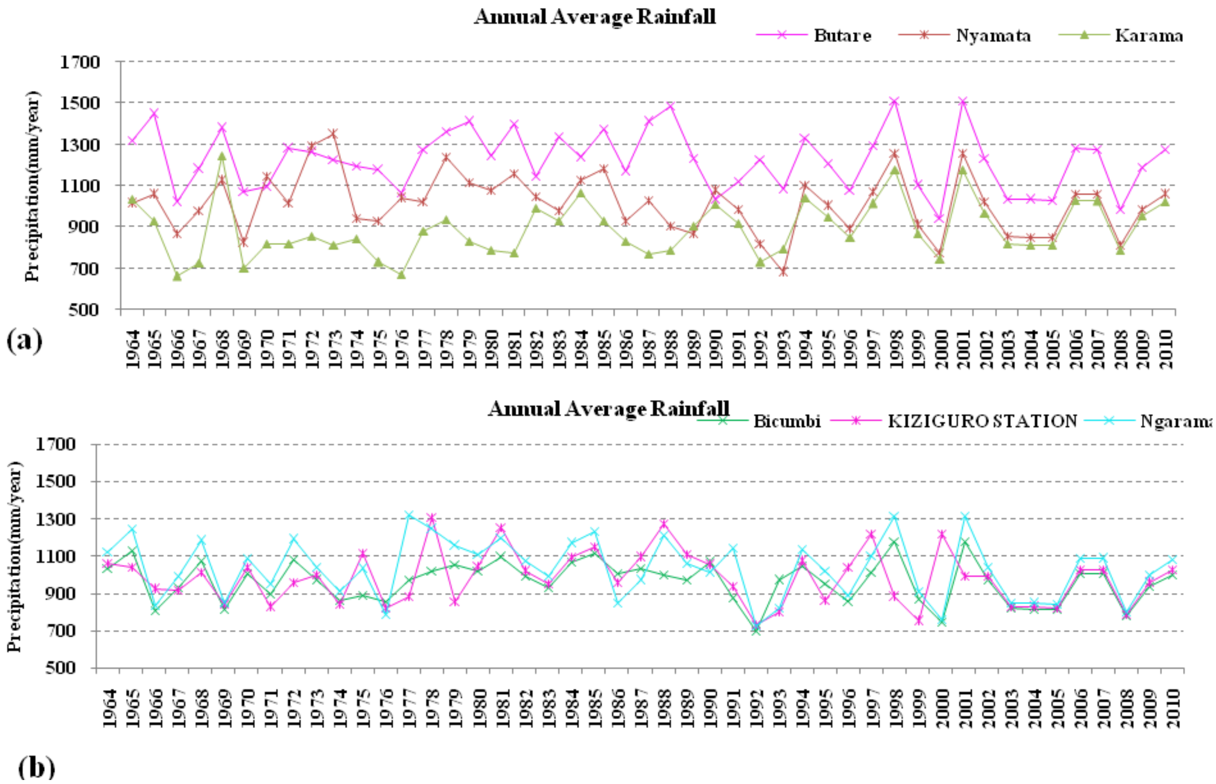

Figure 5. Annual average observed rainfall, for six rainfall stations from 1964 to 2010.

month with the highest monthly rainfall as recorded during the last 47 years with 15% of average annual precipitations while the driest month is July with 2% of average annual precipitation.

2. Long dry season (June to September); with average monthly rainfall between 10 and 50 mm/month, it may reach even zero in July which is the driest month followed by June.

3. Short rainy period (October to November) with average monthly rainfall between 80 and 125 mm for all sites, excluding Nyanza where the average monthly rainfall reaches 145 mm.

4. Short dry season (Dec. to Feb.) with an average monthly rainfall varying between 80 and 95 mm.

Figure 5 illustrates variations of annual average rainfall from 1964 to 2010 at the six sites. All station oscillates between 700 and 1300 mm per year, excluding Butare station with higher annual rainfall, fluctuating between 900 and 1520 mm for the 47 years, with highest values found in 1998 and 2001.

GCMs precipitation

There is a trend of precipitation increase in the range of 1 to 29% corresponding to 2010-2039 and 2070-2099 duration under all cases. Figure 6 shows how the precipitation will change until 2099. Miroc3 A2 SRES has the highest rainfall change varying from 6 to 29% increase, while B1 is varying from 3 to 15%. Cgcm3 A2 SRES has shown a precipitation increment varying from 4 to 26%, while according to B1 SRES the precipitation will vary from 7 to 14%. Echam5.1 A2 SRES gives lowest precipitation change (-1 to 12%) at the end of the century, while corresponding B1 scenario precipitation will vary from -1 to 7%.

The importance of mitigation measures is obvious, where Miroc3 is portraying a precipitation increase difference for A2 above B1 varying from 3 to 14%, while ranges of 0 to 12% and 0 to 6% differences are recorded for Cgcm3 and Echam5.1, respectively. Figure 7a is also demonstrating how mitigations measures will stabilize the precipitation since there is no much change in the average precipitation change factor along the whole year while scenario A2 demonstrates a lot of precipitation fluctuation from June to September (Figure 7b).

With respect to the annual average precipitation, Echam 5.1 has the lowest projections with annual precipitation vary from 942 to 1640 at Bugesera and Nyanza. Miroc3 predics the highest annual precipitation and vary from 784 to 1915 mm/year at Bugesera and Nyanza, followed by Cgcm[3] that vary from 925 to 1832 mm at Kayonza and Nyanza (Figure 8).

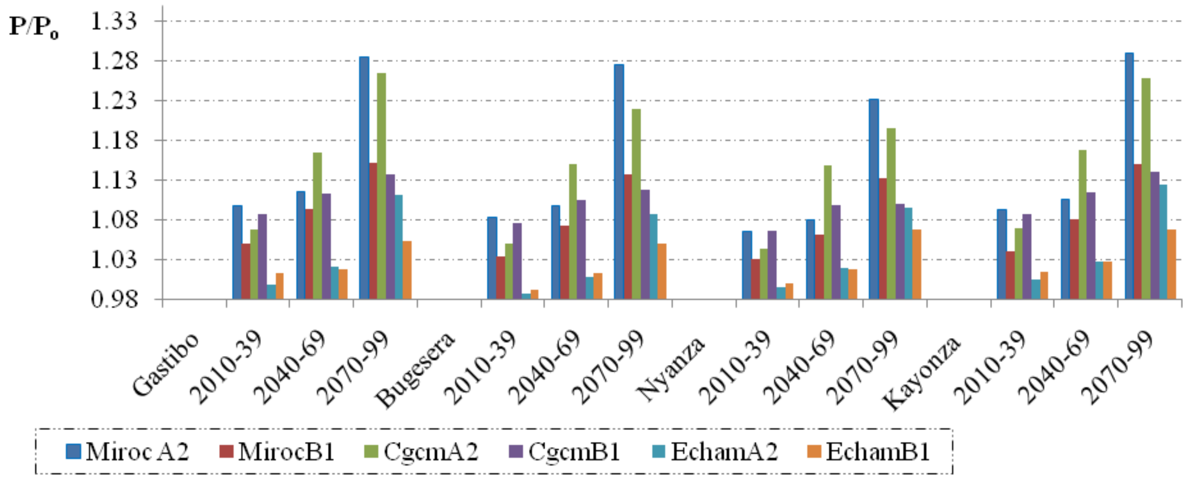

Figure 6. Projection for average 30 years precipitation factor (P/Po) for all models for SRES A2 and B1. (Po is the base line precipitation, 1980 to 2009).

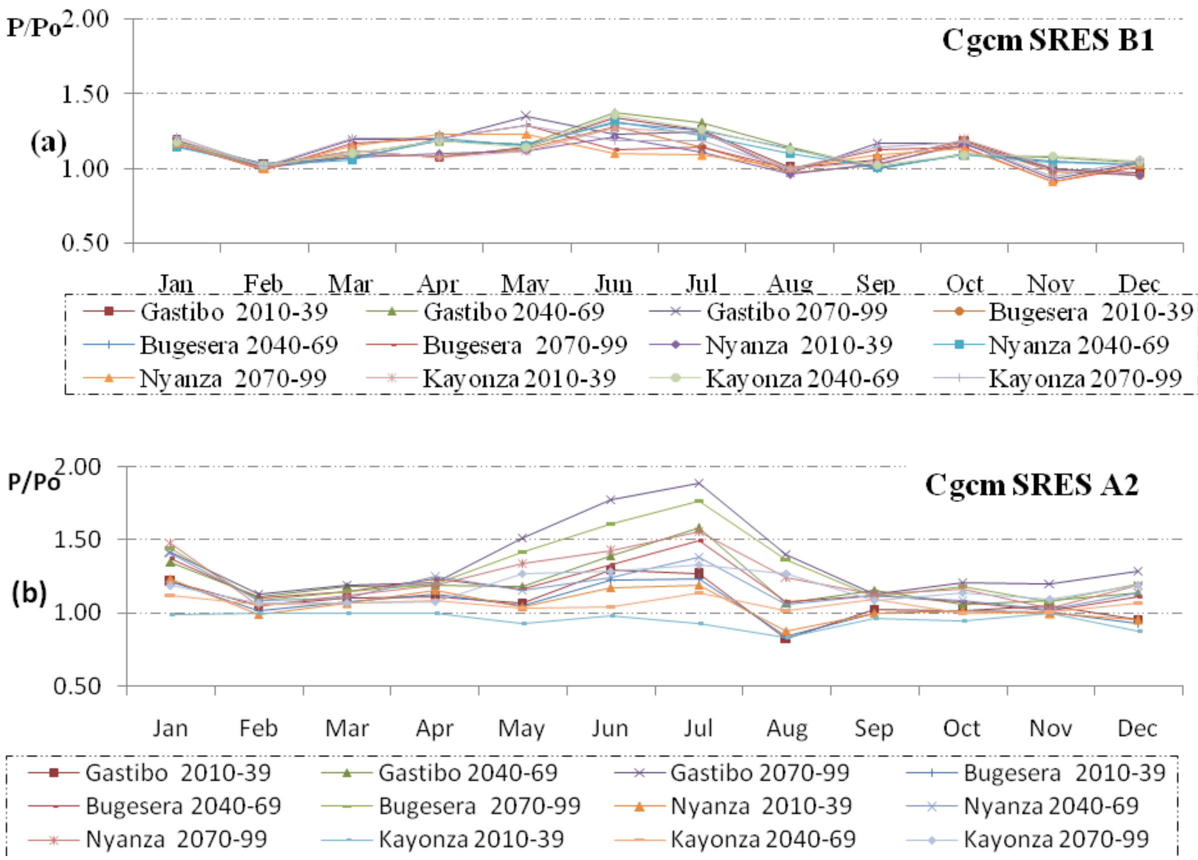

Figure 7. Predicted monthly average precipitation increment for Cgcm3 A2 & B1.

Observed air temperature

Figure 9 shows the average air temperature, lower values are observed at higher altitudes with average values between 15 and 17°C. Moderate temperatures are observed at intermediate altitudes with average values between 19 and 21°C. In the lowlands (east and southwest), temperatures are higher and can go beyond

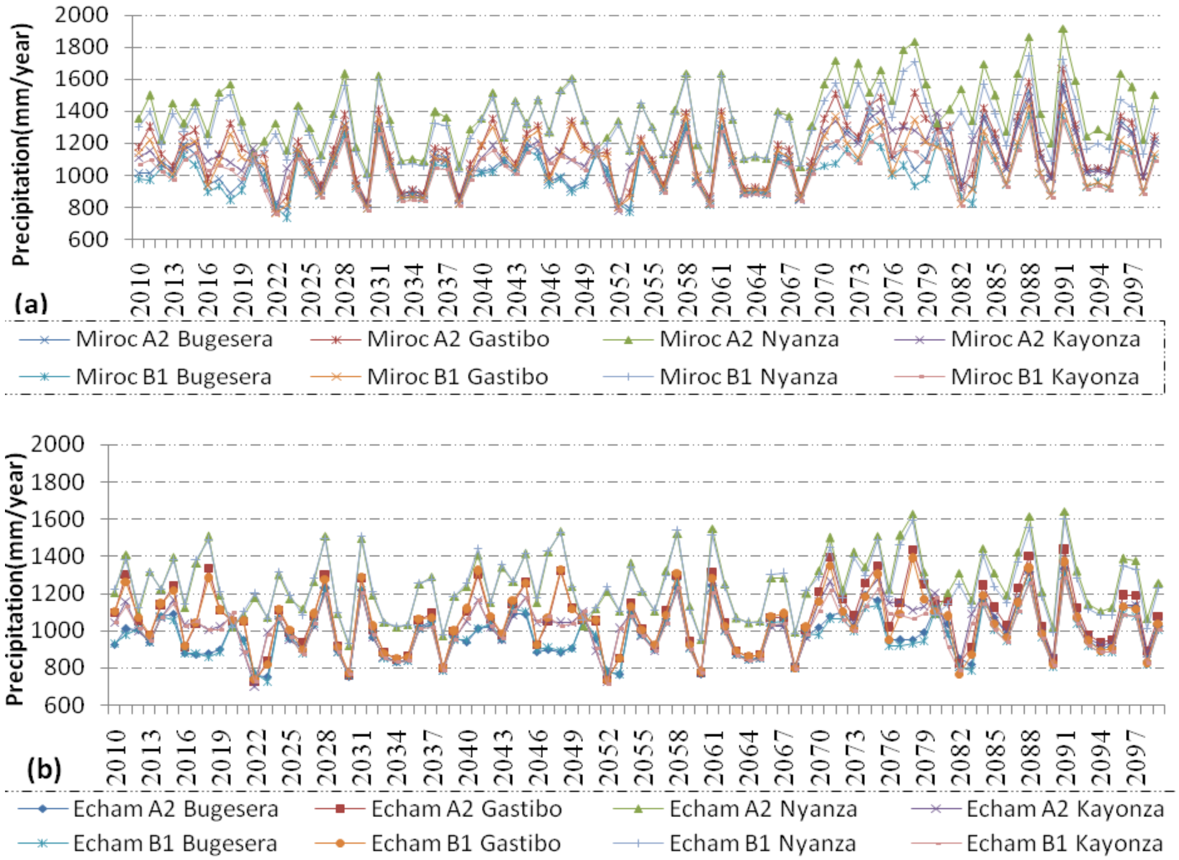

Figure 8. Annual average precipitation from 2010 to 2099 by Miroc, Cgcm and Echam GCMs for SRES A2 and B.

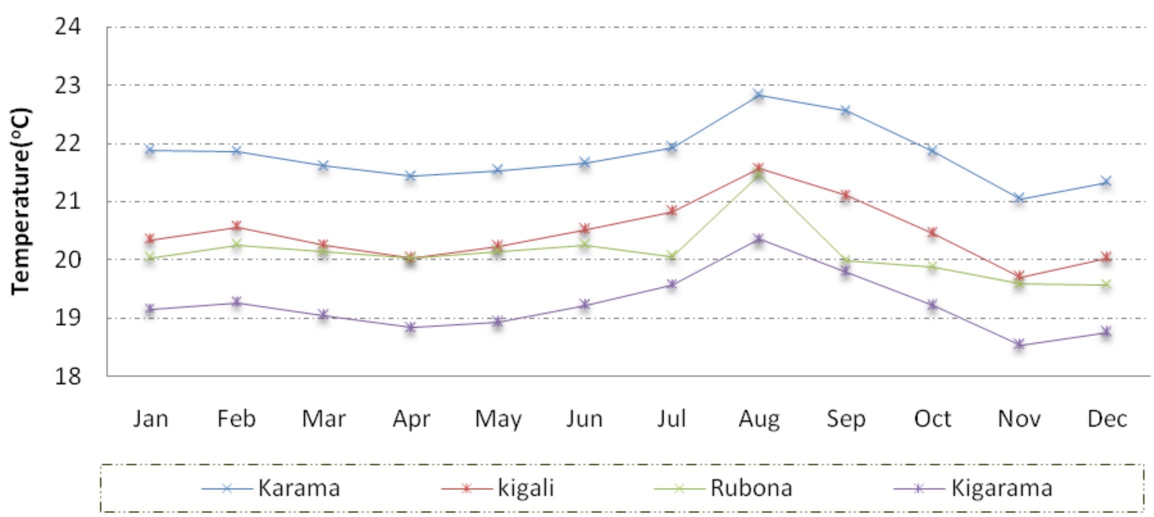

Figure 9. Mean monthly temperature for the last forty years for Karama, Kigali, Rubona and Gahororo meteological stations.

30°C in February, July, and August. During the entire year, there is no significant temperature change for the four sites except for the months of June to September, with a variation between 1 and 1.5°C with the highest monthly average temperatures occur in August and the lowest monthly average temperatures occur in November.

Analysis of observed air temperature records show that

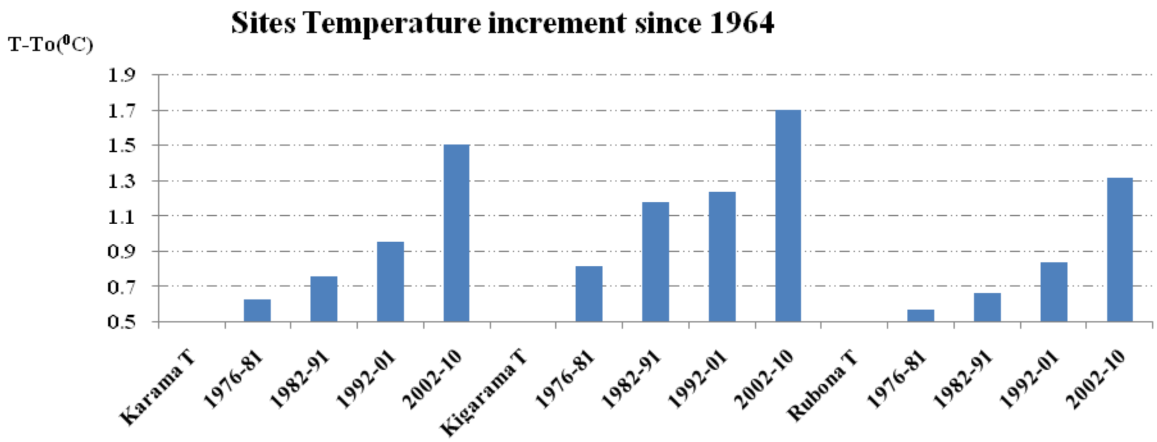

Figure 10. The Rubona, Karama, Gahororo stations temperature increment relative to 1964-1975 baseline period.

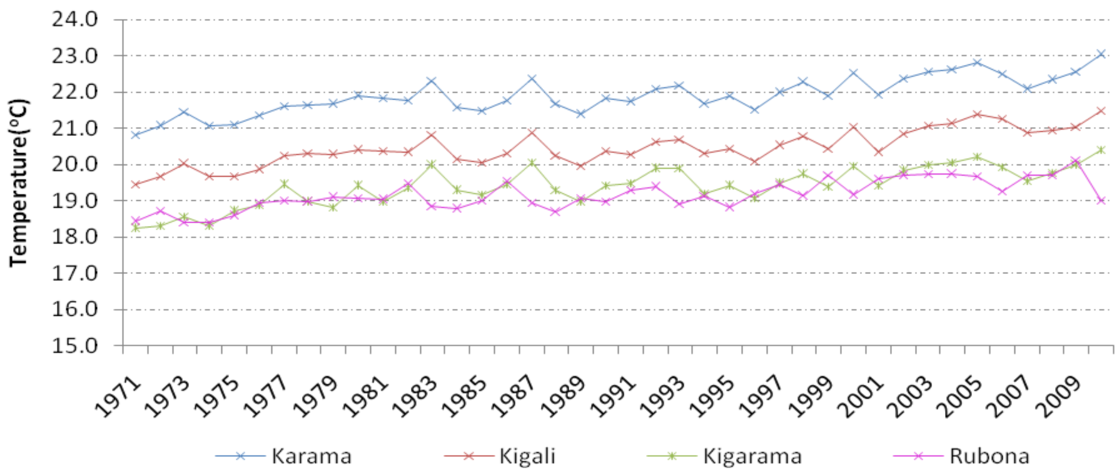

Figure 11. Kigali, Rubona, Karama and Gahororo annual average temperature for the last 40 years.

over the last 47 years there is an increase in the average air temperature. Using the period from 1964 to 1975 as baseline, it is found that since 1964 to 2010, in Karama, Gahororo and Rubona meteorological stations; temperature has increased by 1.51, 1.70 and 1.32°C, respectively, as shown in Figure 10. Maximum temperature increase per decade is found to be always increasing with time progressing, the last period from 2002-2010 witnessed the highest temperature increase at all sites with maximum air temperature increase of 1.7°C at Kigarama site. The increasing temperature trend in Figure 11 shows variation of at least 3°C in the observed air temperature record at different sites confirming the incremental factor calculated and presented in Figure 10.

Air temperature projections from GCMs

Subsequent to the analysis of the air temperature projections, it is found that temperature increase at all sites vary between 0.75 and 4.51°C corresponding to 2010-2039, and 2070-2099 time steps under Miroc3 B1 and Echam5.1 A2, respectively (Figure 12). Air temperatures are analyzed in a batch of thirty years' time steps relative to the base period from 1960 to 1990. The highest temperature increase is projected from Echam A2 and varies between 1.08 and 4.51°C at Gastibo and Nyanza sites, respectively, while under Echam B1 the temperature increase varies between 0.8 to 2.92°C. According to Cgcm A2, air temperature increase increment varies from 1.21 and 3.57°C, while under Cgcm B1, temperature air increase increment fluctuates between 1.11 and 2.14°C at the same sites. Miroc results in the lowest temperature increase increment, whereby A2 scenario projects an increase between 1.11 and 3.28°C and B1 projects a temperature increase increment that vary from 0.75 to 2.14°C from 2010 to 2099.

Furthermore, there's not much change in air

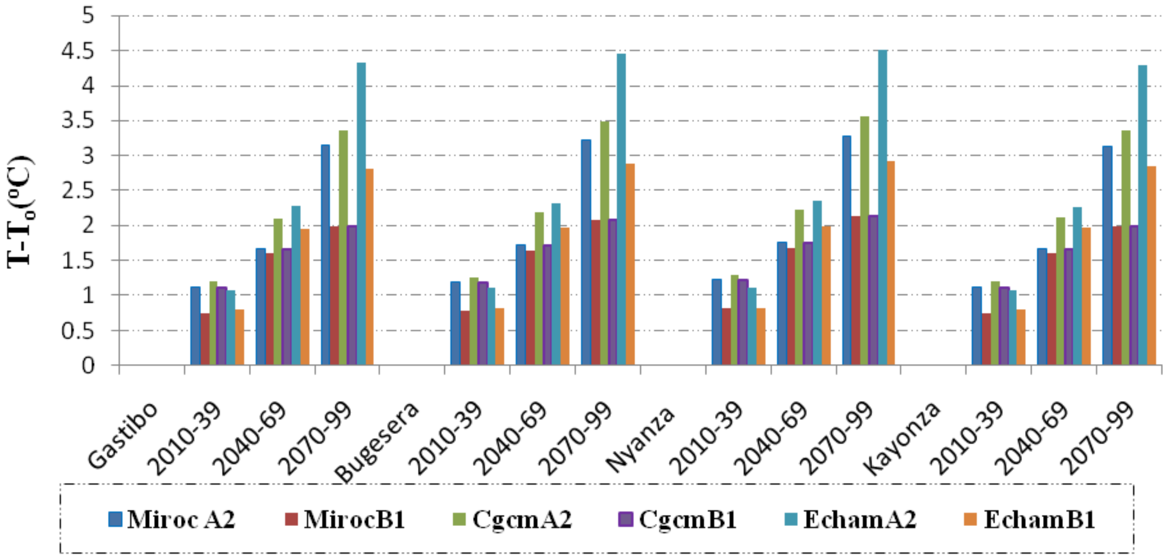

Figure 12. 30 years average temperature increase relative to 20th century base line.

Table 2. GCMs predicted average temperature increment range for all sites.

GCM name	Predicted increment range (°C)
mpi_echam5.1	0.8 to 4.51
ccma_cgcm3_1.1	1.11to 3.57
miroc3_2medres.1	0.75 to 3.28

temperature during different months of the year, with the highest average temperature in August and the lowest in November, varying between 19.5 and 28°C, with a maximum annual temperature variation of 3°C, (not shown). Table 2 summarizes the outcomes of the projected air temperature analysis from the 3 GCMs. All models agreed on a warming trend during the 21st century. The range of warming varies from 0.75 to 4.5°C.

PET calculation using observed data

Similar to the results of the air temperature analysis, there is no doubt that PET is increasing (Figure 13). The 4 investigated sites show an apparent increase in PET in the period from 1964 to 2010, although the increase increments differ from one site to another. Using PET data from 1964-1980 as baseline period, the following changes in PET are established. PET increased by 5, 4, 3 and 3% at Kigarama, Karama, Kigali and Rubona sites, respectively. The PET increase increments, from 1991 to 2000 for all sites are 1%. From 2001-10 PET has increased by 2, 4, 3.7 and 3% for Kigarama, Karama, Kigali and Rubona sites, respectively, and this is the time period with the highest increment at all sites. Finally, it is found that during the last four decades PET has increased by 8, 10 and 7% at Kigarama, Karama and Rubona sites, respectively. Since 1971, the highest PET monthly average increment is 19% observed between 2001 and 2010 at Karama station, followed by 15% for the same time period and all take place in the month of July (Figure 14). As shown in Figure 15, from June to end August there is no enough precipitation to contribute to runoff, since these months correspond to the long dry season in Rwanda, while the trend shows enough precipitation contributing to the runoff during the rest of the year.

PET calculation from GCMs projections

Figure 16 shows that PET projections at all sites have increasing trend by 3 and 55% corresponding to 2010-2039 and 2070-2099 periods under Echam 5.1 B1&A2 SRES 2, respectively. All models predicted high values at Bugesera site, while the lowest values are found at Nyanza site. As Thornthwaite formula is an air temperature based method, the PET trend shows the same behavior as that of the air temperature. Echam5.1 A2 has the highest prediction varying from 6 to 55% increase while B1 is varying from 3 to 28%. Cgcm3 A2 has shown a PET increment varying from 5 to 34% while

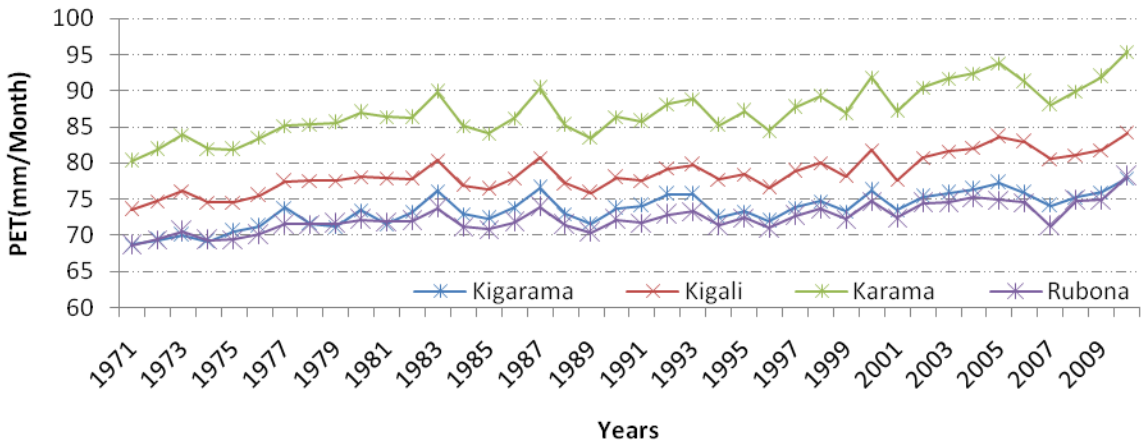

Figure 13. 30 years record for monthly average PET for Kigarama, Karama, Rubona and Kigali station for 1971-1910.

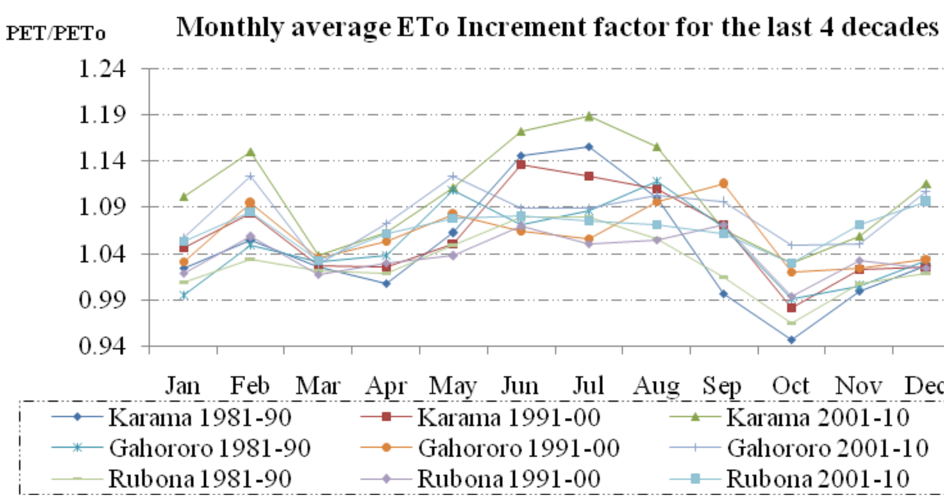

Figure 14. Monthly average PET increment factor for Karama, Rubona, Kigarama and Kigali sites relative to 1964-80 observations.

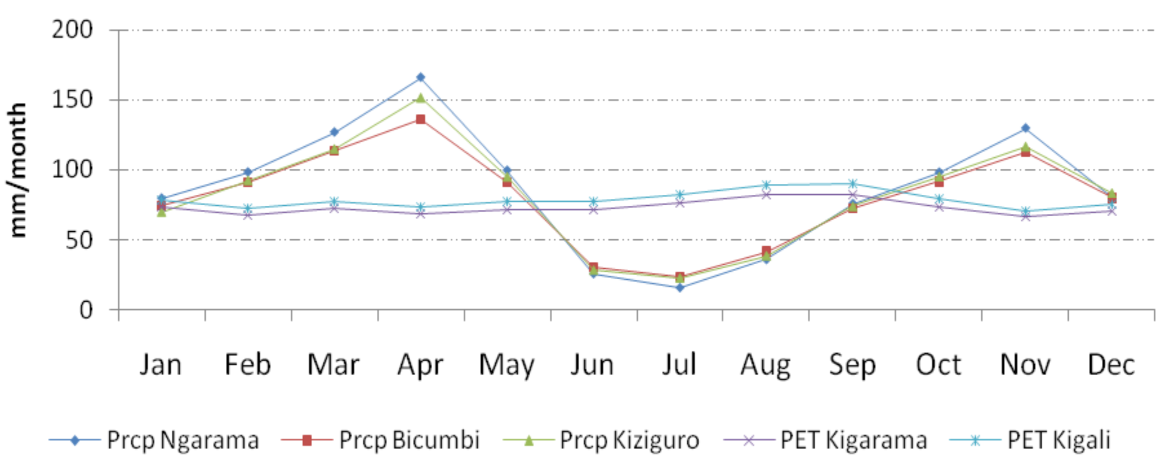

Figure 15. Sites average monthly precipitation versus monthly PET.

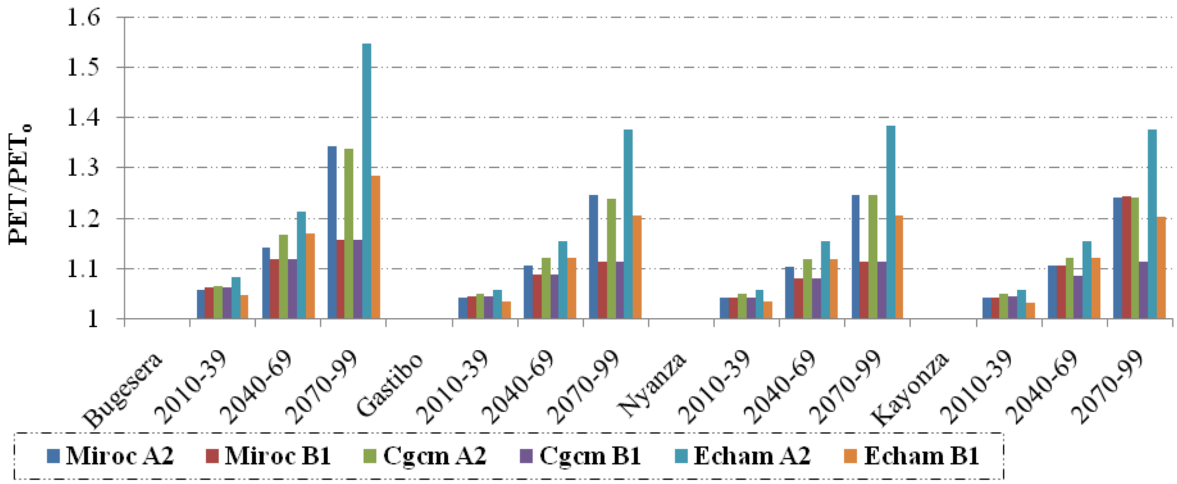

Figure 16. 30 years PET average increment factor relative to the 20 cm^3 base line.

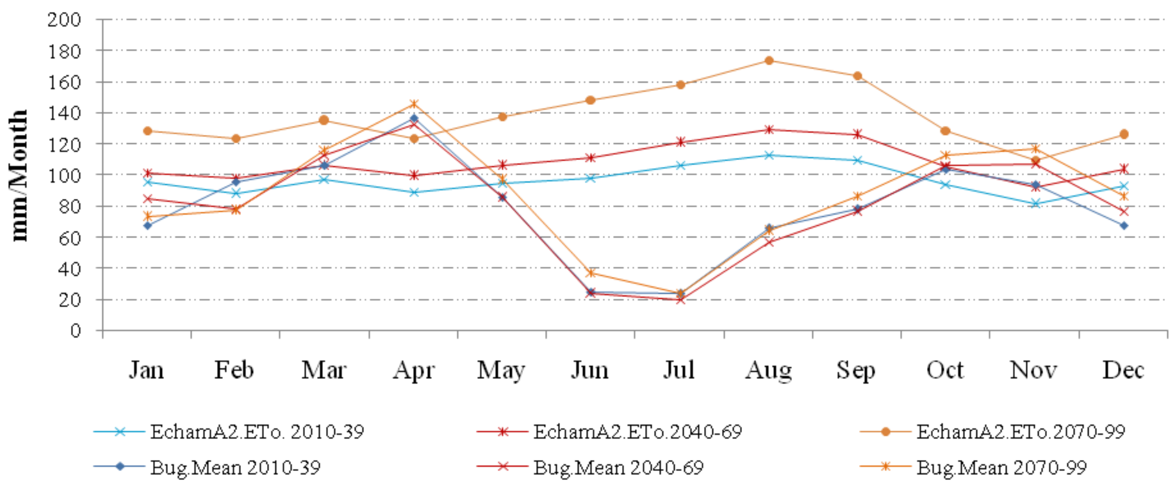

Figure 17. Plot of precipitation versus PET at Bugesera site based on EchamA2 projections.

according to B1 the PET will vary from 4 to 16% Miroc3 A2 has predicted a PET varying from 4 to 34% at the end of the century, while according to B1 scenario the PET will vary between 4 to 24% at the end of the 21st century.

Figure 17 provides a comparison between projected precipitation and projected PET at a sample site. It is noticed that both Cgcm and Miroc predicted 4 months with water deficit at Bugesera while Echam 5.1 predicted more severe conditions in which water deficit last for 10 months with precipitation exceeds PET only in April and November. Although the analysis has shown that precipitation will increase by 8, 10 and 28% in 2039, 2069 and 2099, respectively at Bugesera site, PET projections indicate that there are at least 10 months that experience water deficit in which the PET exceeds the precipitation. This situation is noticed at different sites in the Nile part of Rwanda which emphasize the impact of climate change on the irrigation practice and need for adaptation measures centered about the supplemental irrigation in months that have PET exceeds precipitation.

Conclusions

In this study analysis of Rwanda past/present meteorological observations as well as of climate projections of identified global circulation models and emission scenarios is carried out. The analysis is focused on meteorological parameters that mostly affect the hydrology system and the quantification of irrigation water (surface air temperature, precipitation and potential evapotranspiration). Precipitation and air temperature records from six potential hillside irrigation sites located in the Nile basin part of Rwanda are collected in the period from 1964 to 2010. Future climate projection for the period from 2010-2099 are acquired from 3 CMIP3 general circulation models for 2 emission scenarios (A2 and B1). Temperature and precipitation data from the Canadian ccma_cgcm3_1.1; Japanese miroc3_2medres and German mpi_echam5.1models are used for future projection analysis.

Observed average air temperatures suggested warming pattern over the past 40 years at an average of 0.35°C per decade. Some observed precipitation records from 1964 to 2010 illustrate a decrease from 1980's till 2000. The computed potential evapotranspiration is following the rising trend of the air temperature with potential evapotranspiration exceeds the received precipitation in the months of June, July, August and September.

Analysis of climate projections for Rwanda's through the 21st century indicates a trend towards a warmer and wetter climate conditions. Increases in mean air temperature, precipitation and potential evapotranspiration are projected under all models and all emissions scenarios. The increases in rainfall are generally small relative to the inter-annual variability currently experienced in Rwanda. The highest mean air temperature increase at the end of the 21st century is predicted at Nyanza with a value of 4.5°C corresponding to Echam-A2. The highest increase in potential evapotranspiration is projected at Bugesera with an increase increment of 55% corresponding to Echam-A2. The highest precipitation increase increment is projected to be 29% at Kayonza corresponding to Miroc-A2.

Despite of the projected wetter climate conditions in Rwanda, the increase in potential evapotranspiration will over rule during the 21st century resulting in deficit in water availability for the rainfed agriculture. Deficit periods in which potential evapotranspiration exceeds precipitation will be extended to 10 months at some parts in the country instead of 4 months at present. This situation is projected at different sites in Rwanda which emphasize the impact of climate change on the current irrigation practices. The Rwandan development plans are urged to include adaptation and mitigation measures to cope with potential climate change impacts and meanwhile initiating further climate related investigations.

Conflict of Interests

The authors have not declared any conflict of interest.

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