# EVALUATIONOF SATELLITE DERIVED RAINFALL DATA FOR MT KENYA REGION

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**Abstract**
Rainfall information is crucial more so for an economy that heavily relies on rain fed agriculture like Kenya. However, the spatial distribution of rain gauges is low and is only representative of location of measurement. Satellite based precipitation products can be used to supplement the data acquired from the ground stations available. There is need of validation of the satellite products by establishing a level of confidence and subsequently the probability of use of the data in areas where ground observations are not available. The performance of RFE V2 and GPCP 1DD was evaluated against observations for the region around Mt. Kenya. The aim was to determine the level of correlation between the satellite-based precipitation and the ground observations. Based on the analysis, resolve on the use of the data in cases where ground observations are not available. Observation data from six ground stations for the period between 2001 and 2012 were used in the analysis. Over estimation or underestimation was initially calculated. Weights were assigned based on their range of deviation from the observations. The coefficient of determination was also computed and weights assigned based on their precision to the observed values. Weights from the two parameters were then multiplied to give a combined goodness of fit. RFE performed better in most of the stations. An analysis of the performance of the satellite estimates should be done using daily observation data as opposed to the monthly data used.

**Key words:** Climate change, weather forecasting, precipitation, GPCP, RFE

## 1.0 Introduction

Precipitation information is usually obtained from sparsely located rain gauges distributed around the country. Precipitation from rain gauges is representative at the spatial locations of measurement. The amounts measured are influenced by factors such as spatial location of the gauges and design of the gauges (Gruber *et al*., 2008). The relief of the land surface affects the distribution of precipitation. This creates a need to have higher spatial resolution data which can be obtained from satellite estimates. The estimation of precipitation is done using visible/infra-red and passive microwave sensors aboard earth observation satellites. Data from VIS/IR sensors on geostationary satellites is continually acquired as long as the satellite is in operation mode. On the other hand, low earth orbiting satellites provide high resolution VIS/IR and PM data periodically only for a given region of interest. Thus there is low spatial resolution and poor temporal sampling of data from low orbiting satellites.

VIS radiation infers the thickness and height of clouds whereas IR radiation infers the cloud top temperatures. Precipitation algorithms are developed through precipitation indexes that assign fixed rain rates to each cloud type (Liechti *et al*., 2012). This gives a crude map of precipitation as it relates to cloud top characteristics rather than the precipitation reaching the surface of the earth. In areas with complex topography, IR radiation poses a challenge due to the warm orographic rainfall resulting to rain rates inconsistent with the rain received on the surface of the earth (Dinku *et al.,* 2007).

Observations at microwave frequencies less than 40 GHz add to the upwelling radiation from the surface and the precipitation signal is due to emission of radiation from precipitation sized particles. At frequencies greater than 40 GHz, precipitation particles start scattering and the radiation received by the sensor is reduced. The PM sensors identify the precipitation particles through scattering of the large ice particles present in the clouds (Liechti *et al*., 2012). In areas of complex topography with warm orographic rain, there is reduced ice particles thus reduced scattering resulting to an under estimation of surface rain (Dinku *et al*., 2007). In addition, ice on mountain tops results to an over estimation of rain. PW gives a better instantaneous estimate of precipitation whereas VIS/IR has a better temporal resolution. To acquire improved estimates, PW estimates are used to calibrate VIS/IR precipitation estimates.

## 2.0 Study Area and Data

### 2.1 Study Area

The study area spans ten districts namely Thika, Nyeri, Nyandarua, Muranga, Meru South, Laikipia, Kirinyaga, Embu, Meru and Maragua in the Mt. Kenya region. The area lies between 1°N to 1.5°S and 36°E to 38°E (Figure 1). Mount Kenya (5199 m) lies within the study area. The area has high elevations and has series of hills. The six observation stations lie at elevations of between 1463 m to 2377 m above sea level. Long rains are experienced between the months of March and May whereas short rains are between the months of October and December. The Inter Tropical Convergence Zone (ITCZ) is responsible for the wet and dry seasons in this area.

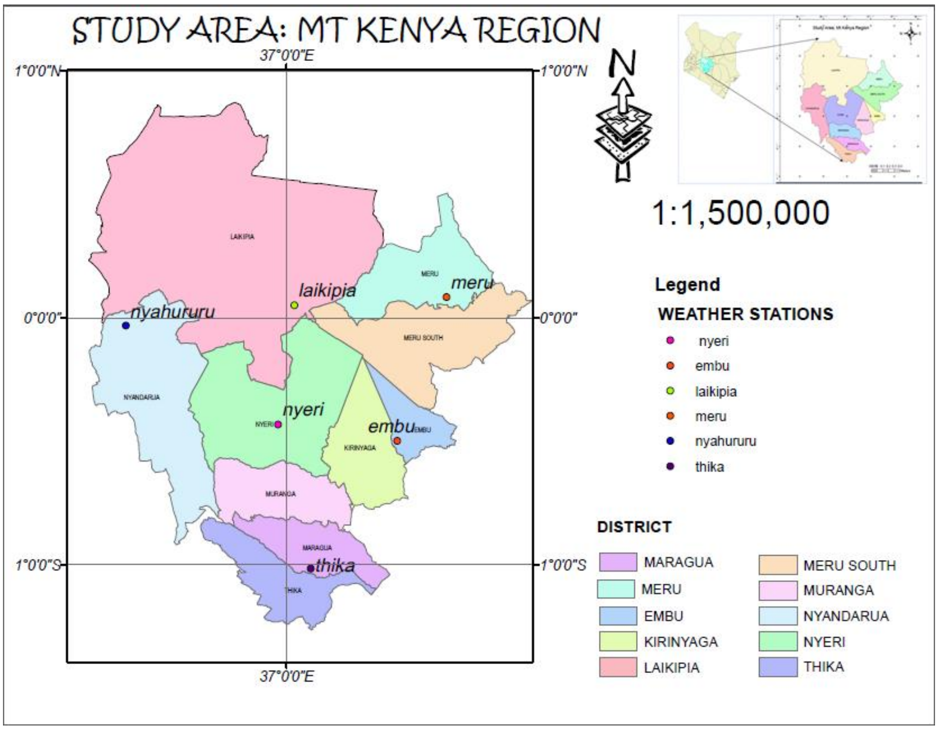



*Figure 1: Study area*

The weather information was obtained from the stations in Table 1.

*Table 1: Weather stations from which data was acquired*

| ID | Name | District | Latitude | Longitude | Elevation |
|---|---|---|---|---|---|
| 8937065 | Meru Meteorological Station | Meru | $0°05'00"N$ | $37°39'00"E$ | 1524 |
| 9037202 | Embu Meteorological Station | Embu | $0°30'00"S$ | $37°27'00"E$ | 1494 |
| 9137048 | Thika Agromet Station | Thika | $1°01'00"S$ | $37°06'00"E$ | 1463 |
| 9036288 | Nyeri Meteorological Station | Nyeri | $0°26'00"S$ | $36°58'00"E$ | 1798 |
| 9036135 | Nyahururu Agromet Station | Laikipia | $0°02'00"S$ | $36°21'00"E$ | 2377 |
| 8937022 | Laikipia Airbase (Nanyuki) | Laikipia | $0°03'00"N$ | $37°02'00"E$ | 1890 |

### 2.1 Precipitation Data

#### 2.1.1 Global Precipitation Climatology Project (GPCP)

GPCP is an initiative of the GEWEX to permit an understating of the spatial and temporal patterns of global precipitation. Daily GPCP data with a temporal resolution of 1.0° was used. Rain images are generated from passive microwave estimates from SSM/I by Goddard Profiling algorithm. Temperature thresholds are determined by comparing the rain images with GPI. A rain rate is then assigned for each Thermal Infra-Red pixel.

The data is acquired at the same local time each day by merging local unbiased estimates of rain gauge data, PW estimates from low earth orbiting satellites and high resolution VIS/IR estimates from geostationary sensors.

### 2.1.2 Famine Early Warning System Rainfall Estimates (FEWS RFE V2)

This is an initiative by NOAA Climate Prediction Center. RFE V2 has a spatial resolution of the data of 0.1° and is collected once daily. Rainfall estimates are initially calculated from Thermal Infra-Red (TIR) data using GOES Precipitation Index (GPI) algorithm that identifies clouds with tops colder than a threshold temperature of 235K, which are assigned a rain rate of 3 mm per hour. The GPI and Passive Micro Wave (PMW) estimates from Advanced Microwave Sounding Unit (AMSU) and Special Sensor Microwave Imager (SSM/I) are then merged, using weighting coefficients inversely related to the mean square difference between gauge data and the satellite estimates. The estimates are adjusted to agree with the Global Telecommunications System rain gauge data (Maidment *et al.,* 2013).

### 2.1.3 Ground Observation Data

This was acquired from Kenya Meteorological Department. Monthly averages for six stations, namely Meru meteorological station, Embu meteorological station, Thika agro met station, Nyeri meteorological station, Nyahururu agro met station and Laikipia airbase (Nanyuki) was acquired (Table 1 and 2).

*Table 1: Summary of data source*

| **Product** | **Source** | **Temporal resolution** | **Spatial resolution** | **Developed by** |
|---|---|---|---|---|
| Ground Observation Data | Kenya Meteorological Department | Monthly | - | - |
| FEWS RFE 2.0 | Geo-IR PM from SSM/I AMSU | Daily | 0.1° | NOAA CPC |
| GPCP 1DD | Geo-IR PM from SSM/I | Daily | 1.0° | GEWEX |

## 3.0 Methods

(i) Analysis was done so as to check for any similarities between the observations and satellite derived precipitation products. Departures from the observations were computed in mm.

(ii) Statistical analysis was done to compare the rainfall estimates from RFE and GPCP with the ground observation data

The following were computed:

$$mean\ error = \frac{\sum(sat\ data - observed)}{N}\ mm$$

$$RRMSE = 100\left(\frac{\sqrt{\frac{1}{N}\sum(sat\ data - observed)^2}}{observed\ mean}\right)$$

$$volume\ ratio\ or\ bias = \frac{\sum sat\ data}{\sum observed}$$

$$coefficient\ of\ determination(r^2) = \left(\frac{\sum(x_i - x_{mean}) * (y_i - y_{mean})}{\sqrt{\sum(x_i - x_{mean})^2} * \sqrt{\sum(y_i - y_{mean})^2}}\right)^2$$

$$over\ \ OR\ under\ estimation = \left(\frac{observed - sat\ data}{observed}\right)\%$$

The overestimation and underestimation of the satellite products was done. A matrix was formed by assigning weights to each variation depending on the magnitude. Those with low over/under estimation had the highest weights. The coefficient of determination was then computed so as to acquire the correlation between the observations and satellite products. Those with the highest correlation were assigned the highest weights. A final weight was acquired by multiplying the corresponding weights from over/under estimation and the correlation weight for each satellite product. The months with the highest scores showed better precision to observations.

**4.0 Results**

A. Analysis was done so as to check for any similarities between the observations and satellite derived precipitation products. To do this, the following criteria were used:

*Table 2: Criteria used to categorize data based on their deviation from observations*

| | |
|---|---|
| NEAR EQUAL | ±9 mm |
| SLIGHT OVER ESTIMATE | 10-29 mm |
| SLIGHT UNDER ESTIMATE | (-10)-(-29) mm |
| OVER ESTIMATE | 30-49 mm |
| UNDER ESTIMATE | (-30)-(-49) mm |
| EXTREME | >50 mm |

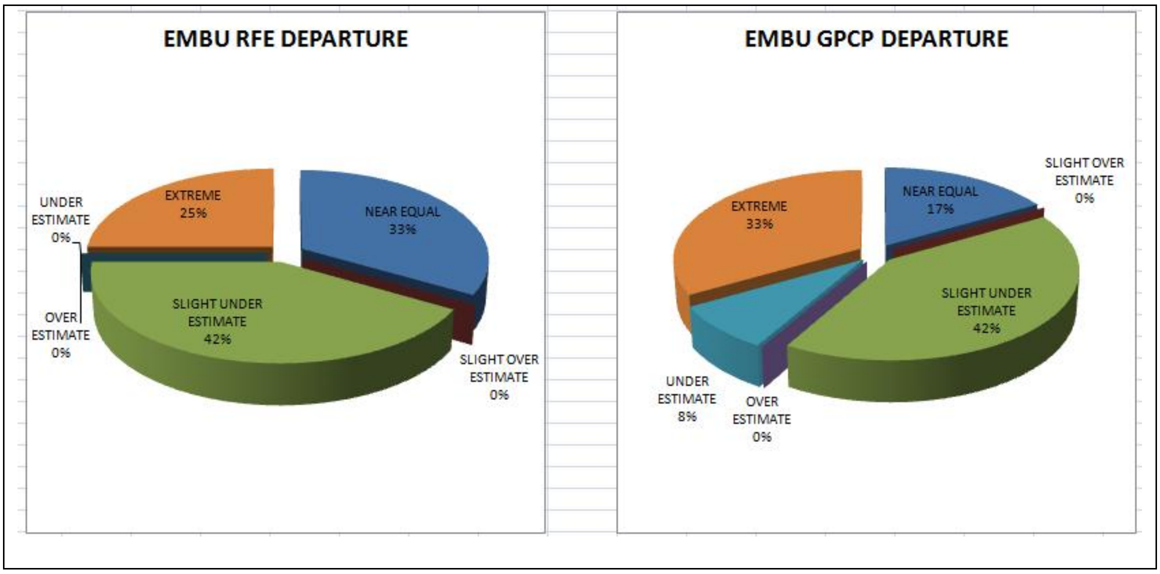



*Figure 3: RFE, GPCP deviation from observation for Embu*

For RFE estimates, 6 months which received rainfall of less than 50 mm had a departure of less than 29 mm from the observation. 1 month which received rainfall of between 50-100 mm had a departure of less than 29 mm. For months which received rainfall of greater than 100 mm, 2 had a departure of less than 29 mm while 3 had a departure of greater than 50 mm (Figure 4).

For GPCP, 6 months which received rainfall of less than 50 mm had a departure of less than 29 mm, 1 month with rainfall 50-100 mm had a departure of less than 29 mm. For months with rainfall greater than 100 mm, 1 month had a departure of between 30-49 mm whereas 4 had a departure of greater than 50 mm. From this analysis, it was seen that the departure from the observations is less when the rainfall experienced in the area was less than 50 mm.

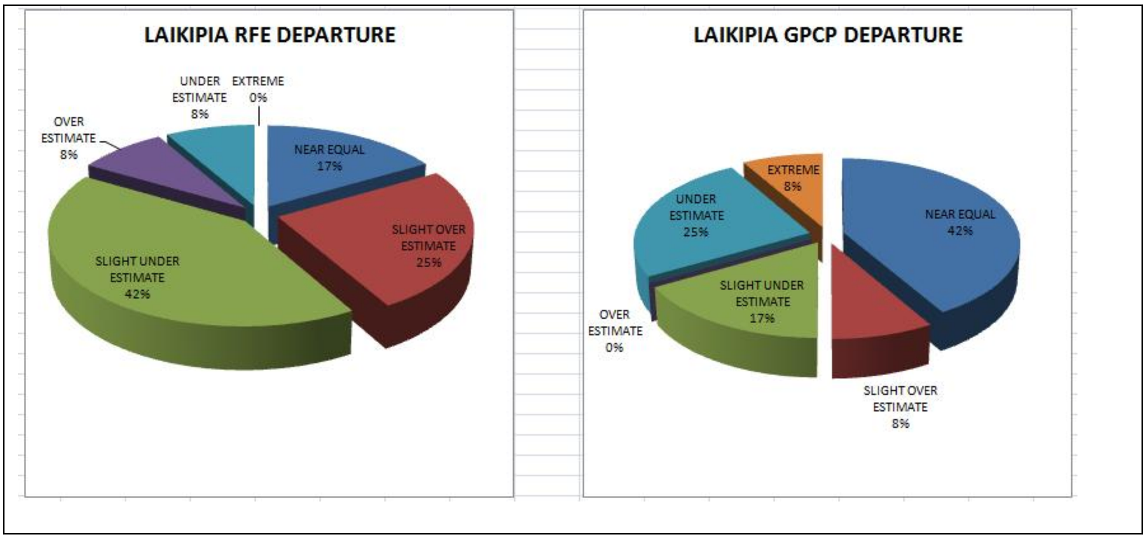



*Figure 4: RFE, GPCP deviation from observation for Laikipia*

For RFE, 4 months which had rainfall of less than 50 mm had a departure of less than 29 mm. For those with rainfall 50-100 mm, 5 months had departure of less than 29 mm and 2 had departures of between 30-49 mm. for those with rainfall greater than 100 mm, one month had a departure of less than 29 mm.

For GPCP, 4 months with less than 50 mm rainfall had a departure of less than 29 mm. In the rainfall range 50-100 mm, 3 months had a departure of less than 29 mm, 3 months had a departure of between 30-49 mm and 1 had a departure of greater than 50 mm. Only one month with rainfall greater than 100 mm had a departure of less than 29 mm. Analysis showed that departure was less with rainfall between 0-100mm (Figure 5).

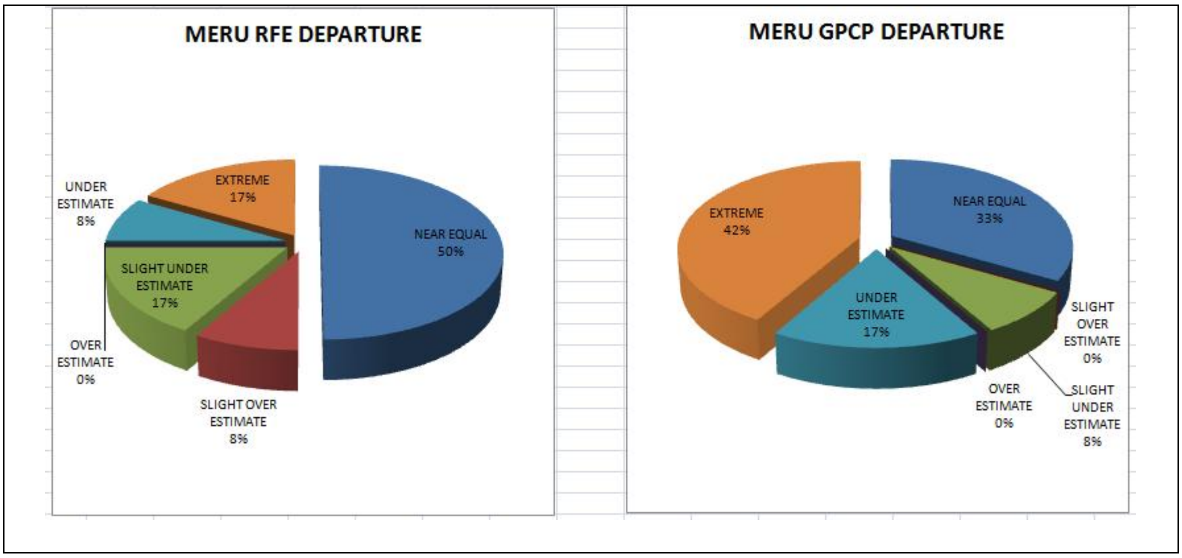



*Table 5: RFE, GPCP deviation from observation for Meru*

For RFE, 5 months with rainfall less than 50 mm had a departure of less than 29 mm and 3 months with rainfall between 50-100 mm had a departure of less than 29 mm. For months with rainfall greater than 100 mm, 1 month had a departure of less than 29 mm, 1 had a departure between 30-49 mm and 2 had a departure of greater than 50 mm. For GPCP, 5 months with rainfall less than 50 mm had a departure of less than 29 mm and 2 months with rainfall between 50-100 mm had a departure of less than 29 mm. 4 months with rainfall greater than 100 mm had a departure of greater than 50 mm (Figure 6).

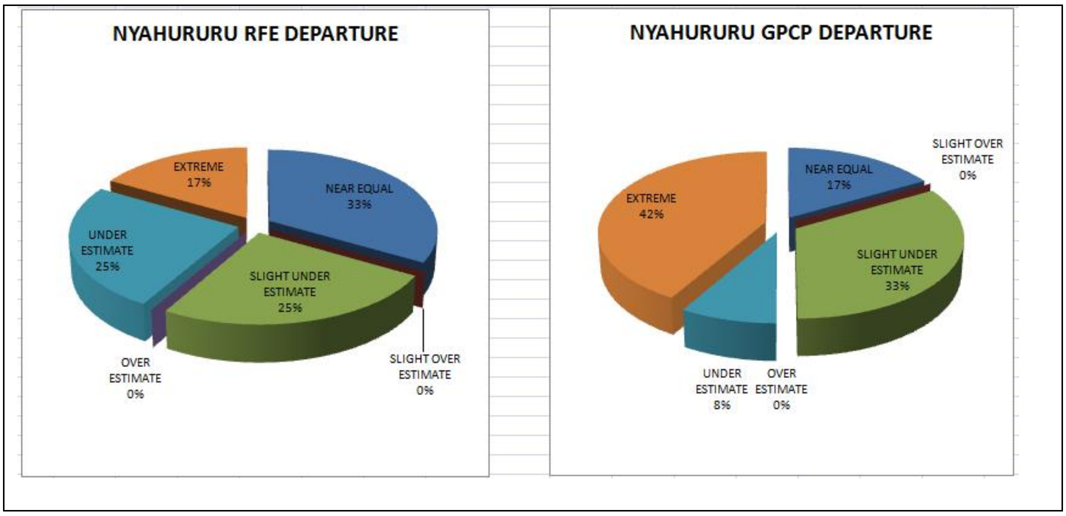



*Table 6: RFE, GPCP deviation from observation for Nyahururu*

For RFE, 2 months with less than 50 mm rainfall had a departure of less than 29 mm. Between 50-100 mm rainfall, 4 months had a departure of less than 29 mm and 2 months had departures of between 30-49 mm. for those months with rainfall greater than 100 mm, 1 had a departure of less than 29 mm, 1 had a departure of between 30-49 mm and 2 had departures of greater than 50 mm. For GPCP, 2 months with rainfall less than 50 mm had a departure of less than 29 mm. In the range between rainfalls 50-100 mm, 3 months had a departure of less than 29 mm, 1 had a departure of between 30-49 and 2 months had a departure of greater than 50mm. for months that experienced rainfall of greater than 100 mm, one month had a departure of less than 29 mm and 3 months had a departure of greater than 50 mm. From the analysis it was seen than the departure was less when the rainfall received was between 0-100 mm (Figure 7).

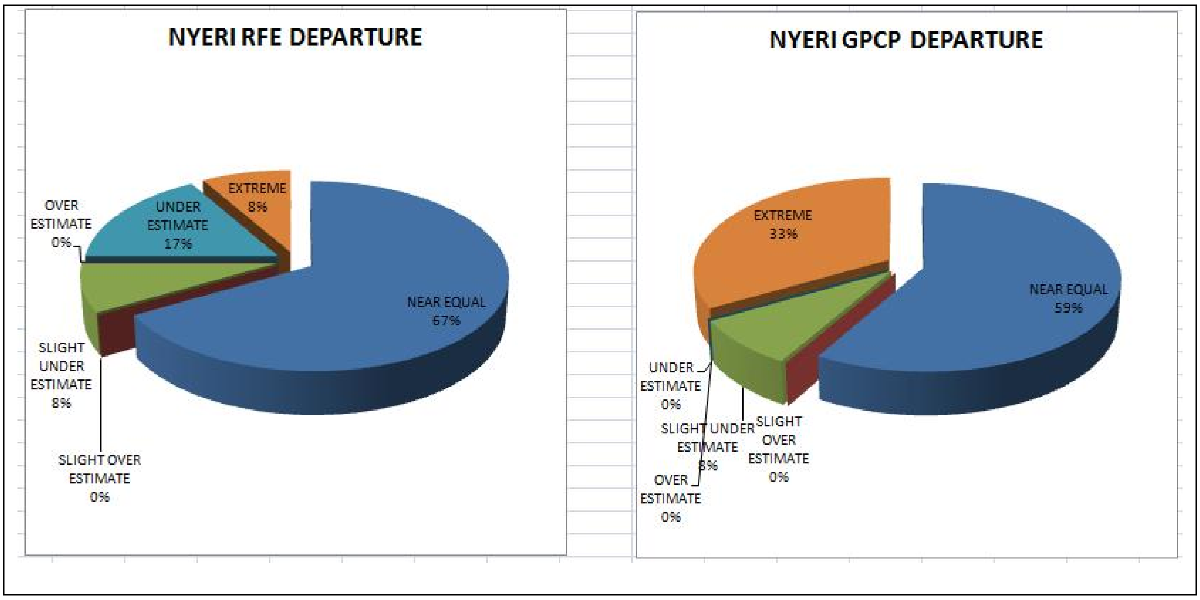



*Table 7: RFE, GPCP deviation from observation for Nyeri*

For RFE, 6 months with rainfall less than 50 mm had a departure of less than 29 mm and 2 months with rainfall between 50-100 mm had a departure of less than 29 mm. For months with rainfall greater than 100 mm, 1 month had a departure of less than 29 mm, 2 had a departure of between 30-49 mm and 1 had a departure of greater than 50 mm. For GPCP, 6 months with rainfall less than 50 mm had a departure of less than 29 mm and 2 months with rainfall between 50-100 mm had a departure of less than 29 mm. 4 months with rainfall greater than 100 mm had a departure of greater than 50 mm. From the analysis, it was seen that the months that experienced rainfall between 0-100mm had less departure (Figure 8).

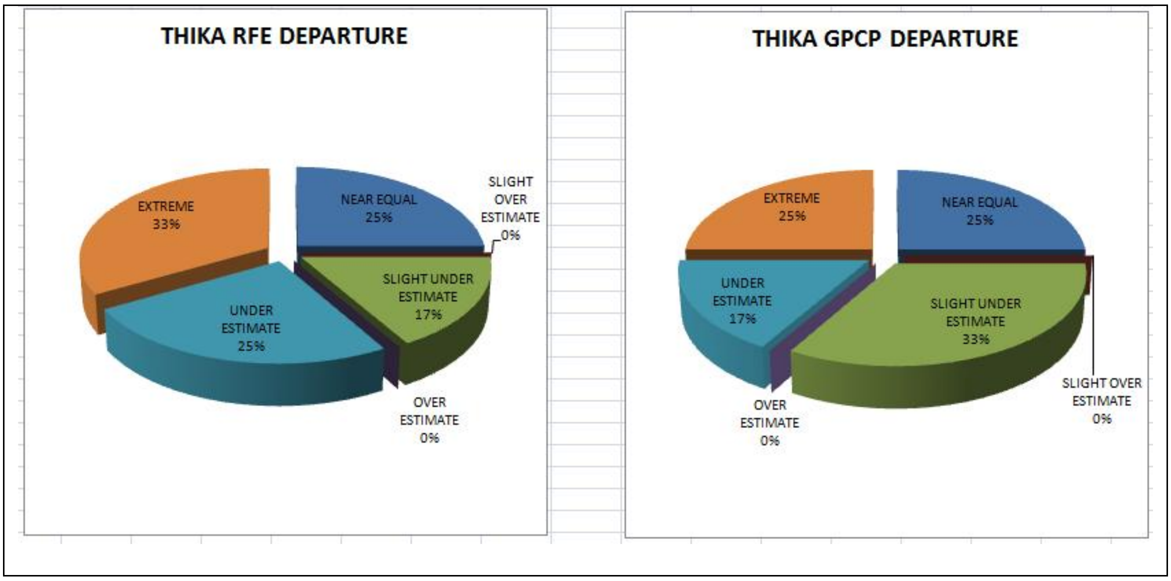



*Table 8: RFE, GPCP deviation from observation for Thika*

For RFE, 5 months with rainfall less than 50 mm had a departure of less than 29 mm. For the range between 50-100mm, 1 month had a departure of between 30-49 mm and 1 had a departure of greater than 50 mm. For months with rainfall greater than 100 mm, 2 months had a departure of between 30-49mm whereas 3 months had a departure of greater than 50 mm. For GPCP, 5 months with rainfall less than 50 mm had a departure of less than 29 mm. For the range between 50-100mm, 1 month had a departure of less than 29 mm and 1 month had a departure of between 30-49 mm. For months which experienced rainfall greater than 100 mm, 1 month had a departure of less than 29mm, 1 had a departure of between 30-49 mm and 3 months had a departure of greater than 50 mm. For this station, departure was less when the rainfall experienced was less than 29 mm (Figure 9).

Statistical analysis was done to compare the rainfall estimates from RFE and GPCP with the ground observation data. For each station, mean error, RRMSE and volume ratio/bias was as follows (Table 4):

*Table 4: Statistical analysis for the six stations*

| Embu | RFE | GPCP | Laikipia | RFE | GPCP |
|---|---|---|---|---|---|
| **Mean Error** | -32.40 mm | -54.88 mm | **Mean Error** | -3.88 mm | -15.35 mm |
| **Rrmse** | 45 % | 75 % | **Rrmse** | 37 % | 46 % |
| **Volume Ratio/Bias** | 0.69 | 0.48 | **Volume Ratio/Bias** | 0.93 | 0.73 |

| Meru | RFE | GPCP | Nyahururu | RFE | GPCP |
|---|---|---|---|---|---|
| **Mean Error** | -20.57 mm | -69.74 mm | **Mean Error** | -27.63 mm | -43.55 mm |
| **Rrmse** | 36 % | 95 % | **Rrmse** | 41 % | 66 % |
| **Volume Ratio/Bias** | 0.82 | 0.38 | **Volume Ratio/Bias** | 0.68 | 0.50 |

| Nyeri | RFE | GPCP | Thika | RFE | GPCP |
|---|---|---|---|---|---|
| **Mean Error** | -13.66 mm | -35.15 mm | **Mean Error** | -37.83 mm | -34.17 mm |
| **Rrmse** | 27 % | 74 % | **Rrmse** | 59 % | 59 % |
| **Volume Ratio/Bias** | 0.83 | 0.56 | **Volume Ratio/Bias** | 0.55 | 0.59 |

In Laikipia, the mean error for RFE data was -3.88 mm whereas that from GPCP data was -15.35 mm. The relative root mean square error for RFE was found to be 37% and that of GPCP was 46%. The bias was 0.93 for RFE and 0.73 for GPCP. For the 3 parameters under investigation, RFE had smaller variations from observations as compared to GPCP.

The mean error for Nyahururu for RFE is -27.63 mm and that of GPCP is -43.55 mm. The RRMSE for RFE is 41% and that of GPCP is 66%. The bias for RFE is 0.68 and that for GPCP is 0.50. The data from RFE gives better results as compared to that from GPCP. The mean error in Thika from the RFE is -37.83 mm and that from GPCP is -34.17 mm. The errors are close in range. The RRMSE is 59% for both RFE and GPCP. The volume ration for RFE is 0.55 and that of GPCP is 0.59. Both RFE and GPCP estimates for Thika show an almost similar variation from the observations. RFE mean error for Embu is -32.40 mm and that for GPCP is -54.88 mm. The RRMSE for RFE is 45% and that of GPCP is 75%. The bias is 0.69 for RFE and 0.48 for GPCP. RFE gives better results as compared to GPCP.

In Meru, the mean error was -20.57 mm for RFE and that for GPCP was -69.74 mm. the RRMSE for RFE is 36% and that for GPCP is 95%. The bias for RFE was 0.82 and that for GPCP is 0.38. RFE gave better results as compared to GPCP results.
The mean error in Nyeri was -13.66 mm for RFE and -35.15 mm for GPCP. The RRMSE for RFE was 27% and that for GPCP was 74%. The RFE bias ratio was 0.83 while that for GPCP was 0.56. RFE gave better results as compared to GPCP.

**Weight Assignment**
The weights assigned were as follows (Table 5):

*Table 5: Criteria used in weight assignment*

| **$R^2$** | **Weight** | **$R^2$** | **Weight** | **Over/Under Estimation** | **Weight** | **Over/Under Estimation** | **Weight** |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| 0.000-0.100 | 1 | 0.501-0.600 | 6 | 00.00-10.00 % | 10 | 50.01-60.00 % | 5 |
| 0.101-0.200 | 2 | 0.601-0.700 | 7 | 10.01-20.00 % | 9 | 60.01-70.00 % | 4 |
| 0.201-0.300 | 3 | 0.701-0.800 | 8 | 20.01-30.00 % | 8 | 70.01-80.00 % | 3 |
| 0.301-0.400 | 4 | 0.801-0.900 | 9 | 30.01-40.00 % | 7 | 80.01-90.00 % | 2 |
| 0.401-0.500 | 5 | 0.901-1.000 | 10 | 40.01-50.00 % | 6 | 90.01-100.00 % | 1 |

The table for the coefficient of determination (***$R^2$***) for the six stations is shown in Table 6.

*Table 6: Weight assignment for $r^2$*

| | | $R^2$ RFE | WEIGHT | $R^2$ GPCP | WEIGHT | | | $R^2$ RFE | WEIGHT | $R^2$ GPCP | WEIGHT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EMBU | JAN | 0.545 | 6 | 0.576 | 6 | LAIKIPIA | JAN | 0.486 | 5 | 0.364 | 4 |
| | FEB | 0.891 | 9 | 0.590 | 6 | | FEB | 0.743 | 8 | 0.563 | 6 |
| | MAR | 0.710 | 8 | 0.320 | 4 | | MAR | 0.008 | 1 | 0.672 | 7 |
| | APR | 0.439 | 5 | 0.420 | 5 | | APR | 0.379 | 4 | 0.341 | 4 |
| | MAY | 0.704 | 8 | 0.666 | 7 | | MAY | 0.434 | 5 | 0.646 | 7 |
| | JUN | 0.219 | 3 | 0.049 | 1 | | JUN | 0.415 | 5 | 0.028 | 1 |
| | JUL | 0.749 | 8 | 0.001 | 1 | | JUL | 0.069 | 1 | 0.050 | 1 |
| | AUG | 0.219 | 3 | 0.059 | 1 | | AUG | 0.253 | 3 | 0.423 | 5 |
| | SEP | 0.673 | 7 | 0.569 | 6 | | SEP | 0.177 | 2 | 0.020 | 1 |
| | OCT | 0.372 | 4 | 0.407 | 5 | | OCT | 0.069 | 1 | 0.021 | 1 |
| | NOV | 0.435 | 5 | 0.489 | 5 | | NOV | 0.601 | 7 | 0.573 | 6 |
| | DEC | 0.876 | 9 | 0.687 | 7 | | DEC | 0.275 | 3 | 0.681 | 7 |
| | | | | | | | | | | | |

| | | $R^2$ RFE | WEIGHT | $R^2$ GPCP | WEIGHT | | | $R^2$ RFE | WEIGHT | $R^2$ GPCP | WEIGHT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| MERU | JAN | 0.170 | 2 | 0.577 | 6 | NYERI | JAN | 0.800 | 8 | 0.462 | 5 |
| | FEB | 0.884 | 9 | 0.561 | 6 | | FEB | 0.675 | 7 | 0.340 | 4 |
| | MAR | 0.924 | 10 | 0.483 | 5 | | MAR | 0.928 | 10 | 0.477 | 5 |
| | APR | 0.898 | 9 | 0.772 | 8 | | APR | 0.775 | 8 | 0.051 | 1 |
| | MAY | 0.790 | 8 | 0.195 | 2 | | MAY | 0.712 | 8 | 0.623 | 7 |
| | JUN | 0.375 | 4 | 0.006 | 1 | | JUN | 0.749 | 8 | 0.072 | 1 |
| | JUL | 0.908 | 10 | 0.013 | 1 | | JUL | 0.986 | 10 | 0.604 | 7 |
| | AUG | 0.420 | 5 | 0.271 | 3 | | AUG | 0.636 | 7 | 0.194 | 2 |
| | SEP | 0.220 | 2 | 0.126 | 2 | | SEP | 0.431 | 5 | 0.199 | 2 |
| | OCT | 0.761 | 8 | 0.297 | 3 | | OCT | 0.396 | 4 | 0.198 | 2 |
| | NOV | 0.760 | 8 | 0.496 | 5 | | NOV | 0.727 | 8 | 0.611 | 7 |
| | DEC | 0.993 | 10 | 0.596 | 6 | | DEC | 0.899 | 9 | 0.672 | 7 |
| | | | | | | | | | | | |
| | | $R^2$ RFE | WEIGHT | $R^2$ GPCP | WEIGHT | | | $R^2$ RFE | WEIGHT | R2 GPCP | WEIGHT |
| NYAHU-RURU | JAN | 0.830 | 9 | 0.393 | 4 | THIKA | JAN | 0.746 | 8 | 0.739 | 8 |
| | FEB | 0.928 | 10 | 0.706 | 8 | | FEB | 0.415 | 5 | 0.319 | 4 |
| | MAR | 0.761 | 8 | 0.913 | 10 | | MAR | 0.493 | 5 | 0.424 | 5 |
| | APR | 0.383 | 4 | 0.389 | 4 | | APR | 0.225 | 3 | 0.164 | 2 |
| | MAY | 0.618 | 7 | 0.297 | 3 | | MAY | 0.743 | 8 | 0.338 | 4 |
| | JUN | 0.396 | 4 | 0.509 | 6 | | JUN | 0.820 | 9 | 0.086 | 1 |
| | JUL | 0.153 | 2 | 0.397 | 4 | | JUL | 0.537 | 6 | 0.036 | 1 |
| | AUG | 0.026 | 1 | 0.323 | 4 | | AUG | 0.385 | 4 | 0.345 | 4 |
| | SEP | 0.517 | 6 | 0.546 | 6 | | SEP | 0.646 | 7 | 0.509 | 6 |
| | OCT | 0.245 | 3 | 0.209 | 3 | | OCT | 0.062 | 1 | 0.407 | 5 |
| | NOV | 0.187 | 2 | 0.477 | 5 | | NOV | 0.553 | 6 | 0.494 | 5 |
| | DEC | 0.826 | 9 | 0.749 | 8 | | DEC | 0.587 | 6 | 0.844 | 9 |
| | | | | | | | | | | | |

The table for the under/over estimation for the six stations is shown in Table 7.

*Table 7: Weight assignment for over/under estimation*

| | | RFE-BIAS | WEIGHT | GPCP-BIAS | WEIGHT | | | RFE-BIAS | WEIGHT | GPCP-BIAS | WEIGHT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Embu | Jan | -20.87% | 8 | -28.60% | 8 | Laikipia | Jan | 2.01% | 10 | -8.53% | 10 |
| | Feb | -5.65% | 10 | 6.83% | 10 | | Feb | 69.20% | 4 | 25.47% | 8 |
| | Mar | -23.11% | 8 | -37.23% | 7 | | Mar | 65.63% | 4 | -20.46% | 8 |
| | Apr | -35.68% | 7 | -53.32% | 5 | | Apr | 11.62% | 9 | -3.44% | 10 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | May | -36.27% | 7 | -71.36% | 3 | | May | 14.77% | 9 | -42.48% | 6 |
| | Jun | -40.12% | 6 | -24.97% | 8 | | Jun | -30.66% | 7 | -72.08% | 3 |
| | Jul | -27.92% | 8 | -56.41% | 5 | | Jul | -49.00% | 6 | -78.30% | 3 |
| | Aug | -35.26% | 7 | -65.42% | 4 | | Aug | -53.15% | 5 | -77.31% | 3 |
| | Sep | -45.60% | 6 | -58.30% | 5 | | Sep | -45.82% | 6 | -73.66% | 3 |
| | Oct | -44.17% | 6 | -63.88% | 4 | | Oct | -20.68% | 8 | 3.87% | 10 |
| | Nov | -13.66% | 9 | -46.44% | 6 | | Nov | -24.09% | 8 | 6.28% | 10 |
| | DEC | -18.68% | 9 | -21.53% | 8 | | DEC | 42.73% | 6 | 44.31% | 6 |
| | | | | | | | | | | | |
| | | RFE-BIAS | WEIGHT | GPCP-BIAS | WEIGHT | | | RFE-BIAS | WEIGHT | GPCP-BIAS | WEIGHT |
| Meru | Jan | -27.25% | 8 | -71.08% | 3 | Nyeri | Jan | -19.63% | 9 | 0.43% | 10 |
| | Feb | 3.15% | 10 | -50.21% | 5 | | Feb | -8.84% | 10 | -10.59% | 9 |
| | Mar | -20.42% | 8 | -48.21% | 6 | | Mar | -12.03% | 9 | -10.81% | 9 |
| | Apr | -17.78% | 9 | -57.82% | 5 | | Apr | -15.96% | 9 | -54.52% | 5 |
| | May | 1.43% | 10 | -53.56% | 5 | | May | -20.18% | 8 | -65.43% | 5 |
| | Jun | 46.58% | 6 | 28.01% | 8 | | Jun | 3.76% | 10 | 6.21% | 10 |
| | Jul | 1.32% | 10 | 17.19% | 9 | | Jul | -8.37% | 10 | 15.91% | 9 |
| | Aug | -10.27% | 9 | 1.22% | 10 | | Aug | -17.47% | 9 | 23.91% | 8 |
| | Sep | -29.01% | 8 | -30.97% | 7 | | Sep | 21.65% | 8 | -8.54% | 10 |
| | Oct | -39.55% | 7 | -75.97% | 3 | | Oct | -37.86% | 7 | -79.03% | 3 |
| | Nov | -17.12% | 9 | -70.85% | 3 | | Nov | -14.56% | 9 | -62.42% | 4 |
| | Dec | 8.86% | 10 | -55.94% | 5 | | Dec | -9.26% | 10 | -25.44% | 8 |
| | | | | | | | | | | | |
| | | RFE-BIAS | WEIGHT | GPCP-BIAS | WEIGHT | | | RFE-BIAS | WEIGHT | GPCP-BIAS | WEIGHT |
| Nyahu-Ruru | Jan | -36.05% | 7 | 10.88% | 9 | THIKA | Jan | -53.88% | 5 | -41.44% | 6 |
| | Feb | -31.30% | 7 | 9.15% | 10 | | Feb | -48.57% | 6 | -32.52% | 7 |
| | Mar | -26.37% | 8 | -25.89% | 8 | | Mar | -33.90% | 7 | -26.59% | 8 |
| | Apr | 6.74% | 10 | -25.60% | 8 | | Apr | -44.26% | 6 | -48.57% | 6 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | May | -30.97% | 7 | -49.41% | 6 | | May | -34.09% | 7 | -67.31% | 4 |
| | Jun | -47.85% | 6 | -71.57% | 3 | | Jun | -18.85% | 9 | 14.56% | 9 |
| | Jul | -44.17% | 6 | -72.21% | 3 | | Jul | 29.49% | 8 | 56.71% | 5 |
| | Aug | -48.58% | 6 | -76.36% | 3 | | Aug | -36.78% | 7 | -21.35% | 8 |
| | Sep | -36.24% | 7 | -74.13% | 3 | | Sep | -54.56% | 5 | -55.88% | 5 |
| | Oct | -14.74% | 9 | -54.90% | 5 | | Oct | -46.96% | 6 | -49.78% | 6 |
| | Nov | -24.16% | 8 | -36.00% | 7 | | Nov | -54.77% | 5 | -34.68% | 7 |
| | Dec | -37.45% | 7 | -17.25% | 9 | | Dec | -51.24% | 5 | -16.66% | 9 |

To determine how good the two parameters analyzed were, the weights for the under / over estimation were multiplied by the weights of the coefficient of determination.

$$W_{final} = (W_{over,u\ nderestimation} * W_{R^2})$$
$$80 - 100\%\ to\ be\ used\ after\ bias\ correction$$
$$60 - 79\%\ is\ to\ be\ analysed\ further$$
$$0 - 59\%\ is\ not\ to\ be\ used$$

*Table 8: Final weights*

| | MONTH | RFE WEIGHTS | GPCP WEIGHTS | | MONTH | RFE WEIGHTS | GPCP WEIGHTS |
|---|---|---|---|---|---|---|---|
| Embu | Jan | 48 | 48 | Laikipia | Jan | 50 | 40 |
| | Feb | 90 | 60 | | Feb | 32 | 48 |
| | Mar | 64 | 28 | | Mar | 4 | 56 |
| | Apr | 35 | 25 | | Apr | 36 | 40 |
| | May | 56 | 21 | | May | 45 | 42 |
| | Jun | 18 | 8 | | Jun | 35 | 3 |
| | Jul | 64 | 5 | | Jul | 6 | 3 |
| | Aug | 21 | 4 | | Aug | 15 | 15 |
| | Sep | 42 | 30 | | Sep | 12 | 3 |
| | Oct | 24 | 20 | | Oct | 8 | 10 |
| | Nov | 45 | 30 | | Nov | 56 | 60 |
| | Dec | 81 | 56 | | Dec | 18 | 42 |
| Meru | Jan | 16 | 18 | Nyeri | Jan | 72 | 50 |
| | Feb | 90 | 30 | | Feb | 70 | 36 |
| | Mar | 80 | 30 | | Mar | 90 | 45 |
| | Apr | 81 | 40 | | Apr | 72 | 5 |
| | May | 80 | 10 | | May | 64 | 35 |
| | Jun | 24 | 8 | | Jun | 80 | 10 |
| | Jul | 100 | 9 | | Jul | 100 | 63 |
| | Aug | 45 | 30 | | Aug | 63 | 16 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Sep | 16 | 14 | | Sep | 40 | 20 |
| | Oct | 56 | 9 | | Oct | 28 | 6 |
| | Nov | 72 | 15 | | Nov | 72 | 28 |
| | Dec | 100 | 30 | | Dec | 90 | 56 |
| Nyahururu | Jan | 63 | 36 | Thika | Jan | 40 | 48 |
| | Feb | 70 | 80 | | Feb | 30 | 28 |
| | Mar | 64 | 80 | | Mar | 35 | 40 |
| | Apr | 40 | 32 | | Apr | 18 | 12 |
| | May | 49 | 18 | | May | 56 | 16 |
| | Jun | 24 | 18 | | Jun | 81 | 9 |
| | Jul | 12 | 12 | | Jul | 48 | 5 |
| | Aug | 6 | 12 | | Aug | 28 | 32 |
| | Sep | 42 | 18 | | Sep | 35 | 30 |
| | Oct | 27 | 15 | | Oct | 6 | 30 |
| | Nov | 16 | 35 | | Nov | 30 | 35 |
| | Dec | 63 | 72 | | Dec | 30 | 81 |

Figure 10 show the graphs of coefficient of determination, bias and final weights for each station.

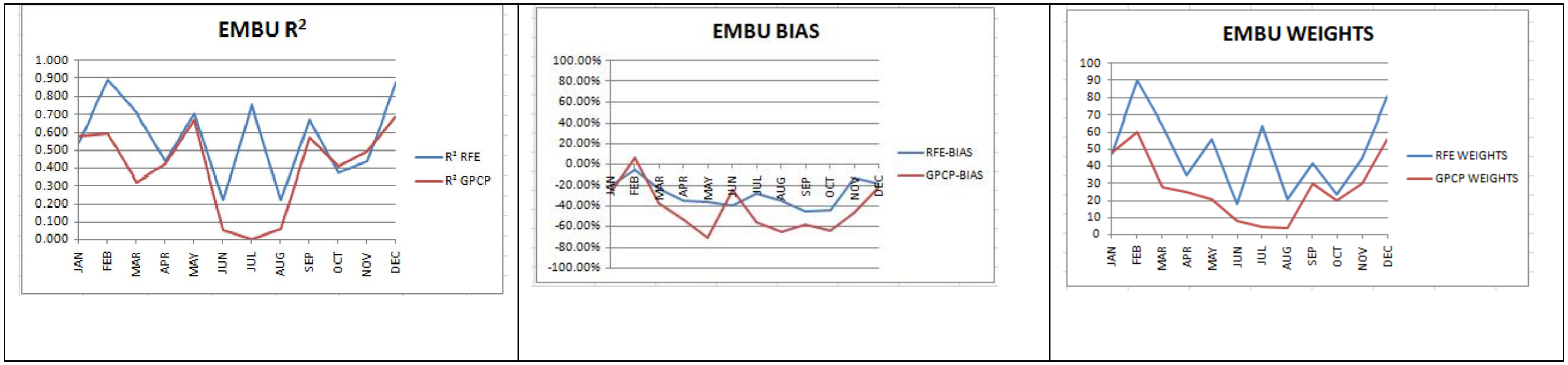



*Figure 10: Embu $r^2$, bias, final weights*

The $r^2$ for RFE was higher for most months. RFE and GPCP showed a pattern except for the months of July and February. Bias for RFE fell within 0-(-40) % whereas that for GPCP had a wider range, between 10 to (-70) %. The RFE weights were higher than those of GPCP indicating that they gave better correlation with the observations as compared to GPCP (Figure 11).

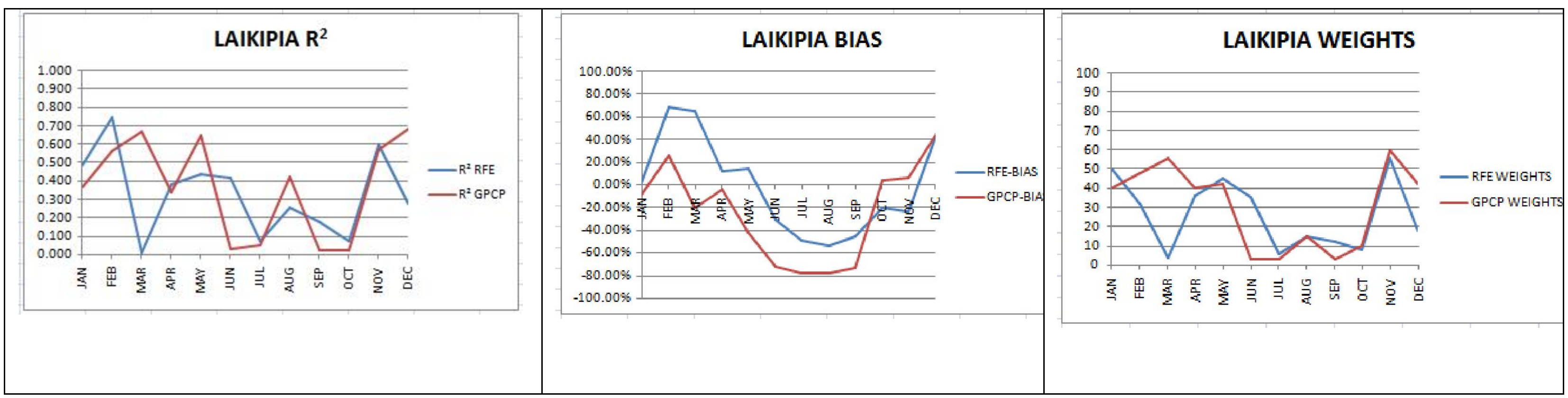



*Figure 91: Laikipia $r^2$, bias, final weights*

The r2 for RFE and GPCP greatly differed in the months of March, June and December. The pattern highly varied between the two sets of data. The bias showed a pattern between the RFE and GPCP. In the month of February and March, RFE bias was extremely high ranging from between 70-65%. GPCP showed a high bias in the months of May to September ranging between (-40)-(-80) %. The combined weights showed varied goodness of fit. RFE recorded extremely low weights in March, July, August, September and October. GPCP recorded low weights in June to October. For this station, the weights recorded for both RFE and GPCP are low and highly varied (Figure 12).

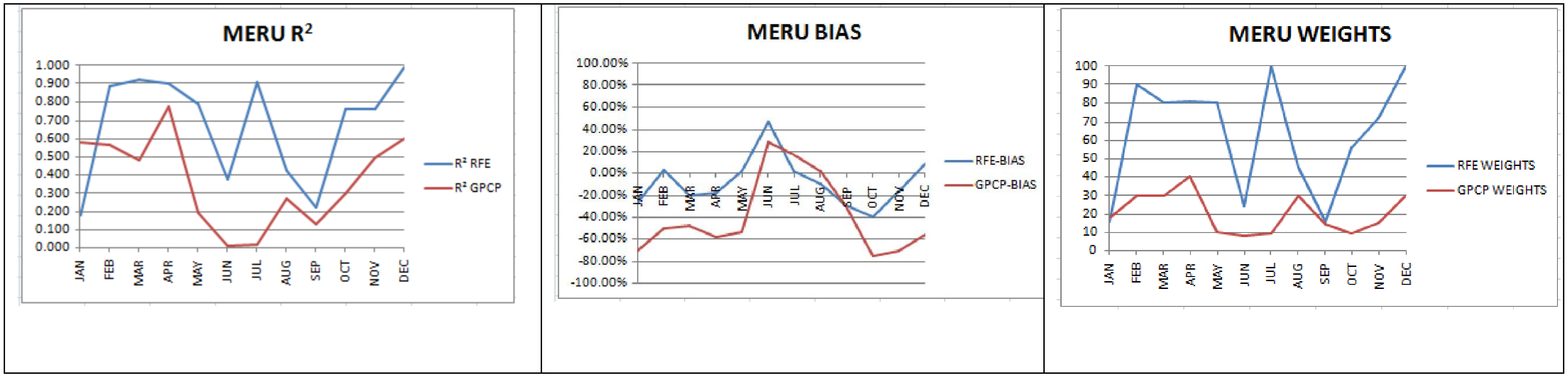



*Figure 102: Meru $r^2$, bias, final weights*

The r2 for RFE is higher than that of GPCP save for the month of January. The bias for RFE ranges from between 50 to (-40) % with the highest bias recorded in June. GPCP shows the greatest bias in the months of January, April, October, November and December. RFE weights are higher than those of GPCP for all the months (Figure 13).

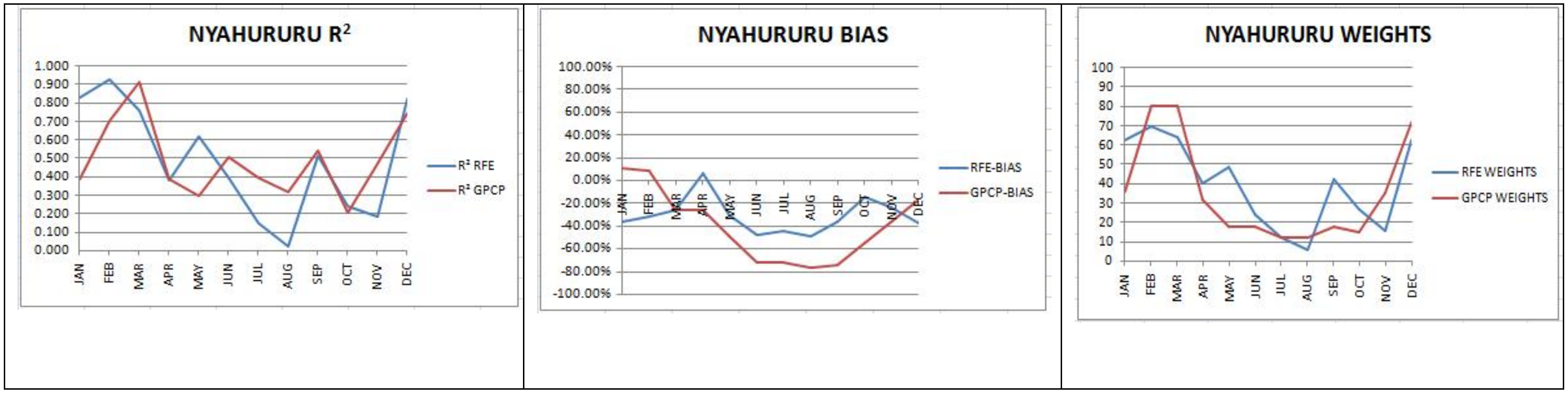



*Figure 113: Nyahururu $r^2$, bias, final weights*

The $r^2$ for RFE show varying patterns with that of GPCP for this station. RFE has very high correlation in the months of January to March and there is very low correlation in the months between June and August and between October and November. The range of bias is smaller for RFE, ranging from 10 to (-55) % where as that for GPCP ranges from 5 to (-78) %. The weights for RFE and GPCP vary for the different months. GPCP shows higher weights for the months of February, March, August, November and December. For the two sets of data, the weights are low between March and November (Figure 14).

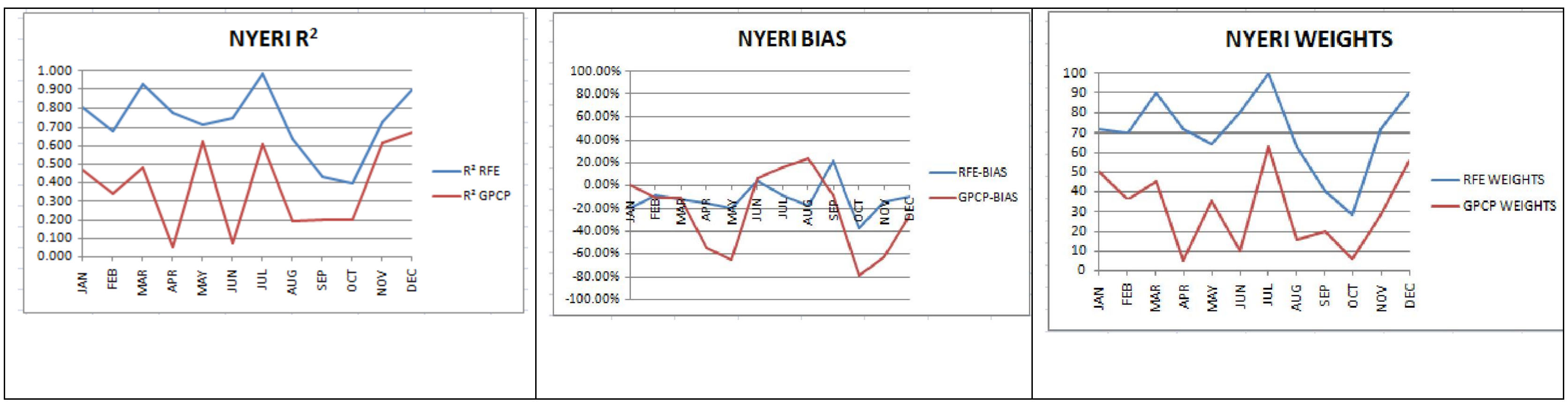
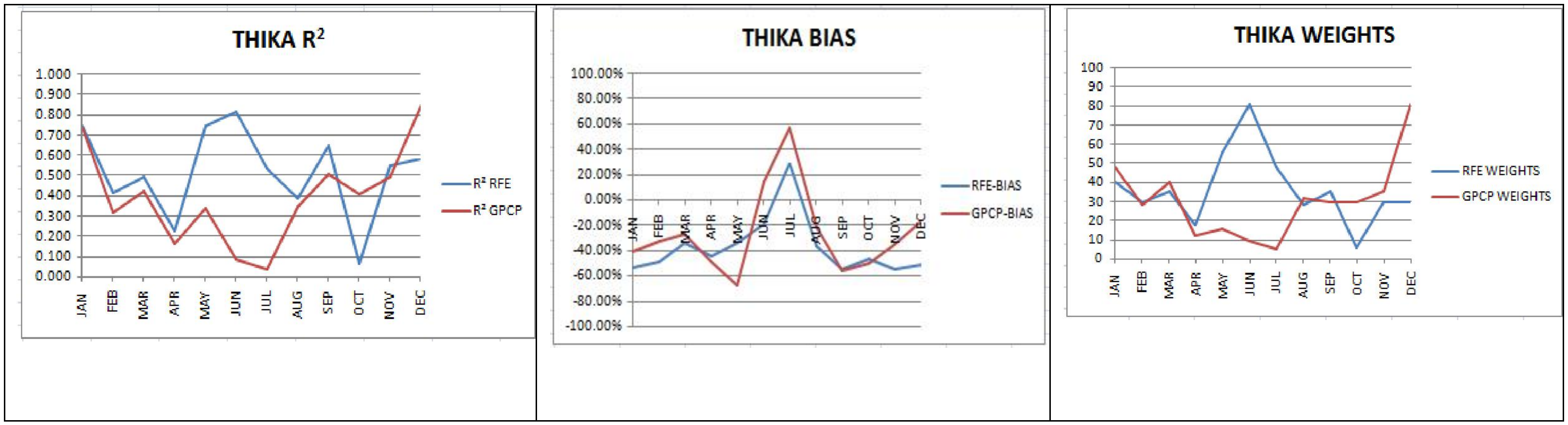



*Figure 124: Nyeri $r^2$, bias, final weights*

RFE r2 for this station is higher for all the months as compared to that of GPCP. The bias for RFE has a smaller range, that is from 20-(-40) %. The bias for GPCP ranges from 20-(-80) %. The weights for RFE are higher for all the months, indicating that they have a better correlation to the observations than the GPCP data.

*Figure 15: Thika $r^2$, bias, final weights*



Save for October and December, RFE recorded a higher r2 than GPCP. The r2 showed extreme variation between the RFE and GPCP for the months of May to August. There was low r2 value for r2 for the months of October. The bias between the two sets of data showed a close pattern. The weights between the GPCP and RFE varied greatly between the months of April to August and December.

In summary, the difference parameters are given in Table 9.

*Table 9: Summarized table of analysis (Embu, Laikipia)*

| EMBU | RFE WEIGHTS | GPCP WEIGHTS | RFE | | | LAIKIPIA | RFE WEIGHTS | GPCP WEIGHTS | RFE | |
|---|---|---|---|---|---|---|---|---|---|---|
| JAN | 48 | 48 | <59 | 8 | | JAN | 50 | 40 | <59 | 12 |
| FEB | 90 | 60 | 60-69 | 2 | | FEB | 32 | 48 | 60-69 | 0 |
| MAR | 64 | 28 | 70-79 | 0 | | MAR | 4 | 56 | 70-79 | 0 |
| APR | 35 | 25 | 80-89 | 1 | | APR | 36 | 40 | 80-89 | 0 |
| MAY | 56 | 21 | 90-100 | 1 | | MAY | 45 | 42 | 90-100 | 0 |
| JUN | 18 | 8 | | | | JUN | 35 | 3 | | |
| JUL | 64 | 5 | GPCP | | | JUL | 6 | 3 | | GPCP |
| AUG | 21 | 4 | <59 | 11 | | AUG | 15 | 15 | <59 | 11 |
| SEP | 42 | 30 | 60-69 | 1 | | SEP | 12 | 3 | 60-69 | 1 |
| OCT | 24 | 20 | 70-79 | 0 | | OCT | 8 | 10 | 70-79 | 0 |
| NOV | 45 | 30 | 80-89 | 0 | | NOV | 56 | 60 | 80-89 | 0 |
| DEC | 81 | 56 | 90-100 | 0 | | DEC | 18 | 42 | 90-100 | 0 |

In Embu, February and December RFE had weights greater than 80. This indicates that the bias was low and correlation high for these months. None of the months showed weights of greater than 80 for GPCP.

In Laikipia, neither RFE nor GPCP showed months whose weights were greater than 80.

*Table 10: Summarized table of analysis (Meru , Nyahururu)*

| MERU | RFE WEIGHTS | GPCP WEIGHTS | RFE | | | NYAHU RURU | RFE WEIGHTS | GPCP WEIGHTS | RFE | |
|---|---|---|---|---|---|---|---|---|---|---|
| JAN | 16 | 18 | <59 | 5 | | JAN | 63 | 36 | <59 | 8 |
| FEB | 90 | 30 | 60-69 | 0 | | FEB | 70 | 80 | 60-69 | 3 |
| MAR | 80 | 30 | 70-79 | 1 | | MAR | 64 | 80 | 70-79 | 1 |
| APR | 81 | 40 | 80-89 | 3 | | APR | 40 | 32 | 80-89 | 0 |
| MAY | 80 | 10 | 90-100 | 3 | | MAY | 49 | 18 | 90-100 | 0 |
| JUN | 24 | 8 | | | | JUN | 24 | 18 | | |
| JUL | 100 | 9 | GPCP | | | JUL | 12 | 12 | GPCP | |
| AUG | 45 | 30 | <59 | 12 | | AUG | 6 | 12 | <59 | 9 |
| SEP | 16 | 14 | 60-69 | 0 | | SEP | 42 | 18 | 60-69 | 0 |
| OCT | 56 | 9 | 70-79 | 0 | | OCT | 27 | 15 | 70-79 | 1 |
| NOV | 72 | 15 | 80-89 | 0 | | NOV | 16 | 35 | 80-89 | 2 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| DEC | 100 | 30 | 90-100 | 0 | | DEC | 63 | 72 | 90-100 | 0 |

In Meru, February, March, April, May, July and December has weights greater than 80 indicating that the bias was low and correlation was high. No months showed weights greater than 80 for GPCP.

In Nyahururu, no month showed weights greater than 80 for RFE. For GPCP, February and March showed weights greater than 80.

*Table 11: Summarized table of analysis (Nyeri, Thika)*

| NYERI | RFE WEIGHTS | GPCP WEIGHTS | RFE | | | THIKA | RFE WEIGHTS | GPCP WEIGHTS | RFE | |
|---|---|---|---|---|---|---|---|---|---|---|
| JAN | 72 | 50 | <59 | 2 | | JAN | 40 | 48 | <59 | 11 |
| FEB | 70 | 36 | 60-69 | 2 | | FEB | 30 | 28 | 60-69 | 0 |
| MAR | 90 | 45 | 70-79 | 4 | | MAR | 35 | 40 | 70-79 | 0 |
| APR | 72 | 5 | 80-89 | 1 | | APR | 18 | 12 | 80-89 | 1 |
| MAY | 64 | 35 | 90-100 | 3 | | MAY | 56 | 16 | 90-100 | 0 |
| JUN | 80 | 10 | | | | JUN | 81 | 9 | | |
| JUL | 100 | 63 | GPCP | | | JUL | 48 | 5 | GPCP | |
| AUG | 63 | 16 | <59 | 11 | | AUG | 28 | 32 | <59 | 11 |
| SEP | 40 | 20 | 60-69 | 1 | | SEP | 35 | 30 | 60-69 | 0 |
| OCT | 28 | 6 | 70-79 | 0 | | OCT | 6 | 30 | 70-79 | 0 |
| NOV | 72 | 28 | 80-89 | 0 | | NOV | 30 | 35 | 80-89 | 1 |
| DEC | 90 | 56 | 90-100 | 0 | | DEC | 30 | 81 | 90-100 | 0 |

In Nyeri, March, June, July and December showed weights greater than 80 for RFE. None of the months had a weight greater than 80 for GPCP. For Thika, Jun showed weights greater than 80 for RFE whereas December showed a weight greater than 80 for GPCP.

## 4.0 Conclusion

RFE performed better than GPCP for the six stations. The inputs for RFE include estimates from PM sensors, IR data and daily GTS data. GPI estimates used in RFE V2 are derived from fixed temperature threshold and fixed rain rate. This poses a problem especially because of the warm rain experienced in the Mt. Kenya region. GPI algorithms underestimate rainfall over coastal and mountainous regions in Africa (Dinku *et al.*, 2007). The proportion of PM data used is small hence the influence on the precipitation received is small.

GPCP combines IR and PM rain estimates and rain gauge observations. It does not use the PM rain estimates and gauge measurements directly. PM (SSM/I) delineates the rain areas in the IR data. Variation between observed and GPCP data could arise if the SSM/I did not sense the rain occurrence due to the warm nature of the rain or rain period experienced after the satellite had passed that location.

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